The Integration of Exhaust Fan and Wheel Stopper to Reduce Indoor Air Pollution Inside the Enclosed Parking Garage

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Abstract. The increasing of people population and vehicle number in big city has caused lack of parking space. This condition has forced the architects to design some parking spaces in form of parking building i.e., underground parking garage. However, an underground a parking garage is having higher risk to the health due to the possibility of hazardous gases trapped inside the room. In a cold start condition, a motorized vehicle will emit higher concentration of hazardous compounds particularly for parameter of Carbon Monoxide (CO). So in this research, the authors aim to maintain, improve the Indoor Air Quality (IAQ) inside the enclosed parking garage by implementing low energy consumption method. Generally, the management of parking garage can operate one or more exhaust fans to create air circulation and remove the air pollutant out of the parking garage. This method works by diluting the air pollutants with the fresh air and decrease the pollutant concentration. However, this method needs more fresh air supply to prevent the accumulation of air pollutants trapped in the enclosed parking garage. In order to decrease the fresh air supply, it is need to short the path flow of the air pollutant. In order to short the path flow, the authors add a secondary exhaust fan near to the emission source (tailpipe of cars) which is integrated to the wheel stopper. Then, we evaluate the performance of the secondary exhaust fan in a simple enclosed parking garage which has maximum capacity of six cars. There are 6 (six) designs of secondary exhaust fan/wheel stopper proposed to remove the air pollutants. The selected is determined based on the uniformity of the air flow absorbed by each hole on the secondary exhaust fan. In the final stage of the study, we evaluate the effects of the secondary exhaust fan in decreasing the Indoor Air Pollution (IAP) inside the enclosed parking garage. The performance of each secondary exhaust fan design and the effects of the addition of secondary exhaust fan are evaluated by using Computation Fluid Dynamics (CFD). By combining the primary and the

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secondary exhaust fan, they create better air circulation inside the parking garage and maintain the CO concentration which is emitted by three idling cars. Based on the CFD simulations, the secondary exhaust fan can effectively reduce the indoor air pollution which caused by the emission of three idling cars. The CFD results also show that the increasing of flow rate of secondary exhaust fan will reduce the CO concentration inside the parking garage.

Keywords: Exhaust Fan · Air Pollution · Garage

1 Introduction

The increasing of motorized vehicle population in many big cities has increased the emission load and degraded the urban air quality. This vehicle emits various types of hazardous compounds such as carbon monoxide (CO). Although some companies have released some types of electrical vehicle, but apparently it needs various expensive infrastructures to support the program and that's why it still takes for years for electrical vehicle to replace the internal combustion engine vehicle [1]. On the other hand, people still need to use the internal combustion engine vehicle as long as the fossil fuel is still available. So, we still need to consider the impact of emission generated by the internal combustion engine vehicle.

Degradation of urban air quality has seriously impacted many health problems through human's respiratory system. Even World Health Organization (WHO) estimates the air pollution leads the premature death to more than seven million people in a year. The air pollution is not only existed in the outdoor environment, but it also harms people health in the indoor environment and it is called as indoor air pollution (IAP). Some research also states that IAP has been significantly contributing the effect of human health and should be anticipated properly [2].

Four-wheel vehicle powered by internal combustion engine emits various kinds of air pollutant particularly for parameter of carbon monoxide (CO). In addition, the highest concentration of CO is occurred when the vehicle idling condition. Even though, the idling vehicle does not consume high amount of fuel, but the catalytic converter on cars still has low temperature and it needs to be heated up to make it works optimally [3]. The air pollutant concentration will be reduced along with the increasing of the temperature and the activation of catalytic converter. In the first of 50 s, concentration of CO can be reach more than 20.000 ppm [4]. However, time for the catalytic converter to set its optimal condition is also depends on the ambient condition, technologies adopted and initial temperature of the catalytic converter [5]. Research reveals that the concentration of air pollutant is very fluctuated and can reach at level of risk for people inside. So it needs to take a proper method to maintain the indoor air quality inside the enclosed parking garage [6].

A natural ventilation system will not enough to remove the air pollutant and maintain the indoor air quality. It needs to install a mechanical ventilation device to circulate fresh air and remove the air pollutant inside the parking garage [7]. This mechanical device should be chosen based on proper specification and good engineering design, so this device can provide enough rate of air circulation and better distribution of air velocity [8–10].

