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Numerical Investigation of Temperature Distribution in a Container-type Plant Factory

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ABSTRACT

A container-type plant factory is a closed facility for crop production with artificial lighting and a controlled environment allowing year-round crop production. In a plant factory, a poor ventilation system can result in physiological problems and unequal post-harvest quality which will lower the crops' commercial value. This study was conducted to investigate the temperature distribution in a container-type plant factory via computational fluid dynamics (CFD), followed by experimental studies for validation. A three-dimensional computational fluid dynamics (CFD) model was developed to simulate the container-type plant factory with air conditioning and an exhaust fan providing cooling air and ventilation across the plant factory. The predicted airflow distribution on the upper shelves accommodating crops shows that the average temperature is about 23.74 °C while for lower shelves is 23.59 °C. This shows the temperature distribution is rather uniformly distributed across the plant factory. A validation between experimental data and simulated values indicated that the temperature distribution had a deviation smaller than 2%, suggesting the validity of the CFD studies. Hence, the CFD model was used to simulate several operational conditions towards optimizing the indoor condition of the plant factory.

Keywords:
Temperature distribution; plant factory; indoor farming; CFD

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1. Introduction

In recent years, the world has faced problems due to population expansion, climate change and environmental pollutants [1,2]. Food security and sustainability become one of the nation's agendas to overcome society's needs, triggered by many issues including an unstable supply of food, shortage of resources, and degradation of land resources. There is an increasing interest in adopting Indoor Farming or controlled environment agriculture (CEA) as a response to land resource issues, especially in the urban area. A plant factory is one of its types, typically place in an indoor area such as a building or warehouse. Inspired by its name, plant factory targets to efficiently perform plant production in a "factory," to increase production quantity and quality in a shorten process times[3]. The new agro-technology uses artificial lighting to provide the light source for the plant

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and generally equipped with air conditioning, nutrient solution system, multi-layer cultivation rack and so on. The interior room is not influenced by the weather due to its airtightness and thermal insulation, thus the high-precision environment can be controlled [1]. Factors including photosynthetic, water vapour pressure deficit, air temperature, CO_2 concentration, light quality, lighting cycle and air current speed can be set up accordingly to achieve optimal growth conditions. It enables continuous production of horticultural crops consistently year around [4]. By performing vertical farming, the agriculture technology promises benefits including high annual productivity per unit land area, high resource use efficiency, and production of high-quality plants without using pesticides. The number of commercial plant factories has been increasing significantly since 2015. As of September 2018, it was estimated over 200 Plant factory was developed in Japan, about 100 in Taiwan, and over 500 in the world including China, the USA, and Korea [1].

In indoor plant factories, controlling room temperature is an extremely important part as it contributes a huge influence on plant cultivation [5]. To provide suitable temperature conditions and effective airflow movement around crops, the plant factory must be designed with proper air conditioning and ventilation system [6,7]. The ventilation system will be the main part of providing cool air and at the same time bringing out the heat inside the container-type plant factory. Incorrect setting temperature conditions can produce physiological problems and unequal post-harvest quality, lowering commercial value. The most common sign of plant physiological disorder is tip burn, which occurs most frequently in plant factories with low air velocity. According to reports [4], lettuce tip burn is caused by the presence of a stagnant air border layer and poor transpiration rates. The tip burn in lettuce crops is caused by a calcium deficit and is characterized by browning lettuce edges. Due to the presence of a stationary boundary layer under high transpiration demand circumstances, it frequently occurs at inner and newly growing leaves with low transpiration rates.

This recent times, computational fluid dynamics (CFD) have been ideally used because it is a numerical modelling technique that can provide an accurate manner of measuring the effects of machinery design, environment characteristics and meteorological conditions inside a virtual environment. As a result, the quantity of physical experimentation can be significantly decreased, but not eliminated [8]. In terms of food production, it could be used as a design tool to forecast fluid flow, heat transport, and chemical reactions inside complicated systems. The vast amount of work done using CFD in the agro-food business over the last two decades indicates its ever-increasing potential to help engineers comprehend the phenomena related to production and the conversion of basic agricultural resources (bio-products) into the healthy food we eat today [9]. In terms of the ventilation system, some studies have utilized CFD for optimizing a ventilation system because good ventilation is crucial for enhancing indoor air quality and lowering occupant exposure [10]. The CFD methodology is recognized as a potent tool for modelling the environment created within greenhouses and developing structural design improvements for ventilation efficacy [11]. CFD modelling is extensively utilized in the field to estimate the airflow and heat patterns of naturally and artificially ventilated greenhouses [12]. CFD systems make it easy to study the scalars and vector fields present in the greenhouse environment by resolving the air transport equations that regulate ventilation [13].

