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Model Feasibility of Air Pollution Treatment Using Plants as Filter by Computational Fluid Dynamic (CFD) Analysis: A Case Study in Laboratory

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Abstract

This research was the study of airflow in model of air pollution treatment using plants by Computational Fluid Dynamic (CFD) analysis as a case study in laboratory. The objective was to explore a suitable plants placement to filtration efficient of air pollution treatment. The size of model was 100 x 80 x 30 cm, with air inlet and air outlet of 10 x 10 cm. All model had 4 size panels inside. Three different methods of panel placement were tested consisted of; 1) placing to block airflow, 2) placing to zigzags panels and 3) placing to parallel panels. The inlet air velocity was setup as; 0.5, 1.0, 1.5 and 2.0 m/s, respectively. The parameters were measured consisted of air velocity and air temperature distribution in 12 locations by CFD modeling. It was found that airflow in treatment box model 2 was able to circulate in all locations that had similar average airflow throughout the model. In model 2, the average airflow velocity (top view/front view) was 0.23/0.27, 0.57/0.43, 0.71/0.80 and 0.97/0.96 m/s, respectively. At all velocities of inlet air, airflow passed through all locations and contacted with surfaces of every panels. As a results, there was a high being absorbed by air pollution treatment by plants such as; ,mosses and lichen to assess the concentration of heavy metal in atmosphere. For the temperature distribution, it was found that the model 2 had the most suitable conditions. Therefore, this study found that the model 2 with alternating zigzags panels was the most filtration efficient model for air pollution treatment. The results will be compared with further testing in laboratory.

Keywords: CFD; Plants as filter; Air pollution treatment; Treatment model; Zigzags panels

1. Introduction

The fossil fuel resources were used in industrial development that has caused air pollution. As well as the use of transportation of internal combustion vehicles has caused air pollutions, such as CO, CO_2, SO_2, NO_x, $PM_{1.0}$, and $PM_{2.5}$ (Gwilliam *et al,* 2004, Krzyzanowski *et al.,* 2005, Gorham, 2002, Perera, 2018, Chaisee *et al.,* 2021, Htwe *et al.,* 2021).

It affects the human life (Rees, 2016; Anenberg *et al.,* 2019; Manisalidis, 2020) and creates impact all over the world. However, the relevant agencies have not yet been able to find solutions to this problem. Many previous research have been focused on air pollution control, for example, air pollution control in wastewater treatment plants (Bonoli *et al.,* 2014; Mashaqbeh *et al.,* 2015), the use of fabric for air filtration (Jagtap, 2018), which had a wide range of applications in industrial dust removal processes. Furthermore, there were studies on dust removal by sprayed water to capture dust particles in the air (Bhargava, 2016), and particle reduction by using the effective scrubbers (Ferella *et al.,* 2018). But there were few studies on the use of plants in air pollution treatment (Cabrera *et al.,* 2019; Palmaab *et al.,* 2017; Siu *et al,* 2017; Thomas, 2005). Plants are mediators in gaseous and particulate compounds (Bender *et al.,* 2020) and air quality assessment can indicate the human health risk. Organisms and biomaterials such as; mosses and lichen were commonly used to evaluate air quality (Berg *et al.,* 1995; Bleuela *et al.,* 2005; Boquete *et al.,* 2013) that moss is an excellent bioindicator for trace element in air (Kayeea *et al.,* 2015). Moss or a non-vascular flowerless plant can be used as air purification and produce oxygen. It can trap dust for air purification, maintain temperature and humidity (Wongkuna, 2009). The moss was cultivated in tall towers to produce oxygen and trap airborne dust in City Park, United Kingdom. It has property of retaining moisture equivalent to 275 trees and cooling the environment (The city tree, 2020). However, moss has not yet been studied for dust treatment that was no study on the suitable model of using moss. Therefore, the study of moss airflow dynamics can increase the efficiency of air pollution treatment.

