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Investigation of Airflow in A Restaurant to Prevent COVID-19 Transmission Using CFD Software

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Abstract: According to the World Health Organization (WHO), COVID-19, like other respiratory infectious diseases, is transmitted via droplets and airborne transmission through respiratory activities. As other past outbreak diseases such as MERS-Cov and SARS-Cov, the role of HVAC in airborne transmission had been studied. Expiratory droplets from pulmonary activities such as breathing, talking, coughing, or sneezing cause airborne transmission. In addition, under some conditions, such as high wind speed, low temperature, or high humidity, aerosol droplets can be transferred exceeding the 2.0 m social distancing limit. The aim of this study is to determine the parameter such as air velocity, temperature and humidity in a restaurant that influence the spreading of COVID-19. Other than that, this study is also conducted in order to investigate the effectiveness of social distancing in indoor space with an airflow. Lastly, by using Computational Fluid Dynamics software, the effect of air flow in spreading of airborne transmitted virus pathogen can be investigated. The overall research methodology consist of a few steps and cases that correspond to the research objectives, which are identifying the characteristic of SARS-Cov, identifying the restaurant parameters, geometry development, boundary condition setup, simulation run, results analysis, collecting data and graph, discussion and conclusion. The simulation is setup with variety of cases consist of manipulated air flowrate, temperature, and inlets and outlets placement. The most effective contaminant removal and the most optimum thermal comfort is the Location 2 case with Contaminant Removal Effectiveness of 0.71 and neutral level of Predicted Mean Vote. It is believed that this research will contribute as guidelines to prevent airborne transmitted diseases outbreak.

Keywords: COVID-19, Computational Fluid Dynamics, Airflow, Contaminant Removal Effectiveness, Local Air Quality Index

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1. Introduction

One of the most critical engineering controls available to the building manager for enhancing or preserving the air quality in the occupational work environment is ventilation. In occupied rooms, ventilation systems deliver conditioned air. Ventilation air may be made up entirely of outside air, as in a laboratory, or a combination of re-circulated internal air and outside air, depending on the building type [1]. Air flow is also essential for moving air from clean to dirty and out. Air flow patterns should generally shift from 'clean' spaces to 'dirtier' areas. It's a safe rule of thumb to keep air flowing from clean to dirty so that children don't inhale toxic air.

Computational Fluid Dynamics (CFD) is a modern approach to the numerical method of solving fluid mechanics problems. CFD is a program that simulates fluid (liquid or gas) flows and their interactions with solid surfaces [2]. Provided that the simulation data is experimentally validated to verify, expand, and refine the formulated models, CFD is one of the most powerful techniques for characterizing flow fields [3].

The relationship between airborne transmission and the role of HVAC system in contributing to the spread of airborne diseases had been study with past outbreak of SARS-Cov and MERS-Cov. Therefore, the aim of the study are to determine the effectiveness of contaminant removal of HVAC system in a restaurant by using value such as CRE, LAQI, and LACI. By using the aforementioned parameters, the effectiveness of 2.0 m social distancing in a restaurant as recommended by WHO is investigated. Moreover, this study also investigate the effect of air flow in spreading of airborne transmitted virus pathogen using Computational Fluid Dynamics software.

2. Literature Review

The term HVAC refers to three term of air management, which are heating, ventilation and air-conditioning. There is also the fourth term which is control. Controls determine how HVAC systems function in order to achieve the design goals of comfort, safety, and cost-effectiveness [1].

2.1 Airflow

There are two definitions of airflow; (1) Air movement that is normally contained within boundaries (such as ducts). (2) the volume of air in each amount of time [3]. Airflow can be categorized into three categories: laminar, turbulence and mixed. Normal convection currents occur as the movement of particles is influenced by the temperature of the atmosphere, allowing warmer air to ascend and cooler air to descend.

Two important factors that influence indoor air distribution are the room air pattern and ventilation airflow intensity [4]. Previous studies have looked into the mechanism of airborne droplet/droplet nuclei dispersion in space, the risk estimation of airborne infection, the function of airflow rate, the impact of airflow pattern, and so on. They also summarized that controlling the airflow path from clean to dirty zones is critical for preventing the transmission of virus-laden aerosols between room[5].

2.2 Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-Cov2)

At the end of the year 2019, the world was shocked with the spread of severe acute respiratory syndrome coronavirus 2 (SARS-Cov2), more commonly known as Coronavirus disease 2019 (COVID19), that caused a worldwide pandemic. The virus traced it origin in the Wuhan, Hubei province, China. The virus SARS-Cov2 share some similarity with the previous SARS-Cov in 200-2003 and MERS-Cov in 2012 in regards that they belong to the genus Betacoronavirus which has high mutation rates. This resulted in viral genetic diversity plasticity and adaptability to invade wide range of host [6]. The possibility of an indoors airborne transmission to the human health can be reaffirmed during the 2003 SARS epidemic. Also, during this time, ventilation system as an important factor contributing towards the transmission of airborne diseases was established[5].

2.2.1 Mechanism Of COVID-19 Airborne Transmission

The transmission of airborne diseases occurs via coughing, sneezing, speaking, singing and laughing which produce expiratory droplet [7]. Expiratory droplet can be categorized into two; respiratory droplets which are larger than 5.0-10.0 µm in diameter, aerosol droplets which are smaller than 5.0 µm in diameter.

Earlier studies shows that the large respiratory droplets are more likely to drop within 1.0-2.0 m. This latter become the basis for the 2.0 m social distancing in order to prevent the spreading of COVID-19. Recent COVID-19 research suggests that smaller respiratory droplets (less than 5.0 µm) can stay airborne for long periods of time, and SARS-CoV-2 can survive for many hours in these smaller aerosolized droplet [8].