This study aims to investigate the temperature distribution in a container-type plant factory with a steady heat load using CFD. It is imperative to observe the temperature distribution to avoid any possible presence of hot spots that can result in tip burn on the crops produced, which will reduce their quality [14]. Apart from that, the usage of air-conditioners can also be minimized so that the total electricity consumption during operation can be reduced.

1.1 Container Type Plant Factory

The container-type plant factory (PF) is a type of indoor farming that uses transport containers either 20 or 40-footer and is equipped with plant cultivation systems such as artificial lights, cultivation racks and air-conditioning systems [15]. This type of PF can be mobile being set up anywhere if electricity and water are available. The container type adopts a modular design, and it is a combination of a modular plant factory that is specifically designed for vegetable cultivation, allowing units and individuals involved in agriculture cultivation to customize the plant space based on their needs. It has many advantages, such as flexible combinations of modules, transferable, mass production, advanced inventories, and others. The container type PF can also be used directly in any typical environmental conditions, though they are preferred to be set up in a ventilated place with a building facility to minimize its operational energy usage. The container type PF is compact, with the highest crop density for a given area as compared to other types of indoor farming [16]. Figure 1 shows a typical container-type indoor farming facility.

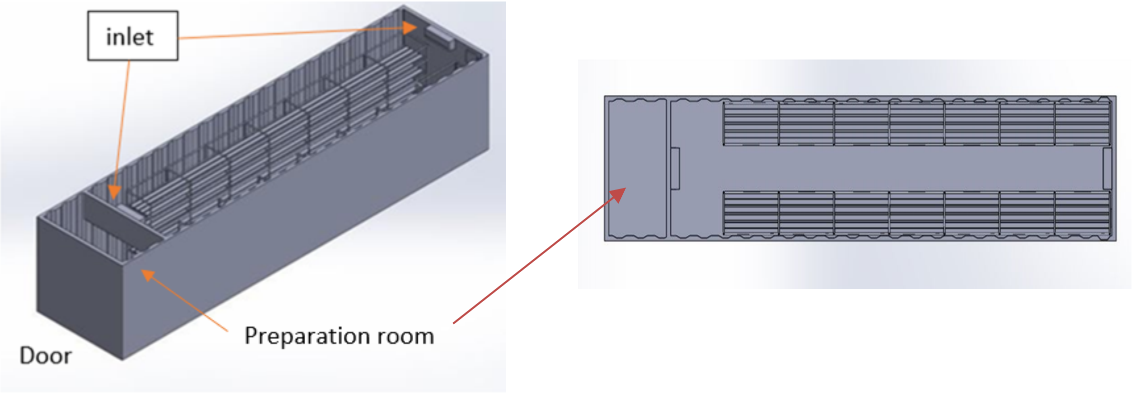
Fig. 1. Container-type indoor farming facility at (a) zero and (b) transplanting stage

2. Materials and Methods

2.1 *Experimental Setup*

The experiment was carried out at University Tun Hussein Onn Malaysia. A container-type plant factory with dimensions 2.8m (W) x 12.2 m (L) x 2.8m (H) equipped with two air conditioners (AC) as an inlet unit. There is also an exhaust fan and ventilation fan to assist air circulation. The location of the first AC was near to preparation area and the other one was at the end side of the wall (Figure 2). Two cultivation shelves were symmetrically placed on the right and left sides of the wall.

Each consisted of 4 tier racks, and there were 4 long gutters on each rack. LED lights were installed at the ceiling of the cultivation bed.