There were studies on the mathematical model of airflow dynamics for engineering applications. CFD model technique can predict indoor air circulation (Malik *et al.,* 2018; Usman *et al.,* 2020; Liu *et al.,* 2018). Many studies used to analyze indoor air quality, thermal comfort and ventilation efficiency (Liu *et al.,* 2017; Barbosa *et al.,* 2018; Liu *et al.,* 2020; Kong *et al.,* 2015). CFD have not be replaced the experimental and theoretical analysis, but compared to experimental methods by flow distribution and concentrations in modeling domains (Li *et al.,* 2011; Liu *et al.,* 2015; Srebric *et al.,* 2015; Muhsin *et al.,* 2017; Ren *et al.,* 2020; Zhang *et al.,* 2020). However, the quality of CFD analysis requires grids sufficiency, model selection, evaluation, numerical error and numerical parameters control for validation (Scislo *et al.,* 2021; Song *et al.,* 2021; Melendez *et al.,* 2021; Kamar *et al.,* 2018). The literature review on CFD techniques in indoor environments (Liu *et al.,* 2020) have application, trends (Hussin, 2020), inspection, validation (Liu *et al.,* 2016), quality control (Alam *et al.,* 2021) and turbulence models (Cao *et al.,* 2018; Cao *et al.,* 2018), that the use CFD algorithms of modeling (Kato, 2018; Wang *et al.,* 2018) to discussions for indoor ventilation (Malik *et al.,* 2018; Li *et al.,* 2011; Ozsagiroglu *et al.,* 2021; Wentao *et al.,* 2018). There was a study of design and development of one-way airflow in drying chamber (Pintana *et al.,* 2017). The influence of the plenum box has been studied on turbulent airflow patterns. There are many experiments that were compared with two numerical estimates using CFD software. The minimum inlet speed can maintain the flow field inside rotor below 100 m/s (ideal turbulence) (Akankwasa *et al.,* 2016). The ventilation design of packaging system was developed to improve the steady of cooling and reduce energy consumption (Gong *et al.,* 2021) that $k - \varepsilon$ turbulence CFD model was used for analysis (Awwad *et al.,* 2017). Previous studies have not been determined a suitable plant for air pollution treatment, but only the design of placing plants for air pollution treatment that provides architectural aesthetic. There was no study on using plant sheets that efficiently trap dust or pollutants and generate biological reaction. Therefore, a modeling of airflow dynamics in air pollution treatment by plants should be studied to investigate the suitability of plant placement patterns for maximum efficiency of air pollution treatment.

Therefore, this research aimed to study the CFD mathematical model of airflow dynamics by using mosses for air pollution treatment filter as laboratory-level case study. Testing boxes for air pollution treatment by mosses were designed to determine the proper placement of plants to achieve the highest efficiency in air pollution treatment. The development of bio-innovative research can solve problems and reduce air pollution in the city. Moreover, air purifier machine is expensive and has higher production cost than using natural technology for air purification.

2. Materials and Method

2.1 Experimental design and setup

Analysis of the behavior of the air was transient with the energy equation. The equation used for calculated from Eq. (1) – (4) (Petrila, *et al.,* 2005; Pozrikidis, 2011; Versteeg *et al.,* 2007)

Continuity

$$\frac{\partial \rho}{\partial t} + div(\rho u) = 0 \quad (1)$$

x-momentum

$$\frac{\partial(\rho u)}{\partial t} + div(\rho u u) = -\frac{\rho p}{\partial x} + div(\mu grad u) + S_{Mx} \quad (2)$$

y-momentum

$$\frac{\partial(\rho v)}{\partial t} + div(\rho v u) = -\frac{\rho p}{\partial y} + div(\mu grad v) + S_{My} \quad (3)$$

z-momentum

$$\frac{\partial(\rho w)}{\partial t} + div(\rho w u) = -\frac{\rho p}{\partial z} + div(\mu grad w) + S_{Mz} \quad (4)$$

The computational fluid dynamics analysis is based on the Navier-Stokes equation. The equation can be calculated from Eq. (5) (Bichkar *et al.,* 2018).