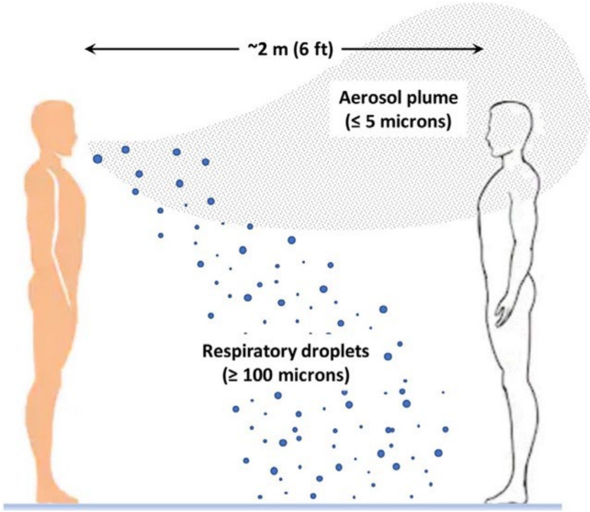

Figure 1: Potential airborne transmission from respiratory droplets and aerosols [9]

2.2.2 SARS-Cov2 Environmental Condition

The association between environmental factors such as rising summer temperatures and the increasing prevalence of coronavirus is currently one of the key concerns due to the prevalence of COVID-19 in most parts of the world. One of the research studied the environmental conditions such as maximum relative humidity, maximum temperature and maximum wind speed. The study concluded that the prevalence of COVID-19 is reduced as humidity and wind speed increase. But at the same time, the correlation between COVID-19 prevalence and maximum air humidity and wind speed was minimal and statistically insignificant [10]. Other studies also showed that there isn't a substantial link between the effectiveness of a virus and many environmental circumstances [11].

2.2.3 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) can be described a computer simulation approach for describing, evaluating, and predicting fluid motion in a given region. Heat and mass movement, chemical reactions, and biological processes are all examples of processes connected with the carrier fluid [12] CFD is becoming increasingly prevalent in all engineering areas that deal with fluids. It is popular because, in comparison to physical modeling, it can significantly reduce the cost and time for a new design, it has flexibility in simulating various conditions, it can reduce the risk associated with physical tests under hazardous conditions, and it can provide a higher level of confidence that a design can meet regulatory criteria.

3. Methodology

3.1 Restaurant Design and 3D Model

The restaurant dimension is 9.2 m x 10.5 m (as shown in Figure 2). This space is based on standard building of restaurant area. This is also supported by building dimension in Malaysia. The restaurant is equipped with a total of thirteen tables (eleven long table, two short table). The maximum capacity of the restaurant is 46 occupants. At the time of infection, there thirteen occupants in the restaurant. Other than that, the restaurant has two ceiling-type air-conditioner without windows or other ventilation. The AC units are located approximately 3.2 m from the floor.

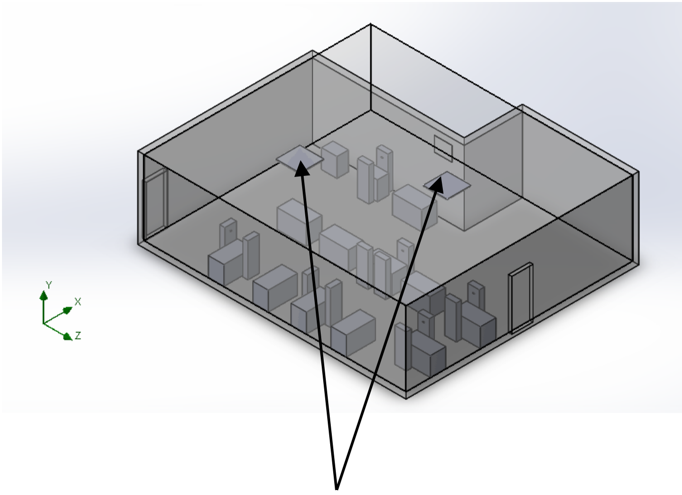

Figure 2: 3D model of the restaurant

3.2 Boundary Condition

Boundary conditions are an essential part of any computational fluid dynamics simulations. To close the differential equation solution set, boundary conditions are required. They depict the environment's impact on the isolated solution model. Additional beginning conditions are required if transient simulation is used [14] . The boundary conditions used in the simulation are listed in Table 2.

Table 2: Simulation boundary condition

Turbulence model	Standard k-ε model
Wall treatment	No-slip, standard logarithm
Human body	31 °C
Floor, ceiling and wall	Adiabatic wall
Air-conditioning unit	Airflow velocity = 1.20 m/s Flow rate = 0.14 m^3/s Temperature= 24 °C Turbulence intensity = 20.00 %
Mouth	Velocity = 4.07 m/s

3.3 Fluid Condition

Fluid conditions are the definition of the fluid used in the simulation. In order to simulate the breathing of occupants and the flow of fluid in the restaurant, air is used as the simulated fluid. The infector exhale breath is assumed to contained SARS-Cov2. The SARS-Cov2 is defined to have a molecular mass of 0.0765 kg/mol.

Table 3: Fluid condition used in simulation

Fluid	Definition	Reference
Gases/Air	Pre-defined	-
Gases/SARS-Cov2	User-defined Molecular mass: 0.0765kg/mol	[18]
Initial condition	Thermodynamics parameters: Temperature = 24°C Concentration: Mass fraction of air: 1 Mass fraction of SARS-Cov2: 0	-

3.4 Simulated Cases

Several simulated cases are proposed to find the parameter of COVID-19. The cases consist of manipulated inlet and outlet flowrate, inlet and outlet location, and inlet temperature. In the flowrate and location cases, the results will consist of Contaminant Removal Effectiveness (CRE), Local Air Quality Index (LAQI), Local Air Change Index (LACI) and flow trajectory. For the varied temperature cases, only Percent Mean Vote (PMV) is produced.

3.4.1 Inlet and outlet flowrate cases

A total of 6 simulated cases of varying flowrate conducted to investigate the effect of airflow in contaminant removal and airborne virus transmission. 3 of the cases are varying inlet flowrate while the other 3 cases varying outlet flowrate. The simulated cases conditions are listed in table 4 and table 5 below.