In overview, the position and specification of mechanical device, the existence of the objects as well as the properties of emission source affect the emission dispersion and also the indoor air quality. Some researchers have been try to improve the indoor air quality by applying some methods, such as setting the high of exhaust fan [11], setting the capacity and position of exhaust fan [12], setting the direction of air jet flow [13]. On other research, some methods have been are compared to find out the advantage, the disadvantage, and the efficiency of each method [10].

This study aims to find out other effective method to remove the air pollutant inside the enclosed parking garage. In this research, it adds a secondary exhaust fan which can short the path flow of the air pollutant. The secondary exhaust fan should be placed as close as possible to the emission source because usually the highest concentration of air pollutant located near to the emission source [14]. The example object which should be available and located close to the emission source is wheel stopper. In this research, this device is designed by integrating the secondary exhaust fan and the wheel stopper. Briefly, this research follows two steps of Computational Fluid Dynamics (CFD) analysis. The first step is designing and analyzing the proposed wheel stopper design and the last step is analyzing the performance of the best design of secondary exhaust fan in reducing the indoor air pollution.

2 Methodology

This research evaluates the effectiveness of secondary exhaust fan which is located near to the emission source. The secondary exhaust fan is designed as integrated with wheel stopper to avoid the addition of device which can hinder the vehicle movement. By implementing this method, the secondary exhaust fan can be placed anywhere inside the parking garage where a or some cars are parked with idling condition. This research evaluates the effects of the addition of secondary exhaust fan to maintain the Indoor Air Quality (IAQ). Considering the position of idling car which is always changed, the secondary exhaust fan should have consistent performance, in this case it can adsorb the amount of air pollutant consistently in various cars position.

The research is conducted by Computational Fluid Dynamics (CFD) simulation. At the first step of research (finding the best design of secondary exhaust fan), we use realizable k- ε viscous model with default mesh size of 40 mm but it reduces the mesh size of 10 mm when the meshes are located inside the secondary exhaust fan. Meanwhile for the second step, the simulations use SST k-Ω model which use the advantages combination of k- ε and k-Ω viscous model. The mesh size is set to 144 mm and reduce to 50 mm for mesh which is located near to the wall. All the simulations are conducted in steady state condition and stop until they have convergence criteria of 10^{-4}.

2.1 Designing the Secondary Exhaust Fan

Some designs of secondary exhaust fan are proposed to determine which one will be applied inside the parking garage. This secondary exhaust fan is made of 4-inch steel

Table 1. Dimension of each hole on wheel stopper

Design	First Left/Right (Hole 2 and 5)	Second Left/Right (Hole 2 and 5)	Centre (Hole 3 and 4)
Design of A	4”	4”	4”
Design of B	4”	4”	3”
Design of C	4”	4”	2”
Design of D	4”	3”	3”
Design of E	4”	3”	2”
Design of F	4”	2”	2”

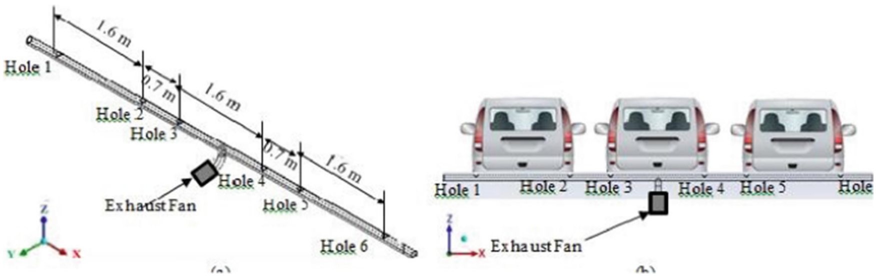

Fig. 1. Wheel Stopper with Secondary Exhaust Fan (a) Hole position on Secondary Exhaust Fan, (b) Position of secondary exhaust fan to Position of Parking Car.

pipe which has six holes with various. In order to adsorb the air pollutant, this device is equipped with an exhaust fan. Figure 1 shows the design of secondary exhaust fan while Table 1 shows the diameter variation of each hole. Each design of secondary exhaust fan has six holes with various diameter. In order to find the most proper design, it uses parameter of the air flow rate uniformity which flows through its each hole.