$$\left(\frac{\partial \rho \phi}{\partial t}\right) + \left(\frac{\partial \rho u \phi}{\partial x} + \frac{\partial \rho v \phi}{\partial y} + \frac{\partial \rho w \phi}{\partial z}\right) = \Gamma\left(\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2}\right) + S(\phi) \quad (5)$$

This experiment investigated the feasibility of CFD model in air pollution treatment using plants as filters and compare air velocity. The k – ε turbulence models were applied in turbulent flows modeling that have mathematical simplicity and need low computational demand. The model size was 100 x 80 x 30 cm. Air inlet had size of 10 x 10 cm and air outlet size of 10 x 10 cm. All designs had 4 similar size panels inside but the placement was different, as shown in Figure 1 and for experiment can be show in Figure 2. The relevant parameters were measured before and after as shown in Figure 3. Three types of models were tested: 1) placing to block airflow, 2) placing to zigzags panels and 3) placing to parallel panels. The hypothesis was shown in Figure 4 - 6 and the conditions used for the analysis were given in Table 1 and Table 2.

The air velocity and temperature were measured inside the treatment box that reduces the speed of airflow when the air passed through panels. It was aimed to investigate inlet air flow throughout the box and panel. Air velocity specified in the model was: 0.5, 1.0, 1.5 and 2.0 m/s with three models were compared. The CFD was used to analyze data and flow rates patterns in different locations within the box that was aimed to study airflow, air circulation and temperature distribution.

Table 1. Assumptions used in analysis

No.	Condition
1	Analysis of fluid properties depends on the coordinates and time (transient)
2	Use of air properties as a fluid property in analysis
3	Analysis in 3D
4	Analysis by considering the gravity
5	The viscosity model uses the Standard k-epsilon equation (2 eqn).
6	Solve the Temperature-Velocity Coupling SIMPLE Schemetic

Table 2. Conditions used in analysis

No.	Parameter	Unit
1	Velocity starts in the model.	m/s
2	Outdoor air temperature	K
3	Heat transfer coefficient	$W/m^2 \cdot K$
4	Simulation time	hr
5	Time step size	s

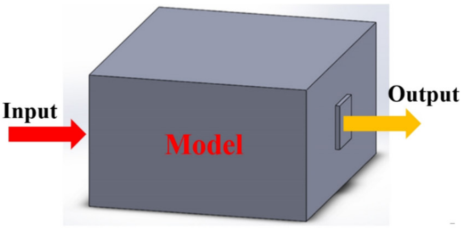


Figure 1. Model used for analysis by CFD.

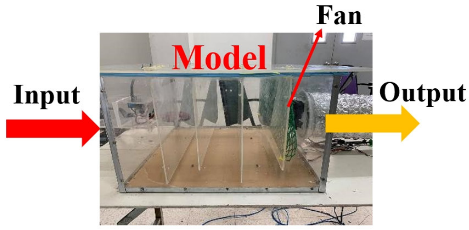


Figure 2. Model used for testing in laboratory.