Table 4: Boundary condition for inlet cases

Case number	Inlet flowrate (m^3/s)	Outlet flowrate (m^3/s)	Infector velocity (m/s)	Occupants' flowrate (m^3/s)	Inlet temperature (°C)
Journal Reference	0.14	0.14	4.07	0.000133	24
I1	0.108	0.14	4.07	0.000133	24
I2	0.117	0.14	4.07	0.000133	24
I3	0.142	0.14	4.07	0.000133	24

Table 5: Boundary condition for outlet

Case number	Inlet flowrate (m^3/s)	Outlet flowrate (m^3/s)	Infector velocity (m/s)	Occupants' flowrate (m^3/s)	Inlet temperature (°C)
I1	0.14	0.108	4.07	0.000133	24

Table 5 (Continued)

I2	0.14	0.117	4.07	0.000133	24
I3	0.14	0.142	4.07	0.000133	24

3.4.2 Inlet and Outlet Cases

2 cases of varying inlet and outlet placement are also performed. The purpose is to find the effect of inlet and outlet location on the effectiveness of contaminant removal and thermal comfort of HVAC system. The placement of the inlet and outlet are as displayed in Figure 3. The cases are known as L1 and L2.

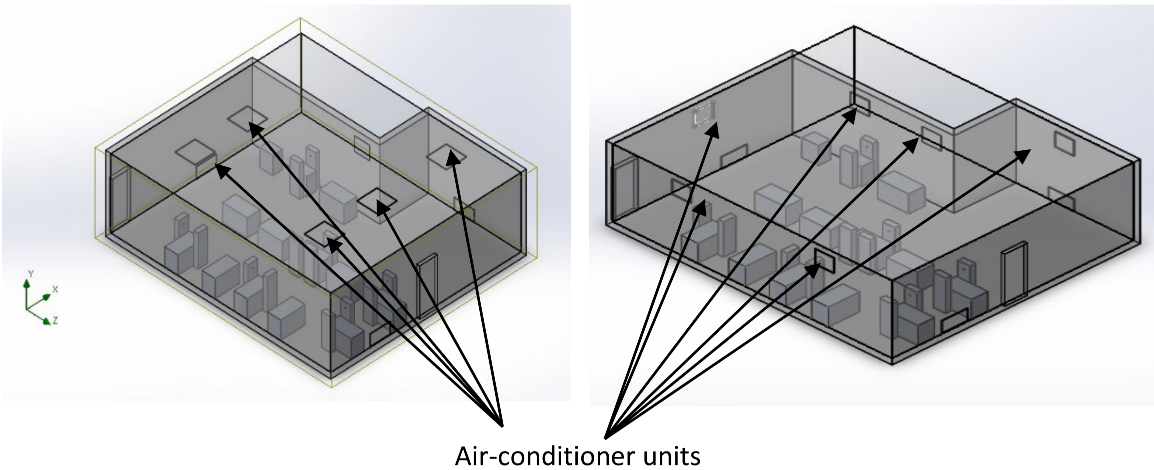

Figure 3: Model with varied inlet outlet placement

3.4.3 Temperature cases

Another 10 cases are conducted with varying the inlet air temperature for the purpose of analysing the ideal thermal comfort of the restaurant. These cases are simulated from the range of 16 °C to 26 °C. All other conditions except for inlet air temperature are kept constant as journal value.

4. Results and Discussion

4.1 1Airflow Rate Effect On CRE

Based on Figure 4, the Contaminant Removal Effectiveness (CRE) from the air conditioner inlet with different airflow rate is shown. The CRE in I1 and I2 is lower than the CRE in the journal while the CRE in I3 exceed the CRE value in the journal. Meanwhile only O1 has a CRE value below the journal. Both O2 and O3 exceed the journal’s value. The CRE depends on the airflow pattern, the contaminant sources’ properties, and positions. If CRE is zero, it means that the contaminants circulate in the room and are not exhausted; if CRE equals unity, the contaminants are perfectly mixed and exhausted with the airflow; if CRE is infinite, the source is just at the air exhaust and the contaminant leaves the domain instantaneously.

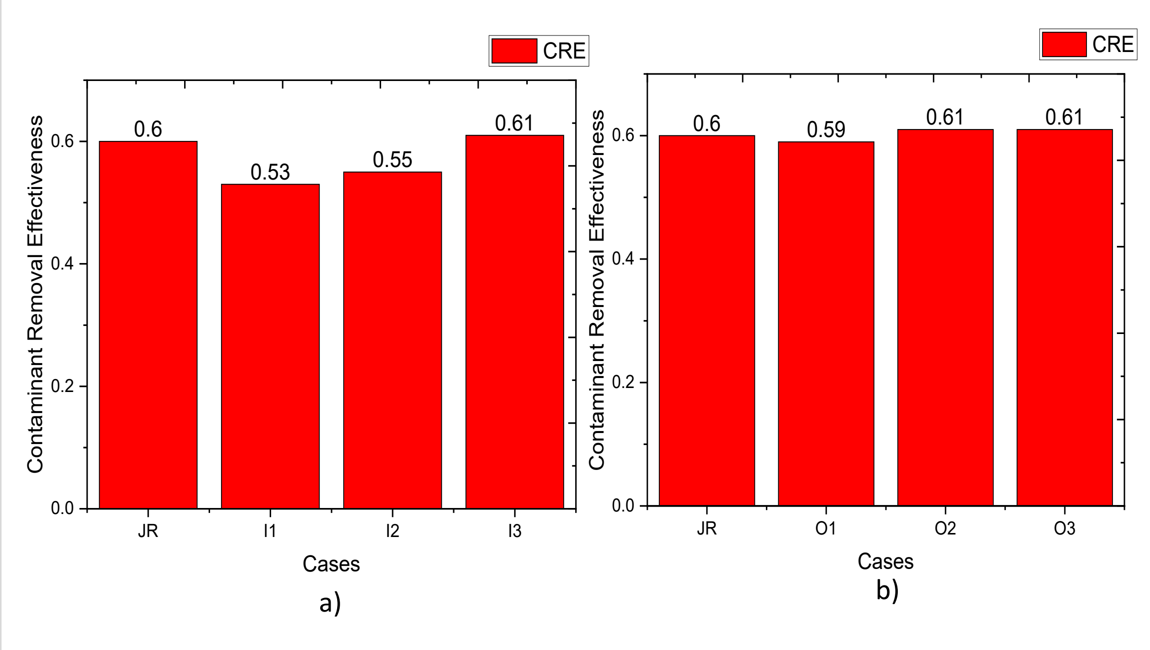

Figure 4: a) Varied inlet cases. b) Varied outlet cases

4.1.2 Inlet and Outlet Location Effect on CRE

The location of the inlets and outlet of an air-conditioning system are an important factor that affect CRE value. From Figure 5, the CRE value of L1 is higher than the journal. While, L2 has the highest CRE value of all the cases. Since the number of the inlets and outlets is increased in both L1 and L2, the CRE values are also increase. In L2, the distance between most of the inlets and outlets are closer which helps in reducing contaminants spreading.