(a) (b)

Fig. 2. (a) 3D and (b) top view drawing of inner container plant factory

2.2 Measurement Point

The container was divided into the upper and lower area. The upper part was then divided into 12 sections, and point measurement was identified at the midpoint of each section at z=0.075 from the reference datum. The next point was set up at the lower part at z=0.905. A total of 24 points were identified to measure temperature and later used for simulation and verification. The cross-section view of location points was shown in figure 3.

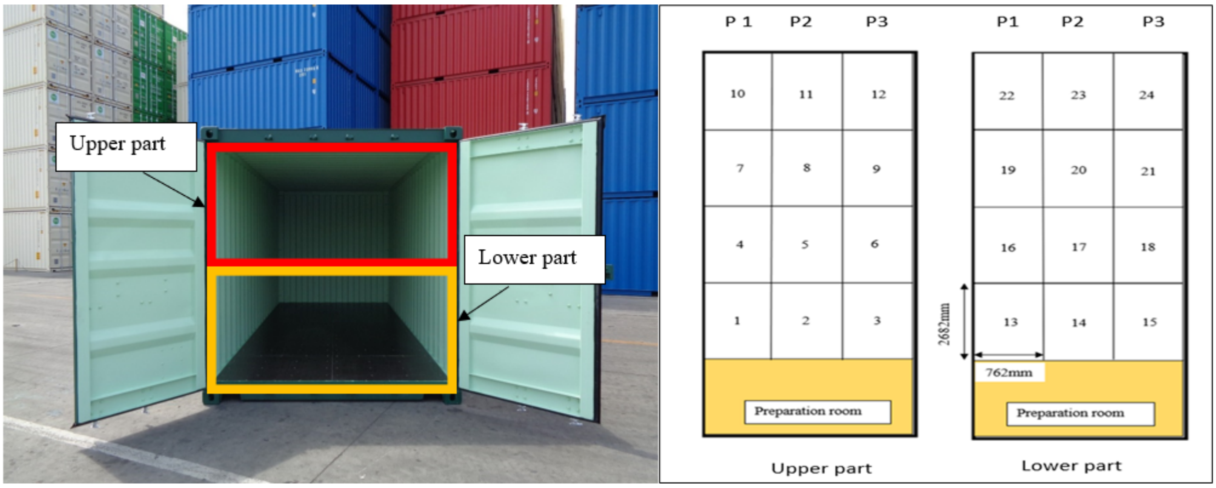


Fig. 3. (a) Upper and the lower part in container (b) location of data point measurement

For comparison and analysis, all the points have been organized into 3 planes (P1-P3) in each area. Plane 1 is across the container at the left side of the wall, while Plane 2 and Plane 3 represent middle and right access from the door.

2.3 *CFD Analysis Process*

The workflow for the numerical investigation is given in Figure 4. The first step of the CFD analysis process is to formulate the flow problem by acknowledging the objective of the analysis. In this project, the aim is to investigate the temperature distribution in a container-type plant factory with a steady heat load. To attain this, the easiest way is to simulate the temperature distribution across the container using ANSYS software.