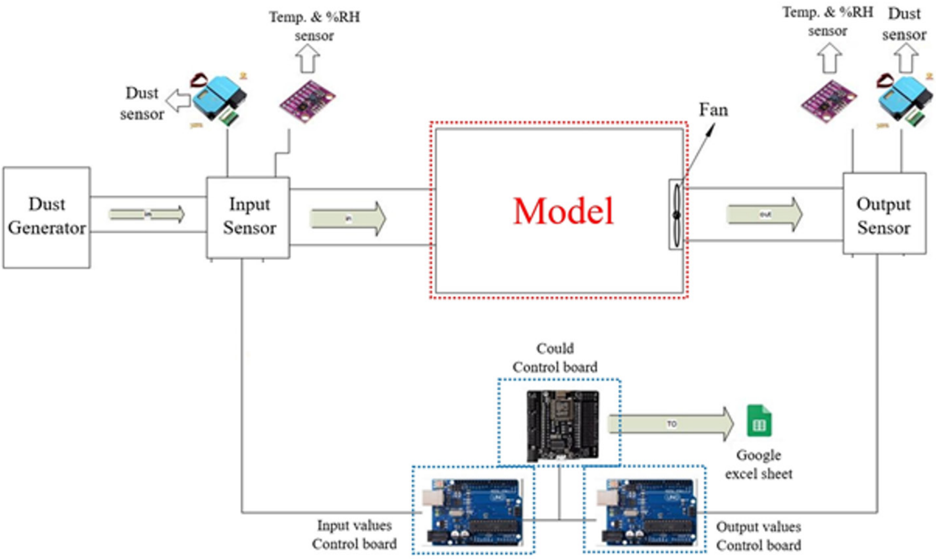


Figure 3. Diagram of the instrument for measuring the parameters of the plant dust treatment system.

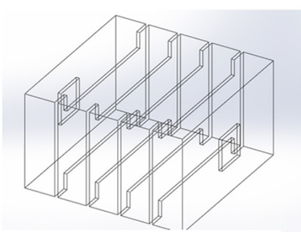


Figure 4. Placing plants blocking panels to allow airflow

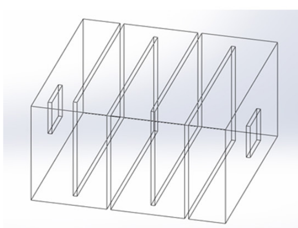


Figure 5. Placing plants zigzags panels to allow airflow

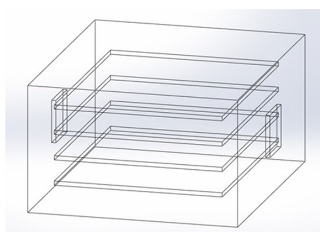


Figure 6. Placing plants parallel panels to allow airflow

2.2 Materials

The model was constructed to study airflow through air treatment plants to maximize the efficiency of air pollution treatment, as showed in Figure 6-8. Three different models were used to study air velocity at the panels that were installed with treatment plants. Air circulation around treatment plants can increase dust absorption.

Twelve locations inside air treatment box were determined for airflow analysis. Each position was evenly distributed within the treatment box through panels. All 12 locations were arranged in 4 rows, 3 columns each, with space of at 20 cm distance. The position codes were assigned starting from the air inlet side to the air outlet, as of A - 1, A - 2, A - 3, B - 1, B - 2, B - 3, C - 1, C - 2, C - 3, D - 1, D - 2, D - 3, respectively, as showed in Figure 10. Average data of the velocities and temperatures at each position was collected to analyze efficiency of air distribution of each treatment box which the sufficient air distribution results in high efficiency of exhaust gas treatment.