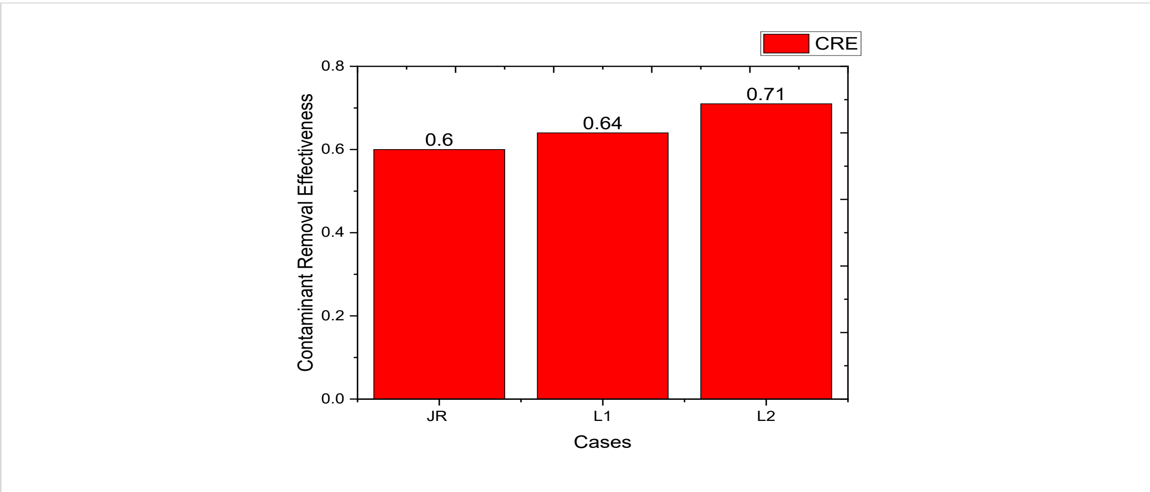

Figure 5: Varied inlet and outlet location cases

4.1.3 CRE Comparison Between Airflow and Location Effect

From the results, it can be determined that by increasing the value of inlet and outlet flowrate, the removal of contaminant is easier. This is indicated by the CRE value. The worse the contaminant removal performance, the smaller the CRE [15]. The CRE value increased as the airflow rate increased. The highest CRE obtained by increasing the inlet and outlet airflow is 0.61.

The location of inlet and outlet are also one of the factors influencing contaminant removal. The impact of the position and the number of openings has been the subject of various studies. According to a study by [16], it was determined that the inlet opening's position was more critical than the outlet's. In the simulation, both the location of inlets and outlets are varied. For L1, the location of the inlets are mounted on the ceiling while the outlets are wall-mounted. In L2 case, only the inlets' locations are adjusted from ceiling-mounted to wall-mounted. The results show that there is significant improvement from aspect of contaminant removal. L2 has a higher value of contaminant removal than L1.

4.1.4 Airflow Effect on LAQI

The LAQI cut plot for the JR is fairly high. The reason is that the journal case has high airflow rate for both the inlet and outlet of the air-conditioner. Other than that, the journal case has one of the highest CRE value among other simulated cases. In I1, the cut plot shows that the left side of the restaurant has lower LAQI value (dark green). In both I2 and I3, the cut plots show an increase in LAQI value. In Figure 6 and Figure 7, the case O1,O2 and O3, only the outlet airflows are varied while the inlets stay at 0.14 m^3/s. From the cut plot, all cases of varied outlet airflow have good LAQI value.

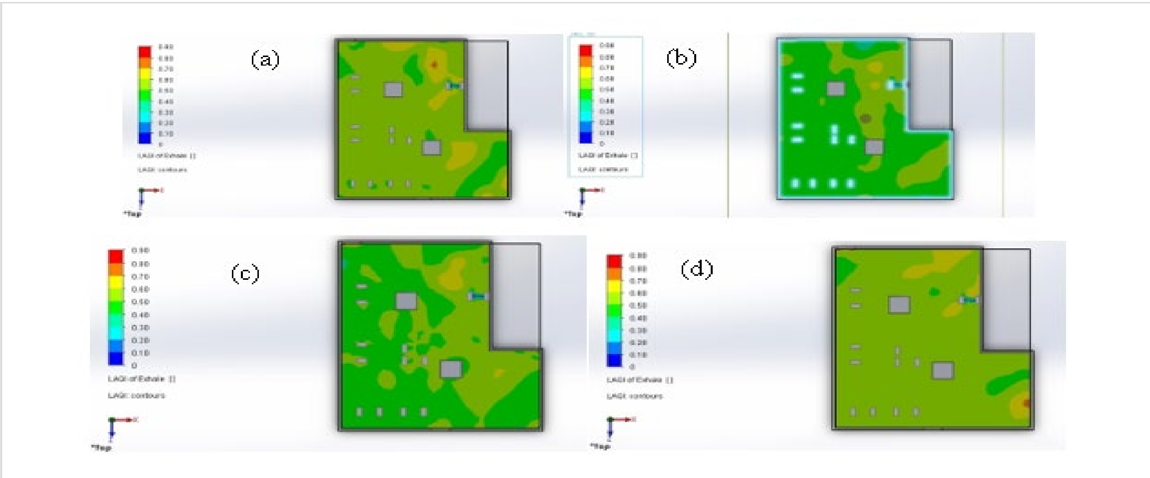

Figure 6: LAQI cut plots of journal and varied inlet airflow rate. (a) Journal Reference. (b) I1. (c) I2 (d) I3