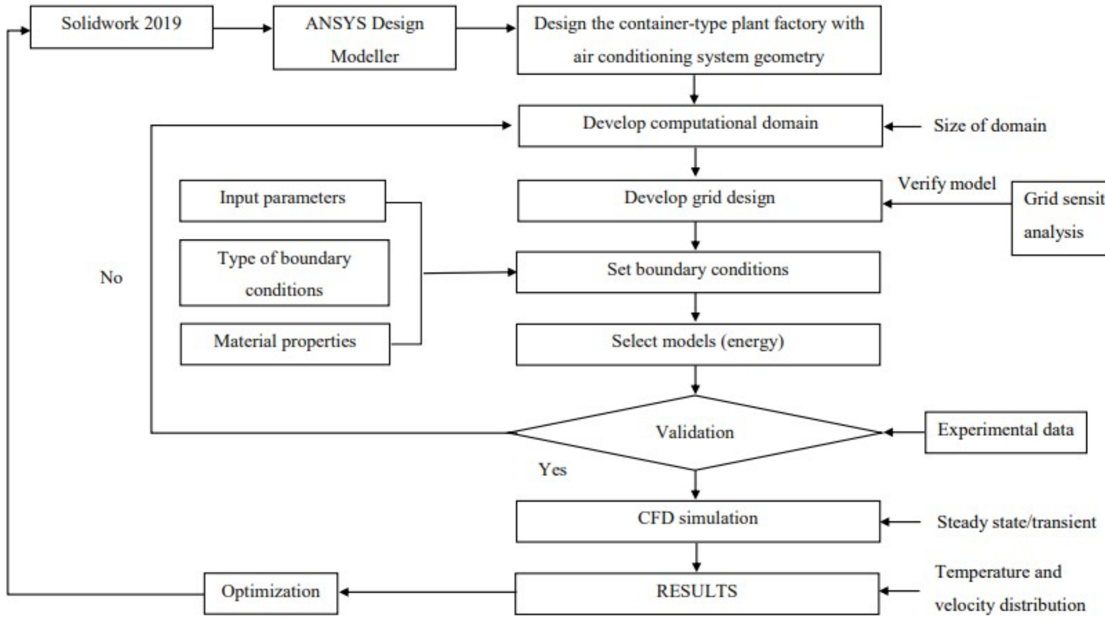


Fig. 4. Design planning of the numerical investigation

Design planning is the most important step before data measurement. The simulation process starts with developing the model of the container-type plant factory including the ventilation system. Next, develop the domain with a suitable size. Boundary conditions were set considering indoor temperature data, material properties and also air conditioning system. Finally, the simulation and experimental data will be validated and measured.

2.3.1 Formulation of the Flow Problem

The flow domain for this project is mainly sourced from the air conditioner unit and ventilator fan. Therefore, AC was set as an inlet and the ventilator fan would be the pressure outlet. With a realistic input of parameters towards the inlet and pressure outlet, it would simulate a real-life flow inside the container-type plant factory. The streamlines or operating pressure condition was set up at 101325 Pascal meanwhile the reference location is (0,0,0) from the x-axis, y-axis and z-axis respectively. The gravity pressure was measured at the y-axis with a 9.81 m/s^2 in a downward direction. The Boussinesq parameters applied is 24℃ operating temperature. The variable density parameters are specified operating density which is 1.225 kg/m^3

The appropriate temporal modelling for this study would be steady state. Even though there are some heat loads produced from the device used such as the ventilator fan, water pump and also heat from the wall of the container, it could be neglected because it does not affect the result against time. The nature of viscous flow of this project is viscous in a turbulent flow. The gas in this project would use air with a constant density of 1.225 kg/m^3. The specific heat is constant which is 1006.43 J/kg.K. The thermal conductivity is constant at 0.0242 W/m.K. and lastly, the viscosity of the air is at a constant of 1.7894 x 10-5 kg/m.s.

2.3.2 Establish Modelling Geometry

Geometry modelling is a physical domain's geometry modelling where all the physical processes occur inside the container-type plant factory, disregarding the occurrence outside the plant factory itself. The geometry modelling for this study was using Solidwork 2019 and then converted into ANSYS Space Claim.

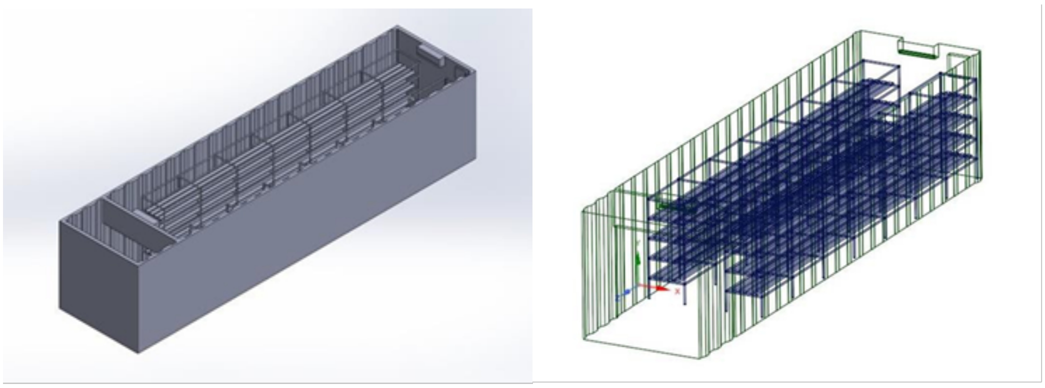


Fig. 4. Geometry of Container-plant factory drawn by Solidwork and converted to ANSYS Space Claim

2.3.3 *Mesh Generation*

Mesh generation is the discretization of the geometrical domain and is based on the production of a numerical grid that is used to solve the governing (model) equations numerically. A specified amount of non-overlapping and mutually related pieces make up the domain subdivision in cells. The mesh generation process which has been applied in the geometry is mostly on global mesh with the setting of element sizing of 90 mm.