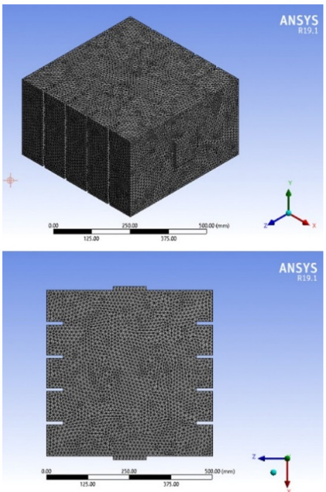


Figure 7. Model for placing plants blocking panels to allow airflow

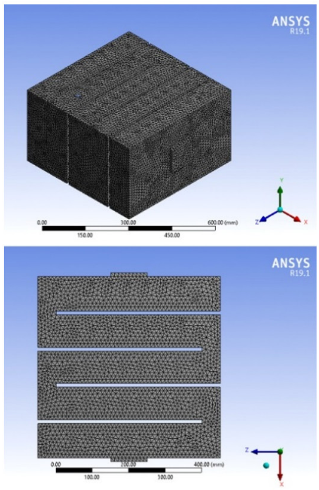


Figure 8. Model for placing plants zigzags panels to allow airflow

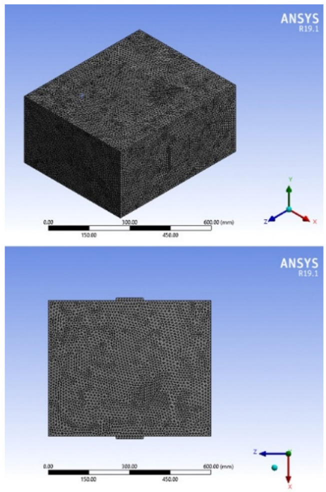


Figure 9. Model for placing plants parallel panels to allow airflow

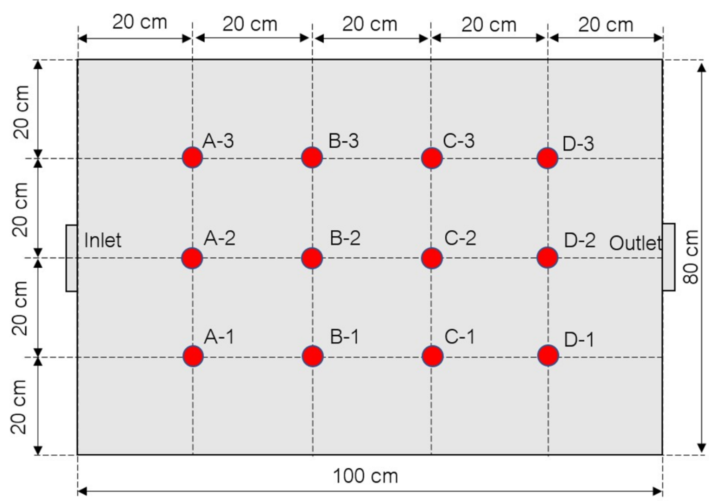


Figure 10. Twelve locations inside air treatment box were determined for airflow analysis.

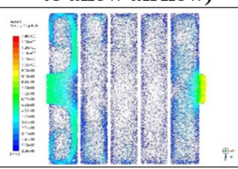
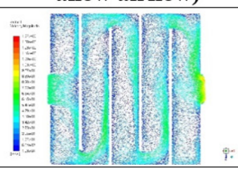
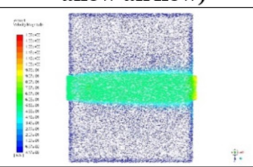
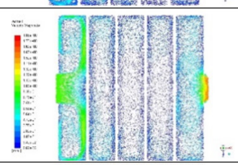
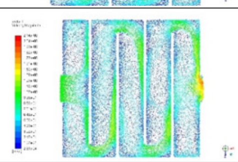
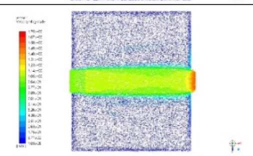
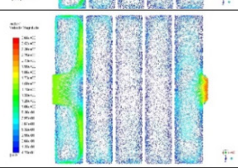
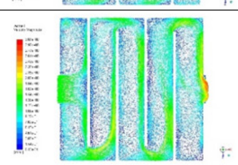
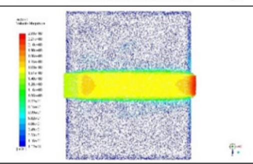
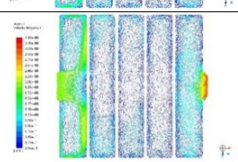
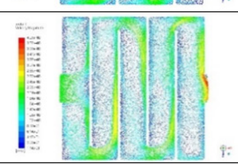
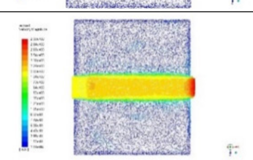
3. Results and Discussion

3.1 Velocity of the models for using plants as filters in air pollution treatment

Air velocity which specified in the model was 0.5, 1.0, 1.5 and 2.0 m/s, respectively. Airflow at different locations within the treatment box represented airflow through every panel. Data from experiments using the analytical program, consisted of 1) velocities of air from top-view, as showed in Table 3. The modelling results of airflow characteristics were shown in Figures 11-13. Table 3 demonstrated the front-view of airflow within air treatment boxes. The results showed that the airflow through 12 locations of the top-view and front-view of treatment box. It was found that model 2, both the top-view and front-view, had average air velocity of (Top-view/Front-view) 0.23/0.27, 0.57/0.43, 0.71/0.80 and 0.97/0.96 m/s, respectively, at all inlet air velocities of 0.5, 1.0, 1.5 and 2.0 m/s, respectively. The model box 1, both top-view and front-view, had no flow in one location at C-2. While model 3 had average air velocity of (Top-view/Front-view) 0.09/0.09, 0.24/0.26, 0.35/0.34 and 0.49/0.35 m/s, respectively, at inlet air velocities of 0.5, 1.0, 1.5 and 2.0 m/s, respectively, with no airflow in 8 locations.