2.2 Creating the Geometry of Enclosed Parking Garage

Having found the best design, it continues the research by simulating the secondary exhaust fan in a simple enclosed parking garage. This parking garage has maximum capacity of six cars it is equipped with a primary exhaust fan installed on the wall near to the area of parking space. More information related to the position of and dimension of exhaust fan is shown in Fig. 2. In order to evaluate the performance of the secondary exhaust fan, it simulates the model with four variations. Each variation has same total air change rate of six Air Change per Hour (ACH), but each of them has different variation of flow rate on both of the primary and the secondary exhaust fan. Table 2 shows the detail of the simulations.

In these simulations, three idling cars emit some air pollutants particularly for parameter of carbon monoxide (CO). The cars are assumed in cold engine condition and emit

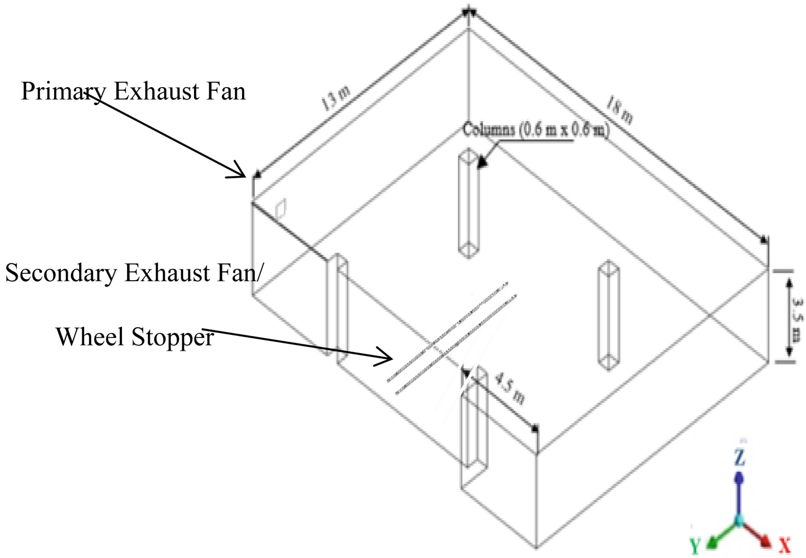

Fig. 2. Dimension of Enclosed Parking Garage and with Primary Exhaust Fan and Secondary Exhaust Fan.

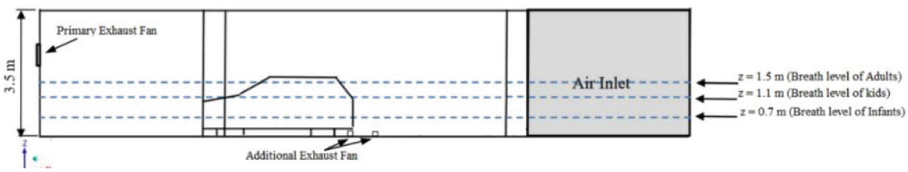

Fig. 3. Various levels of breath level for infants, kids, and adults.

Table 2. Detail variations of simulation to investigate the performance of secondary exhaust fan

Variation	**Percentage of the Total Air Change Rate**		
	Primary Exhaust Fan	**Secondary Exhaust Fan**	Total
1st Variation	100%	0%	100%
2nd Variation	95%	5%	100%
3rd Variation	90%	10%	100%
4th Variation	85%	15%	100%

much higher concentration of CO. Three levels of human breathing height are highlighted in this study since these levels relate to breath level for the infants (z = 0.7 m above the ground), the kids and (z = 1.1 m above the ground) the adults (z = 1.5 m above the ground) [15, 16]. Figure 3 shows the definition of these levels.

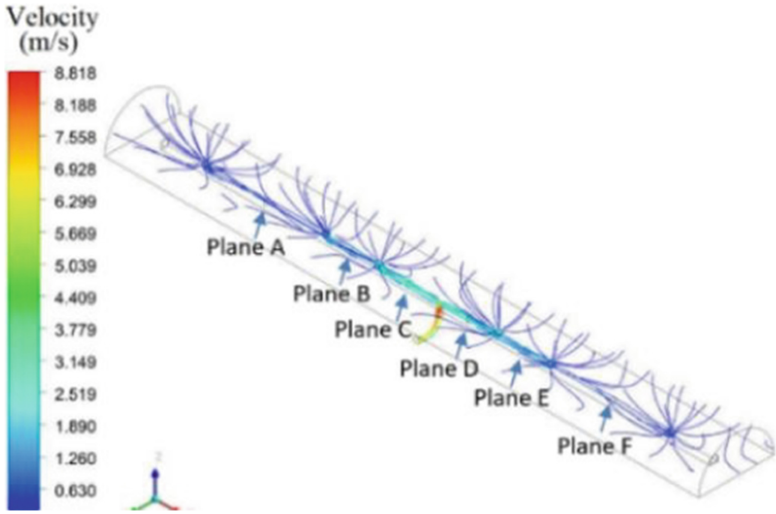

Fig. 4. Streamline of Air Flow and position of Sampling Plane to determine mass flow from each hole.