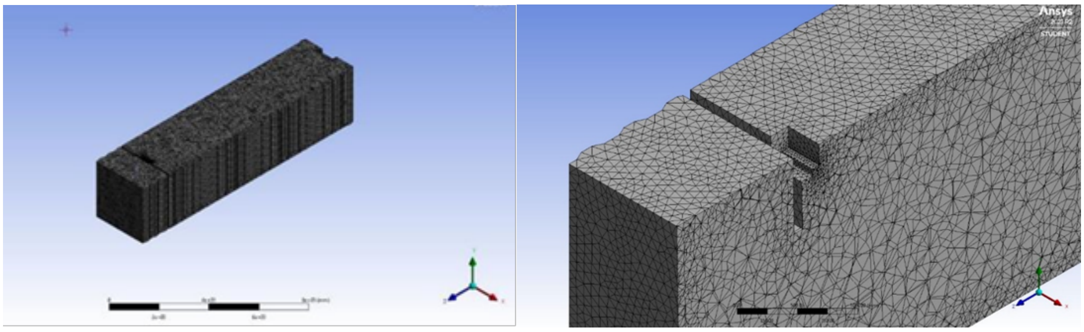


Fig.5. Close up of meshing geometry

2.4 Establish boundary condition and simulation strategy

A few boundary conditions need to be identified which are inlet, wall and also outlet. For inlet, the boundary conditions will be velocity-inlet type. The velocity magnitude will be 1.0 m/s with a turbulent intensity of 1% and a turbulent viscosity ratio of 5%. The walls around the container-type plant factory has been established as solid no-slip boundaries. Lastly, for the ventilator fan, the boundary conditions will be set as pressure outlets. The pressure gauge for the pressure outlet is 0 Pa.

Table 1
Input parameter for simulation

No	Input parameter	Boundary Conditions	Value
1.	Air Conditioner	Inlet	Velocity: 1.0 m/s Pressure: 0 Pa
2.	Ventilator fan	Pressure outlet	Pressure: 0 Pa
3.	Container-type plant factory wall	Wall	-
4.	Rack	Wall	-

The Chien *k*-epsilon two equations model (*KE*-Chien) was applied to compute the turbulence to the mean flow by simultaneously solving two additional governing equations.

2.5 Establish Aerodynamics model

The airflow inside the container-type plant factory can be calculated by using numerical calculation of airflow which will be considered as mathematical formulations of the conservation law of fluid mechanics. Therefore, by applying mass, momentum, and conservation of energy, the equation can be written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_j) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial}{\partial x_i}\left[-\rho\delta_{ij} + \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g_i \tag{2}$$