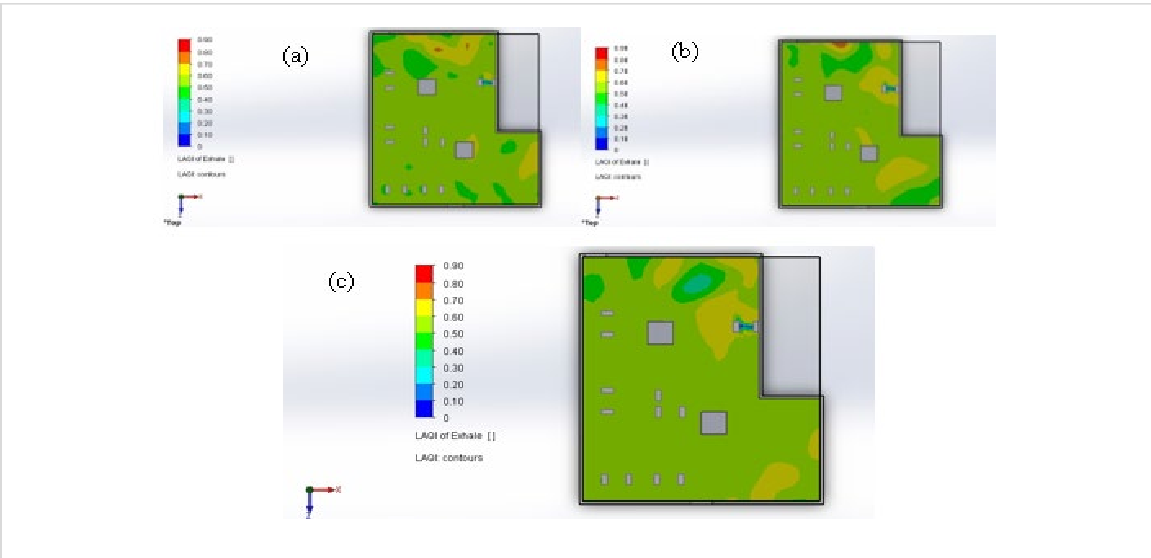

Figure 7: LAQI cut plots with varied outlet airflow rate. (a) O1 (b) O2 (c) O3

4.1.5 Inlet and Outlet Location Effect on LAQI

In Figure 8 below, the cut plots show that the area with less concentration of contamination in L1 and L2 cover larger area than in JR. Comparing the LAQI of L1 and L2, LAQI in L2 are mainly made of up of 0.6 to 0.7 (yellow coloured area) while LAQI in L1 are mainly from 0.5 to 0.6 (green coloured area). Considering that the CRE value in L2 is higher than L1.

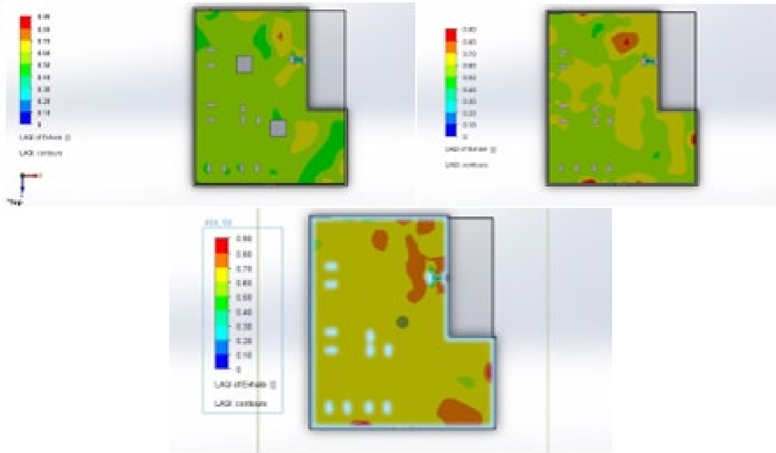

Figure 8: LAQI cut plots of journal and varied inlet and outlet location. (a) Journal Reference. (b) L1. (c) L2

4.1.6 LAQI Comparison Between Airflow and Location Effect

Results from sub-topic 4.1.4 and 4.1.5 indicated the LAQI between varying inlet and outlet airflow, and inlet and outlet location. From result the result in sub-topic 4.2.4, it can be concluded that increasing the airflow will increase the area with less concentration of contaminant

In the cases of varied inlet and outlet location, both L1 and L2 has a higher LAQI value than all of the airflow cases. In L1, most of the area are light green while L2 area are cover with yellow colour. L2 also has the highest LAQI when compared between all of the airflow cases. The correlation between CRE value and LAQI can also be seen. As CRE increased, the LAQI also increased. This is proven as L2 also has highest CRE value.

4.1.7 Airflow Rate Effect on LACI

In Figure 9, the cut plot from the JR shows that the concentrated exhaled air is mainly within the infector and around the first air-conditioner. Figure 4.10 also showed case I1, I2, and I3 that are varied the air conditioner inlet airflow rate. In I1, high concentration of exhaled air takes up larger space than in the journal reference. In I2, the concentration is still high but takes up smaller space than I1. I3 has the lowest level of concentrated exhaled air with the space around the infector is the only highly concentrated.