3 Result and Discussion

3.1 Choosing the Secondary Exhaust Fan

Eight teen CFD simulation have been completed to determine the performance of secondary exhaust fans. The six design of secondary exhaust fan follows three simulations which has mass rate of 5%, 10%, and 15% of 6 Air Change per Hour (ACH). In the CFD simulations, it only investigates a half pair of secondary exhaust fan to simplify the simulation. Figure 3 Shows the example of airflow streamline inside the secondary exhaust fan (Fig. 4).

Air flow distribution determines the performance of secondary exhaust fans. In this study, it expects that each hole will has equal airflow or rate of mass. In order to measure the distribution of the rate of mass, some virtual planes are placed inside the wheel stopper to measure the rate of mass as shown in Fig. 3. Based on Law of mass conservation, it can determine rate of mass through each hole by using the following equations.

$$\dot{m}_{H1} = \dot{m};\ \dot{m}_{H6} = \dot{m}_{PF} \tag{1}$$

$$\dot{m}_{H2} = \dot{m}_{PB}; -\dot{m}_{H1}; \dot{m}_{H5} = \dot{m}_{PE} - \dot{m}_{H6} \tag{2}$$

$$\dot{m}_{H3} = \dot{m}_{PC} - \dot{m}_{H2} - \dot{m}_{H1}; \dot{m}_{H4} = \dot{m}_{PD} - \dot{m}_{H5} - \dot{m}_{H6} \tag{3}$$

where:

$\dot{m}_{H1}, \dot{m}_{H2}, \dot{m}_{H3}, \dot{m}_{H4}, \dot{m}_{H5}, \dot{m}_{H6}$ = Rate of mass through Hole1, Hole 2, Hole 3, Hole 4, Hole 5 and Hole 6;

$\dot{m}_{PA}, \dot{m}_{PB}, \dot{m}_{PC}, \dot{m}_{PD}, \dot{m}_{PE}, \dot{m}_{PF}$ = Rate of mass through Plane A, Plane B, Plane C, Plane D, Plane E, and Plane F.

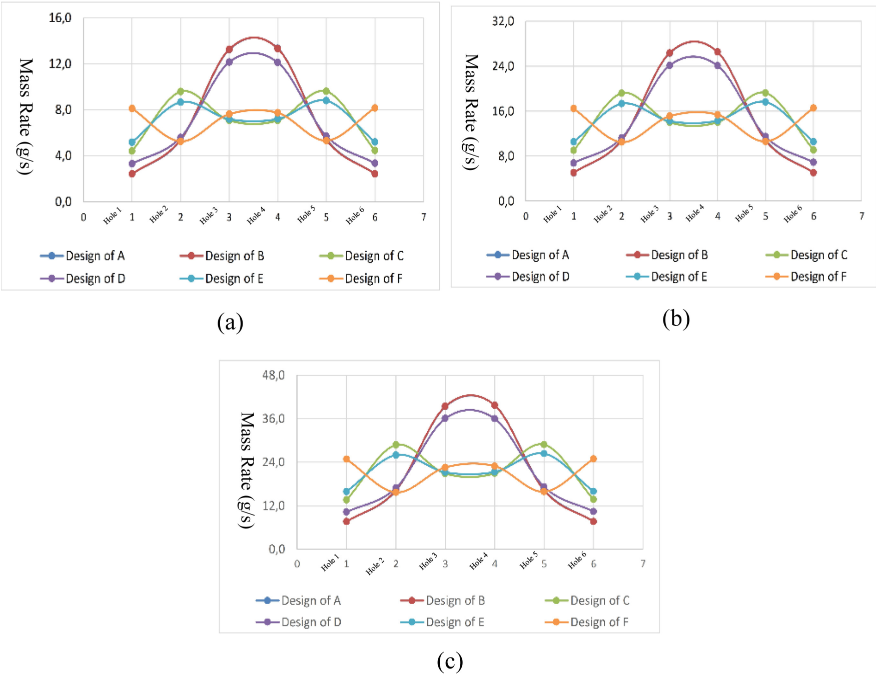

Fig. 5. Graph of mass rate distribution adsorbed by each of hole in secondary exhaust fan (a) Mass rate = 5% of 6 ACH, (b) Mass rate = 10% of 6 ACH, (c) Mass rate = 15% of 6 ACH.