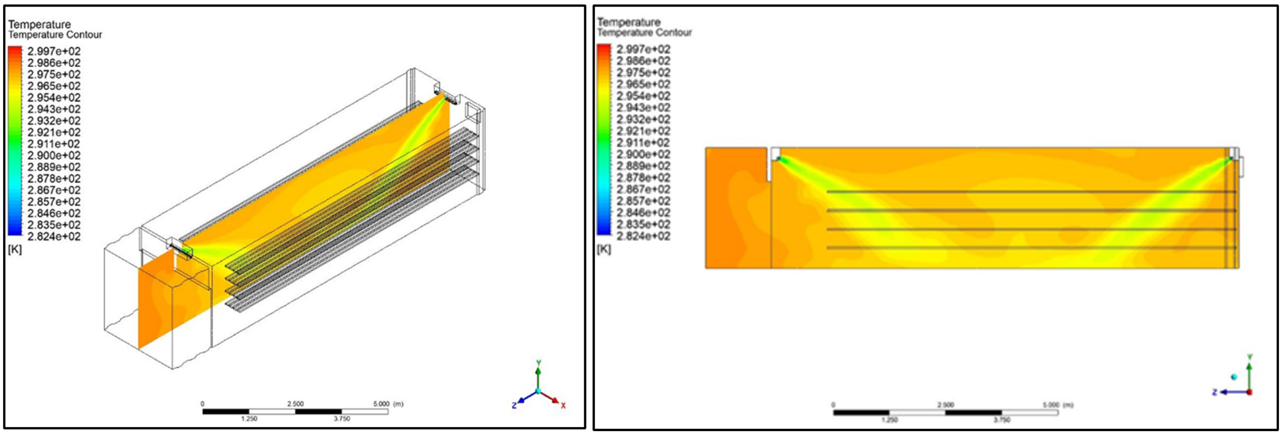
$$\frac{\partial}{\partial t}(\rho C_a T) + \frac{\partial}{\partial x_j}(\rho u_j C_a T) - \frac{\partial}{\partial x_i}(\alpha \frac{\partial T}{\partial x_j}) = S_T \tag{3}$$

3. Result and Discussion

The governing equations for the conservation of mass, momentum and energy equations were solved simultaneously using FLUENT to obtain the temperature distribution inside the container-type plant factory. The steady-state assumption is adequate in the present study as the operating parameters inside the container-type plant factory were almost constant, particularly the heat dissipated by the grow lights which were the primary heat source. Other equipment has negligible heat transfer. As for the heat transfer from the sun during daytime, this also has a very minor effect as the studied plant factory container is made from a refrigerated container which is heavily insulated with negligible heat infiltration.

3.1 Numerical Simulation: Temperature Distribution Inside Plant Factory

The air-conditioners in the plant factory have a capacity of 1.5 hp (1.01 kW) and the pre-set temperature for both air-conditioners was 16 ºC, considering the relatively large size of the container as well as the length in comparison to width and height. Figure 6 shows the contours figure obtained from the simulation result. The temperature distribution across the container plant factory was focused specifically on the centre of the container, by considering the location of AC and the angle projection at 18 degrees which projects the airflow downward. It can be concluded that the temperature from the air conditioners which has been set as 16℃ cools down the whole container with an initial temperature of 22℃ to create a controlled temperature inside the plant factory.



(a) (b)

Fig. 6. Temperature distribution across the container-type plant factory in simulation view (a) 3D view (b) Vertical plane

3.2 Validation of Temperature Distribution

As described in section 2, the plant factory was divided into upper and lower levels with rectangular grids where the temperature values were measured at the midpoint of each of these grids. The division of upper and lower levels was done based on the operational practice in the plant factory where the upper levels and lower levels were planted with different leafy vegetables such as green coral and oakleaf which physically differs in size. These measurement locations were labelled as datapoints 1 to 12 for the upper plane and 13 to 24 for the lower plane whereby the planes were based on the height (y-axis) and length (z-axis) of the container. To enable comparison from CFD simulation, a total of 24 points were extracted in post-processing with the same locations as the experiments. Both temperatures obtained from experimental work.

For the upper level, the measured temperatures from experimental work range from 18.9 ºC to 23.6 ºC, while the simulation indicated a smaller band of distribution ranging from 22.07 ºC to 24.33 ºC. The larger temperature distribution from experimental measurements was expected as it represents the actual interior condition of the plant factory, while the simulation uses a rather simplified model with several assumptions as mentioned in the previous section. On the other hand, referring to Table 3 which presents the lower level in the plant factory records a smaller temperature distribution from both experimental and simulation work. The temperature measured from the experiment ranged between 21.2 ºC to 23.7 ºC while from simulation, it ranged from 22.67 ºC to 24.19 ºC. The lower plane has better temperature distribution because the cool air supplied by the split unit air-conditioners is relatively higher in density and therefore descends. Hence the cooler air was able to absorb heat generated by the grow lights much faster at the bottom section.