The model 2 showed the air circulation in all air inlet that was contacted with surface of every panels. While the airflow in model box 1 circulated and flowed through only the first panel. Airflow in model box 3 was projected in straight line, partially passed panels and immediately flowed to the outlet. It was found that model 2 allowed airflow in all locations and air contacted with the surface of all panels. Dust can be well-absorbed by air treatment plants. The high velocity of inlet air cause higher air velocity in each position. While low air velocity caused slow air movement, which increase the chance of plant adsorption than those with high air velocity. Models 1 and 3 were less likely to be absorbed by the air treatment plant.

Table 3. Models of air flow characteristics in treatment each model (front-view) in analysis

Velocity of air flow (m/s)	**Air flow characteristics in top view**		
	Model 1 (Model for placing plants blocking panels to allow airflow)	**Model 2 (Model for placing plants zigzags panels to allow airflow)**	**Model 3 (Model for placing plants parallel panels to allow airflow)**
0.5			
1.0			
1.5			
2.0			

3.2 Temperature of the models for using plants as filters in air pollution treatment

The air temperature dispersed through different locations within the treatment box indicates temperature distribution through every panel. It can affect the increasing or decreasing of treatment box efficiency. Since air temperature had direct impacts on the installed treatment system. Results of front-view temperature distribution showed in Table 4. The analyze data of temperature distribution were showed in Figure 14 - 16.

Table 4 demonstrated the temperature flow that contacted and passed through each panel in top-view. The model 2 showed that the air temperature was distributed throughout the treatment box. High temperature was found at the inlet and gradually decreasing to the outlet. High air inlet velocity caused more temperature stable and maintain to the outlet. For model box 1, temperature was distributed only the first and last panels, and found less distribution in the middle panels. Air velocity of 1.5 and 2.0 m/s found the evenly distribution in all panels. While model box 3 found high temperature centered in the middle as hot stream and passed through the outlet, with no temperature decreasing.

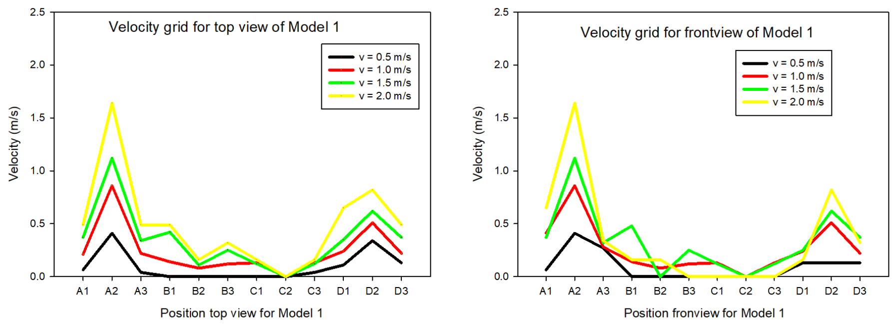


Figure 11. Air flow rate of model for placing plants blocking panels to allow airflow in different positions.