Figure 10 shows that cases which are varied their air-conditioner outlet airflow rate. In all cases, there are no high concentrated exhaled air except with the infector. By increasing the outlet airflow, the LACI value is decreasing which demonstrates that effectiveness of the ventilation systems are increasing

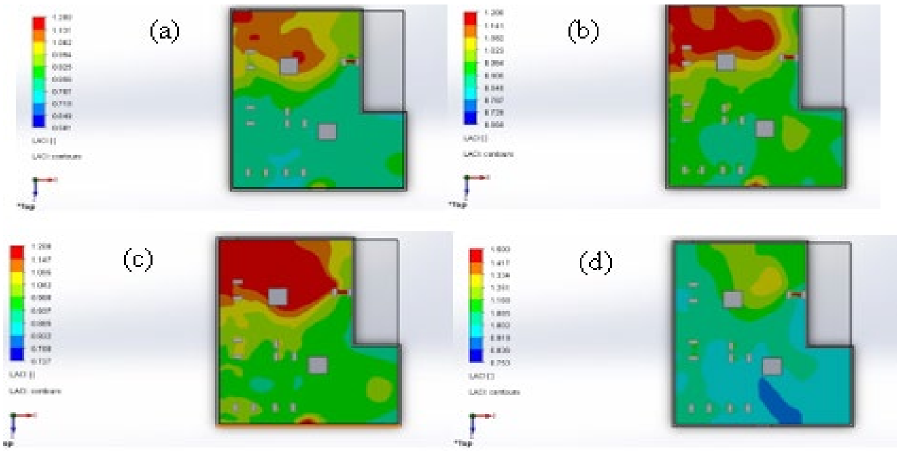

Figure 9: LACI cut plot by varying inlet airflow rate. a) Journal Reference. (b) I1. (c) I2 (d) I3

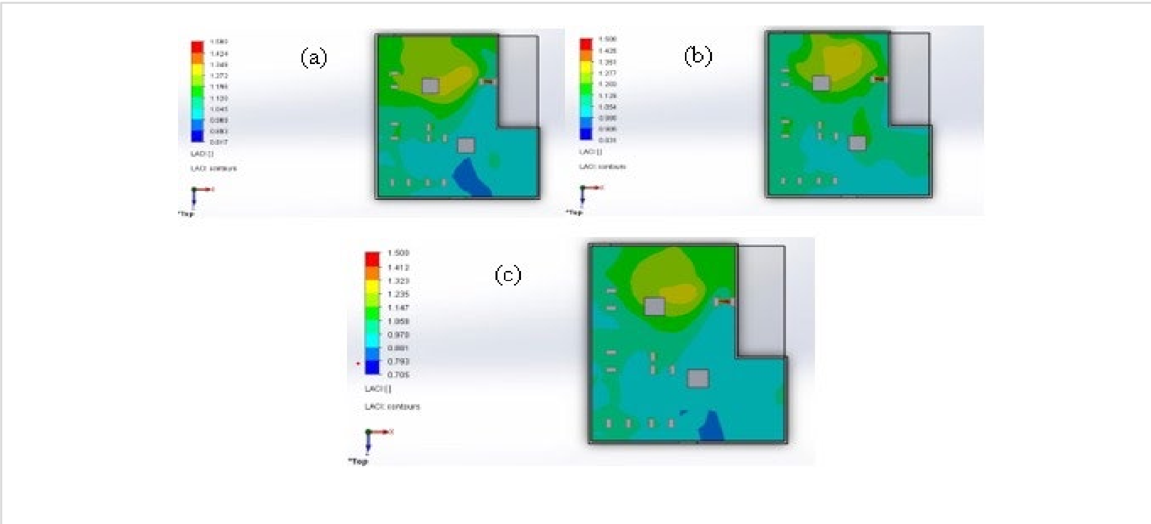

Figure 10: LACI cut plot by varying outlet airflow rate. (a) O1 (b) O2 (c) O3

4.1.8 Inlet and Outlet Location Effect on LACI

Figure 11a) show the LACI for journal reference which show that the large portion of the area are covered light green and light blue colour which mean middle to low value of LACI. The lower the value, the less concentration of contaminant in the area. In Figure 12b) the LACI for L1 show the area with low concentration of contaminant cover a larger area than in journal. The LACI for L2 showed that most area of the room is low concentration of contaminant. Comparing the three cases, L2 has the most optimum level of LACI.

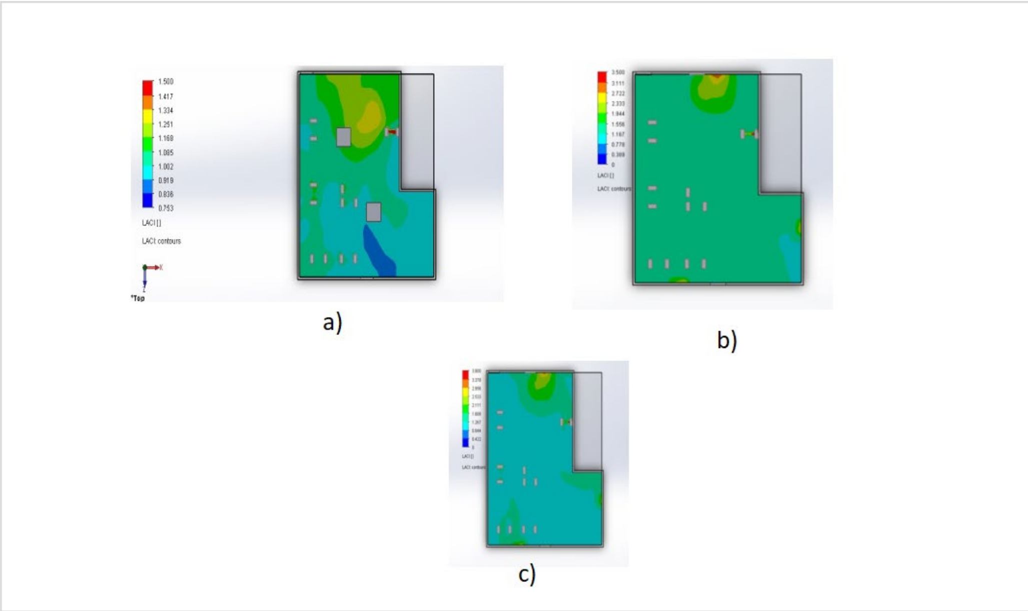

Figure 11: LACI cut plot by varying inlet and outlet location. (a) JR (b) L1 (c) L2

4.1.9 LACI Comparison Between Airflow and Location Effect

From the result of airflow effect on LACI, it can be concluded that, as the airflow increased, the LACI value decreased. LACI indicated the value of air change. A higher value of LACI suggested a higher concentration of contaminant.