Table 2
Comparison of temperature distribution from the experimental data and CFD modelling on each plane at the upper level

	Plane 1				Plane 2				Plane 3			
Point	1	4	7	10	2	5	8	11	3	6	9	12
Experimental data (°C)	23.6	25.5	22.3	22.5	18.9	21.5	22.4	22.4	23.1	21	22.4	22.4
Simulation data (°C)	23.741	23.830	23.914	24.083	23.813	23.558	22.076	24.235	23.813	23.53	23.975	24.335
Difference	0.141	1.33	1.614	1.583	4.913	2.058	0.324	1.835	0.713	2.53	1.575	1.935
Deviation (%)	0.048	0.45	0.547	0.536	1.683	0.70	0.107	0.621	0.241	0.861	0.533	0.655

Table 3
Comparison of temperature distribution from the experimental data and CFD modelling on each plane at the lower level

	Plane 1				Plane 2				Plane 3			
Point	13	16	19	22	14	17	20	23	15	18	21	24
Experimental data (°C)	22.5	21.6	21.2	21.2	23.7	21.6	21.6	22.4	22.9	21.2	21.6	21.4
Simulation data (°C)	23.500	23.483	23.549	23.746	22.674	23.48	23.694	24.086	23.126	23.34	24.225	24.186
Difference	1.000	1.883	2.349	2.546	1.026	1.88	2.094	1.686	0.226	2.14	2.625	2.786
Deviation (%)	0.338	0.639	0.798	0.865	0.346	0.638	0.711	0.571	0.076	0.727	0.891	0.946

In terms of deviation between both experimental and simulation values, the percentages were very small indicating very good agreement between both. It can be seen here that the deviation between experimental data and simulation data is below 2% at the upper and lower level. The difference between experimental data and simulation data is varied between 0.141 and 2.058 at the upper level. Table 3 represents the comparison between experimental data and simulation data at the lower level of the container-type plant factory. The difference between the temperature distribution of experimental data and simulation data is 0.226 and 2.786. The deviation between experimental data and simulation data is between 0.076% and 0.946% which is below 1%.

The data can be figured out and presented in Figure 8 and Figure 9. Graph of temperature distribution between experimental data and simulation data at the upper level indicates that the average temperature distribution at the upper level and lower level of the container-type plant factory is within ±5% and it shows that the container-type plant factory has a good temperature distribution across the container-type plant factory

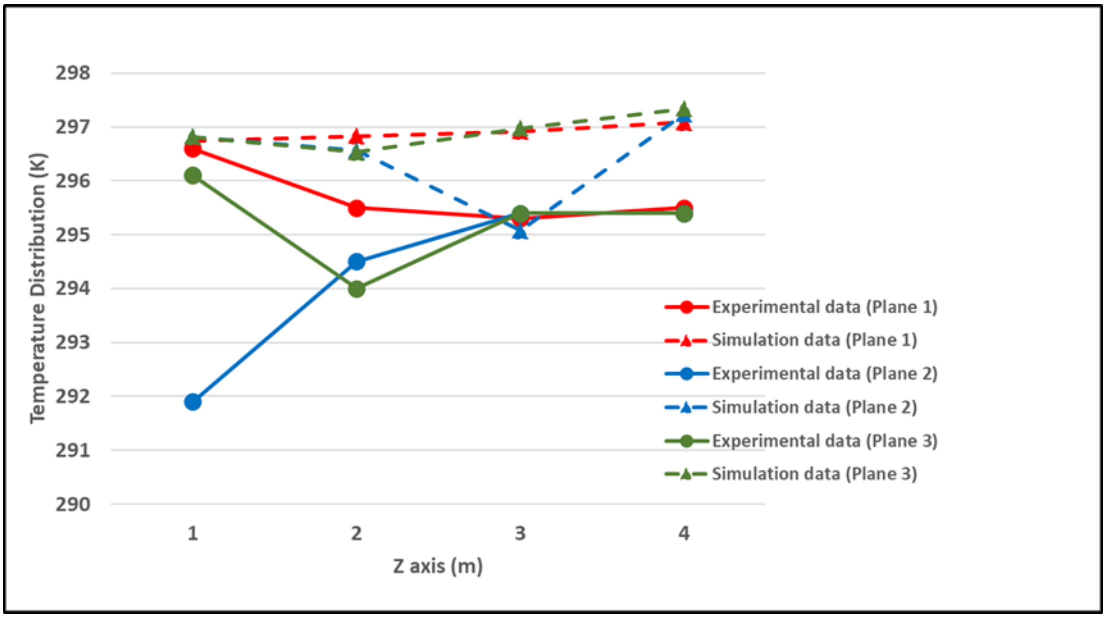


Fig. 8. Graph of temperature distribution inside plant factory (upper level)