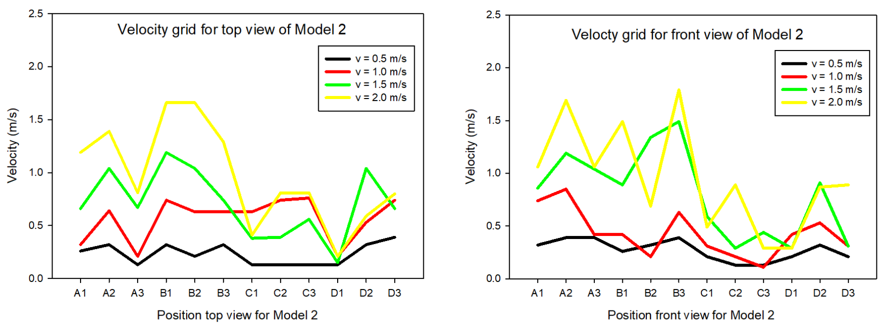


Figure 12. Air flow rate of model for placing plants zigzags panels to allow airflow in different positions.

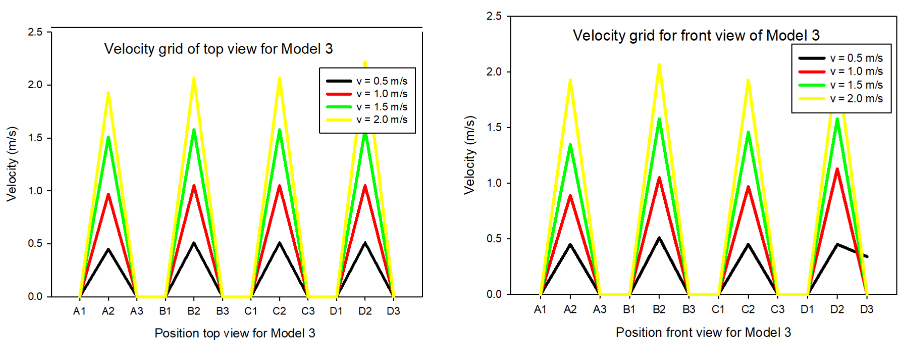
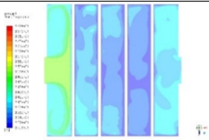
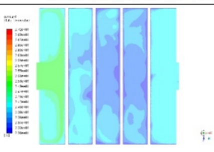
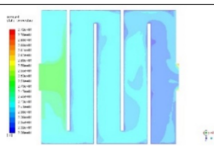
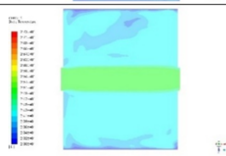
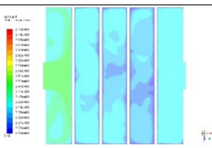
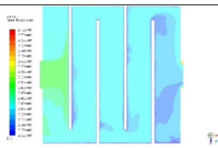
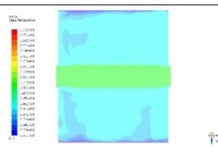
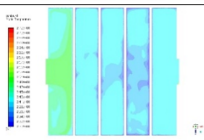
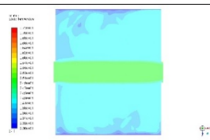


Figure 13. Air flow rate of model for placing plants parallel panels to allow airflow in different positions.

Table 4. Model of the distribution effect of air temperature within the treatment model (front-view) in analysis

Velocity of air flow (m/s)	Air flow characteristics in top view		
	Model 1 (Model for placing plants blocking panels to allow airflow)	Model 2 (Model for placing plants zigzags panels to allow airflow)	Model 3 (Model for placing plants parallel panels to allow airflow)
0.5			
1.0			
1.5			
2.0			

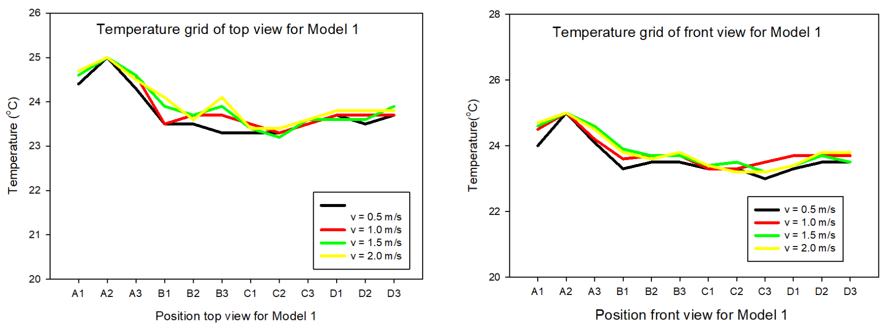


Figure 14. Air flow rate of model for placing plants blocking panels to allow airflow in different positions.