As showed in sub-topics 4.1.8, the LACI of varying inlet and outlet location showed a decreased between L1 and L2. The efficiency of air change is improved when the inlet and outlet openings are on the same wall [17]. This study proved that L2, which has inlet and outlet on the same wall, has a better LACI than L1. The local air change index represents the efficacy of air exchange within a certain domain [18]. Opposite of both CRE and LAQI, the LACI value decreased as the airflow increased

4.1.10 Airflow Rate effect on Airflow Trajectory

Figure 12 shows the trajectory of exhaled air by manipulating the inlet airflow values. The trajectories are display by using the LAQI of the exhaled air as the parameter to be measured. Figure 13 shows the trajectory of exhaled air by manipulating the outlet airflow values. In both cases, the probable airflow trajectories carrying airborne particle can be seen. The airflow showed that airborne particle can be affected by airflow rate and can be carried further than 2.0 m, which is the recommended social distancing by WHO.

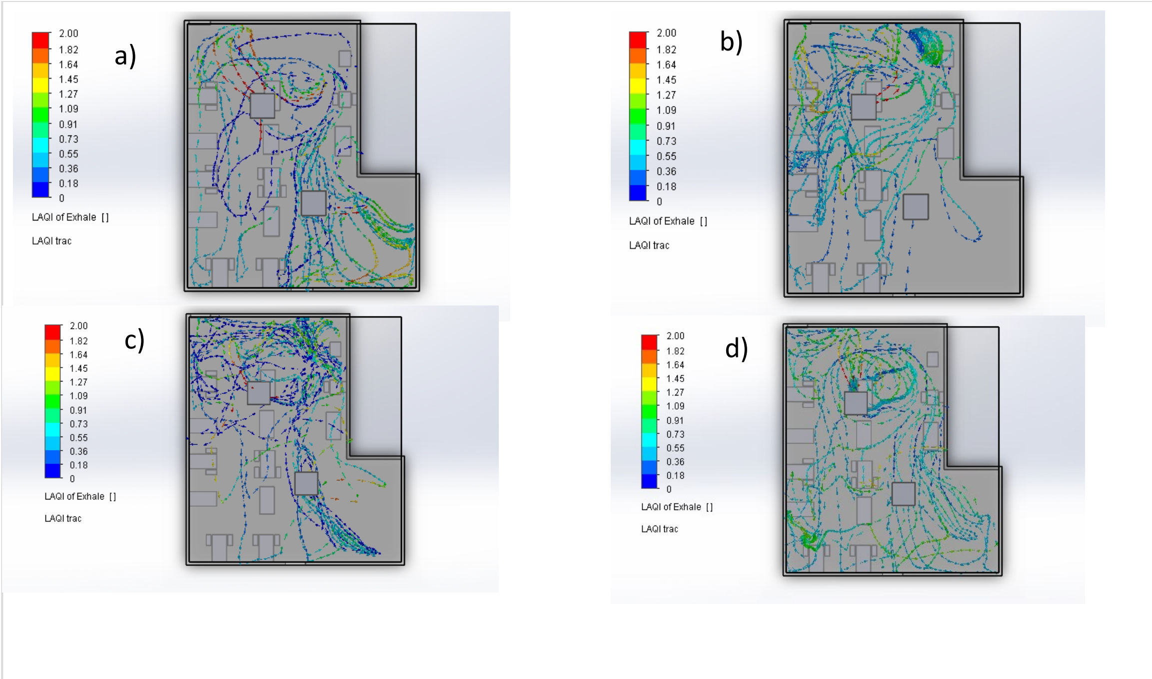

Figure 12: Airflow trajectory in varying inlet airflow values. (a) Journal Reference (b) I1 (c) I2 (d) I3

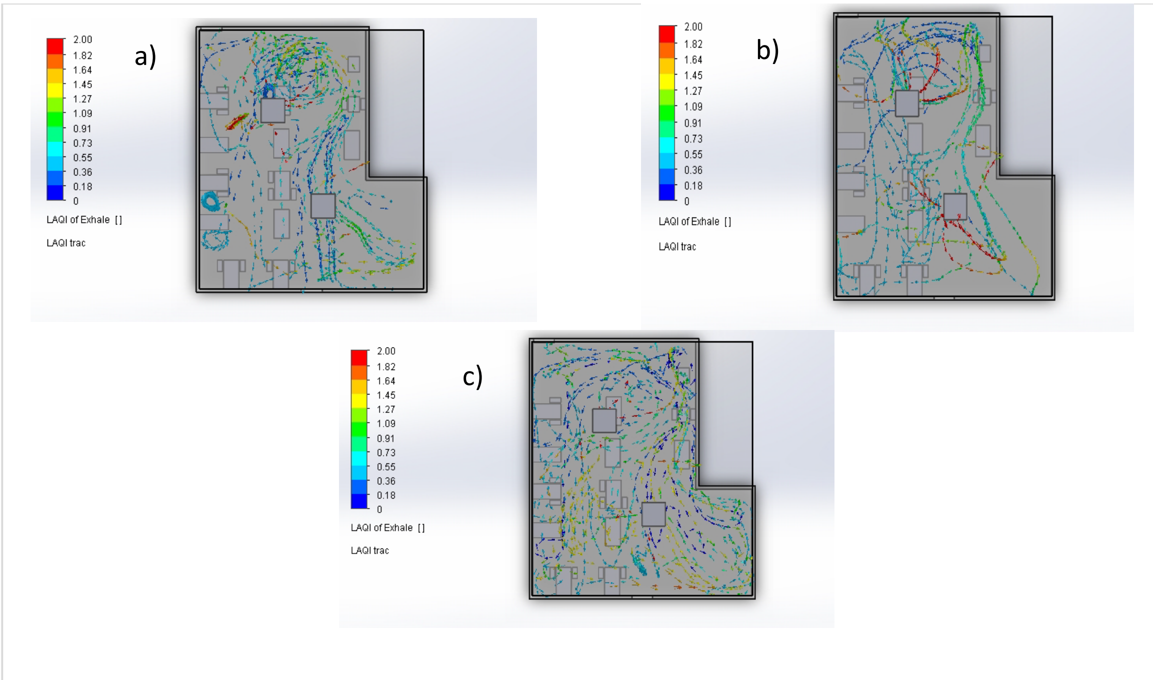

Figure 13: Airflow trajectory in varying outlet airflow values. (a) O1 (b) O2 (c) O3