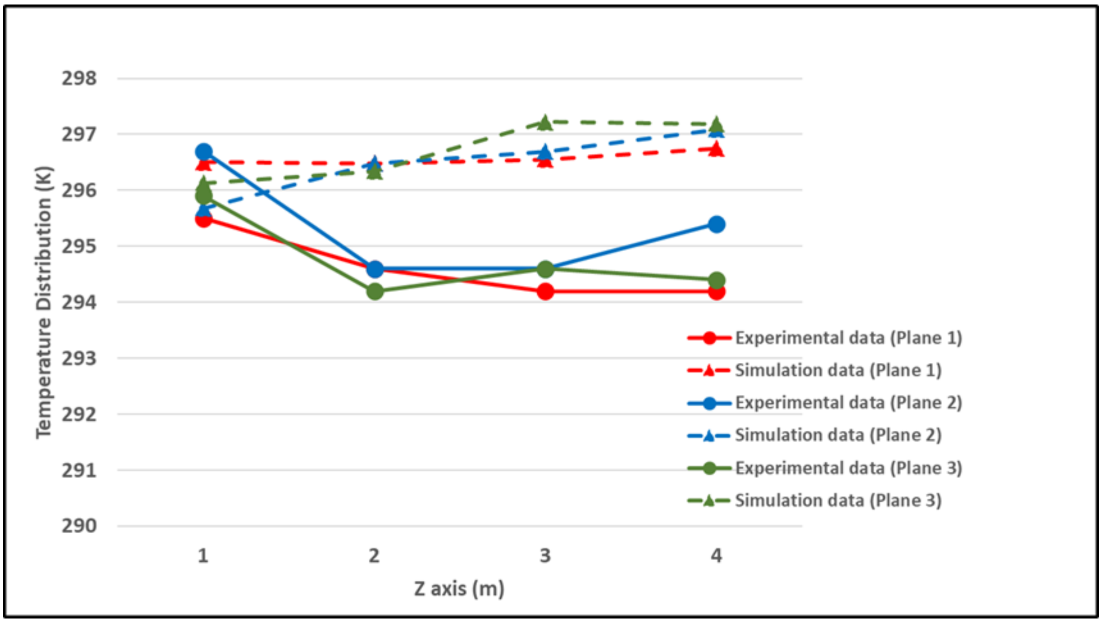


Fig. 9. Temperature distribution inside the plant factory (lower level)

The data can be figured in Figure 8 and Figure 9. Graph of temperature distribution between experimental data and simulation data at the upper and lower level are presented. Both graphs show a good agreement between experimental work and simulation, indicating the validity of the present CFD work. The maximum deviation between both was less than 2%, as shown in Table 1. Overall, the temperature has a very small distribution inside the plant factory which is highly desired in indoor farming. This also indicates that the present layout of the cultivation system which involves nutrient film technique (NFT) gutters, piping, a racking system, seeding pots and grow light location was satisfactory. However, it should be noted that small temperature distribution shall be complemented with good airflow in between the plants and racking to enhance the exchange of CO2 during photosynthesis and O2 during respiration among plants, hence small fans can be added at the end of each rack in the plant factory. This shall be followed by an investigation of the airflow and velocity distribution in the plant factory in the future study.

4. Conclusions

In summary, the main objective of the study to investigate the temperature distribution inside the container-type plant factory with a steady heat load using CFD analysis has been achieved. The experimental work carried out resulted in a deviation of less than 2% when compared with temperature distribution obtained from CFD works, indicating good agreement between both. The major conclusion that can be derived from this study is the temperature distribution is small in a container-type plant factory and hence ideal for indoor farming. Some improvements can be incorporated into the existing system such as integrating small fans on every shelf to enhance air circulation and further improve the present condition.

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