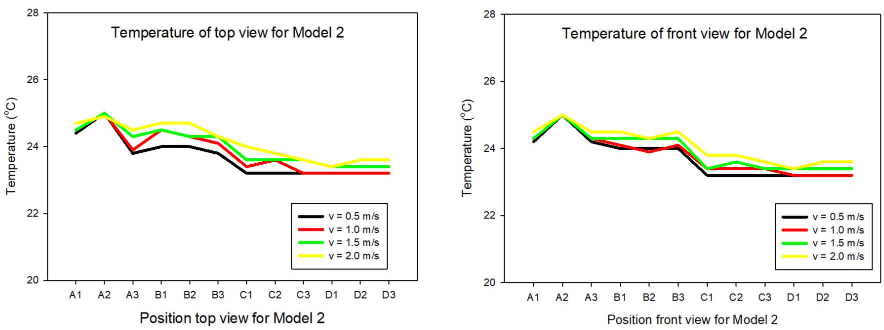


Figure 15. Air flow rate of model for placing plants zigzags panels to allow airflow in different positions.

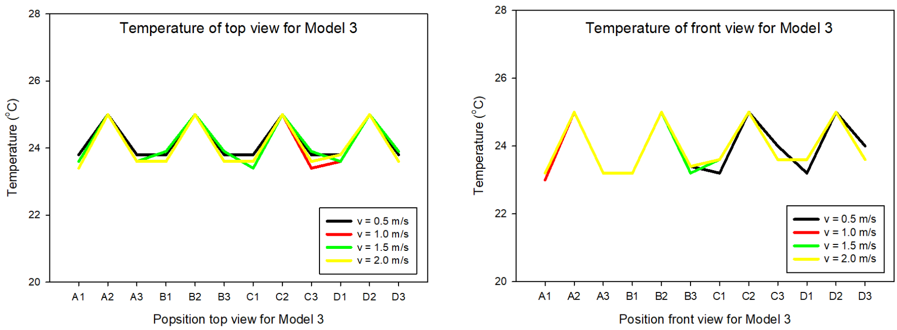


Figure 16. Air flow rate of model for placing plants parallel panels to allow airflow in different positions.

The air temperature distributed through 12 locations of the top-view and front-view of treatment box. It was found that model 1, had mean temperature distribution within the model of (Top view/Front view) 23.75/23.61, 23.88/23.83, 23.92/23.85 and 23.98/23.85 °C, respectively, at air velocity of 0.5, 1.0, 1.5 and 2.0 m/s, respectively. It is close to that of model box 2 with the mean internal temperature distribution of the model equal to (Top view/Front view) 23.68/23.72, 23.84/23.79, 23.99/23.93 and 24.15/24.09 °C, respectively.

4. Conclusion

The study focused on the airflow in the 3 treatment models by CFD analysis as a case study in laboratory. Air velocity and air temperature distribution were constructed to study airflow data through 12 locations in the treatment box model. In model 2, airflow was circulated through every location and passed through smoothly. The model box 2 had average airflow velocity are (top view/ front view/ inlet air velocity) 0.23/0.27/0.5, 0.57/0.43/1.0, 0.71/0.80/1.5 and 0.97/0.96/2.0 m/s, respectively. For temperature distribution, it was found that the treatment box model 2 was the most suitable and should be used for further laboratory testing. Next to study, it will compare with testing in laboratory that use the 3 treatment models at all velocities of inlet air. The treatment plant is use for experimental such as; mosses and lichen have developed for using as a bio-indicator to assess the concentration of heavy metal in atmosphere (Kayeea *et al.,* 2015). As for the temperature distribution, it was found that the air treatment model 2 had the most suitable conditions. Therefore, this study found that the model 2 with alternating zigzags panels was the most filtration efficient model for air pollution treatment.

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