4.11 Inlet and Outlet Location Effect on Airflow Trajectory

The geometrical design of the room, as well as the input and outlet configurations, influence the flow pattern in the room. In this section, the placement of the inlets and outlets and the effect of airflow trajectories are studied. In figures below, the trajectories of airflow are developed using LAQI of contaminant as base. The trajectories in Figure 14a) had been discussed in sub-topic 4.2.10. In Figure 4.14b), the trajectories can be seen flown throughout the whole restaurant. But the airflows are less concentrated with contaminant as compared to the journal reference. Figure 14c) presents the trajectory of airflow in L2 case. The airflow covers much more space and also the concentration of the contaminant are lower than both other cases.

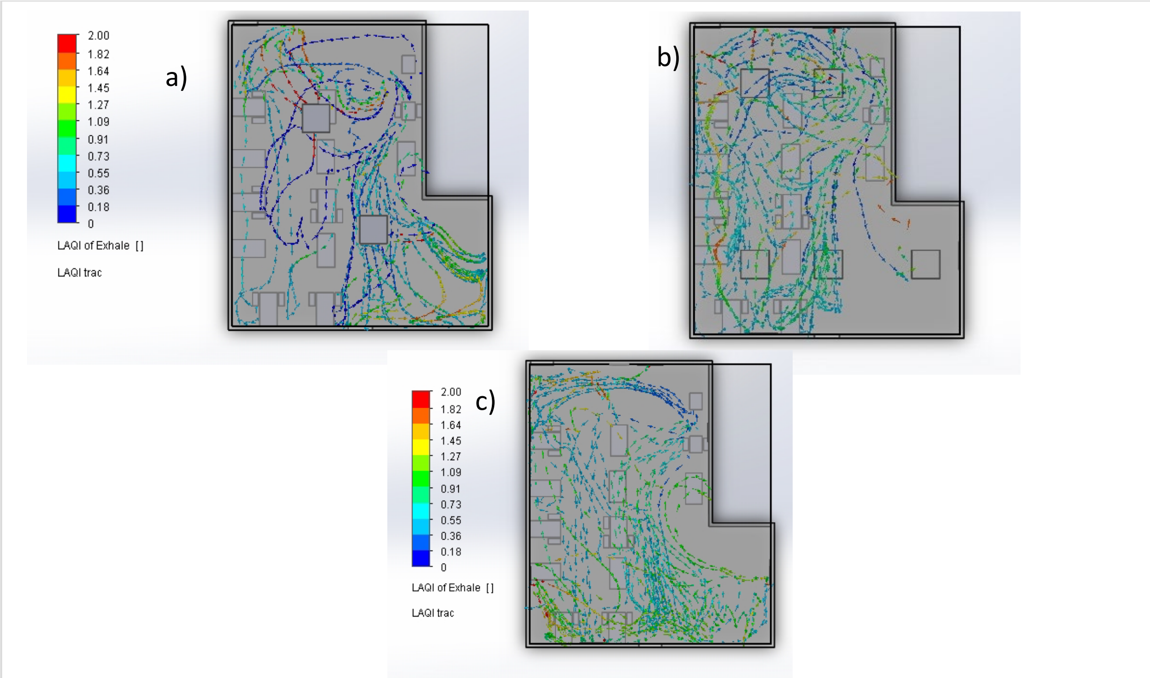

Figure 14: Airflow trajectory by varying inlet and outlet location. (a) JR (b) L1 (c) L2

4.12 Trajectory Comparison Between Airflow and Location Effect

In sub-topic 4.10 and 4.11, it was discussed the effect of airflow and location of inlet and outlet toward airflow trajectory. The airflow trajectories are projected using the LAQI of contaminant as medium. By increasing the inlet airflow rate, the airflow trajectories go further. This indicated that the airborne contaminant may be able to be carried further than the recommended social distancing recommendation by WHO. However, since the CRE values are increasing, the concentration of the contaminant being carried are decreasing as the distance is also increasing.

When varying the location of inlet and outlet, different airflow trajectories are projected. The L2 case cover more area than in L1. This is because the inlet and outlet L2 are located to cover a larger portion of the restaurant. Also, comparing the cases in sub-topic 4.10 and 4.11, L2 has the highest coverage of airflow. Given that L2 also has CRE with highest value among other cases, it can be considered that the concentration of contaminant is low although the trajectory covers more area.

5. Conclusion and Recommendation

As a conclusion, a higher efficiency of contaminated air removal from the restaurant can be achieved by increasing the flowrate for either inlets and/or outlets or by manipulating the placement of inlets or outlets. A higher CRE value can be seen when increasing the flowrate for the outlet. Since the contaminant is in the restaurant, a higher outlets' flowrate can remove the contaminant better. The biggest achievement can be seen at L2 case since it resulted in the highest CRE value, LAQI and lowest LACI. L2 also has an acceptable range of thermal comfort with the PMV reading for the whole restaurant is within neutral level. Although the airflow trajectories are more spread out, since the LACI is lowered, the overall airflow caried less concentration of contaminant.

For the recommendation, to better improve the contaminant removal, it is recommended to install High Efficiency Particulate Air (HEPA) filter in both the inlet and outlet of HVAC system. Restaurant owners may also consider a portable room air cleaner or purifier with HEPA filter since existing HVAC systems may have difficulties changing to finer filter media. Moreover, in a less congested space, it is advisable to increase fresh air supply which can increase the effective dilution ventilation per person. Other non-HVAC recommendations that can be implemented are, increase the disinfecting of areas that are often touched, provide or install hand sanitizer, and reduce occupancy of the restaurant

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