Table 3. Mass Rate of air flow through each whole on selected secondary exhaust fan / wheel stopper

Mass Rate on secondary exhaust Fan	Mass Rate at each hole (g/s)		
	Hole 1 & 6	Hole 2 & 5	Hole 3 & 4
5% of 6 ACH	5,19	8,73	7,20
10% of 6 ACH	10,54	17,46	14,25
15% of 6 ACH	15,92	26,17	21,28

Since diameter and distance to the center of Hole 1 is same with Hole 6, Hole 2 is same with Hole 5, and Hole 3 is same with Hole 4 it assumes that: $\dot{m}_{H1} \approx \dot{m}_{H6}; \dot{m}_{H2} \approx \dot{m}_{H5}$ and $\dot{m}_{H3} \approx \dot{m}_{H4}$.

Based on the results, the design of E of secondary exhaust fan (See Table 1) is selected due to it has the most uniform air flow which flows through its each hole. The simulation result shows that selected design has mass rates as shown in Table 3. By using the previous result of CFD simulation, the performance of this secondary exhaust fan will be investigated inside the parking garage in order to evaluate its effect to mitigate the indoor air pollution.

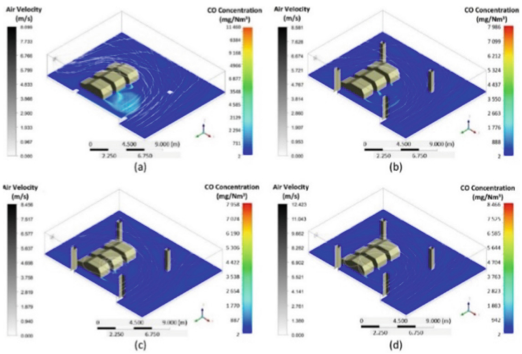

Fig. 6. Streamline of air inside the enclosed parking garage; (a) With no secondary exhaust fan, (b) Rate of secondary exhaust fan = 5% of Total Air Change Rate (ACH), (c) Rate of secondary exhaust fan = 10% of Total Air Change Rate (ACH), (d) Rate of secondary exhaust fan = 15% of Total Air Change Rate (ACH).

3.2 Evaluating the Influence of Secondary Exhaust Fan

Based on the previous step of research, it conducts four CFD simulations to evaluate the air circulation and the emission dispersion inside the parking garage. The secondary exhaust fan is set to adsorb the air with the rates of mass are equal to Table 3 while the mass rate of primary exhaust fan is set that each the simulation has ='[total air circulation of 6 Air Change per Hour (ACH). Based on Fig. 6, the addition of secondary exhaust fan affects the streamline or air flow as well as the exhaust gas flow from the tailpipes. Although this exhaust fan has much lower flow rate but it significantly changes the dispersion of exhaust gas. Since its position closed to the emission source, most of the exhaust gas flows through the secondary exhaust fan.

In order to evaluate the effects to Indoor Air Quality (IAQ), Fig. 7 shows the contour of CO concentration. The red color at the figures shows the contaminated area where the CO concentration has already excessed the limits of 100 000 $\mu g/Nm^3$. When it has excessed the limits, the CO concentration could endanger people health even a death [17].

This figure also shows that increasing the secondary exhaust fan flow rate can significantly reduce the dispersion of CO. By paying attention to each part of the figures, it gets an information that the secondary exhaust fan can change the pattern of exhaust gas flow of and create a vortex near to the tailpipe and the secondary exhaust fan. When the parking garage does not have secondary exhaust fan, all level of human breathing height has endangered area as we can see at Fig. 7 particularly in Fig. 7 of (a), (b), and (c). But when it installs a set of secondary exhaust fan, the secondary exhaust fan can significantly reduce the concentration of air pollutant and it reduces CO concentration along with the increasing of its mass/flow rate. In addition, the air pollutants at breathing height of infants always have the highest air pollutant concentration among the other breathing heights. This CO concentration are reduced with the increasing distance between the breathing height and the emission source. Finally, the air pollutant concentration is

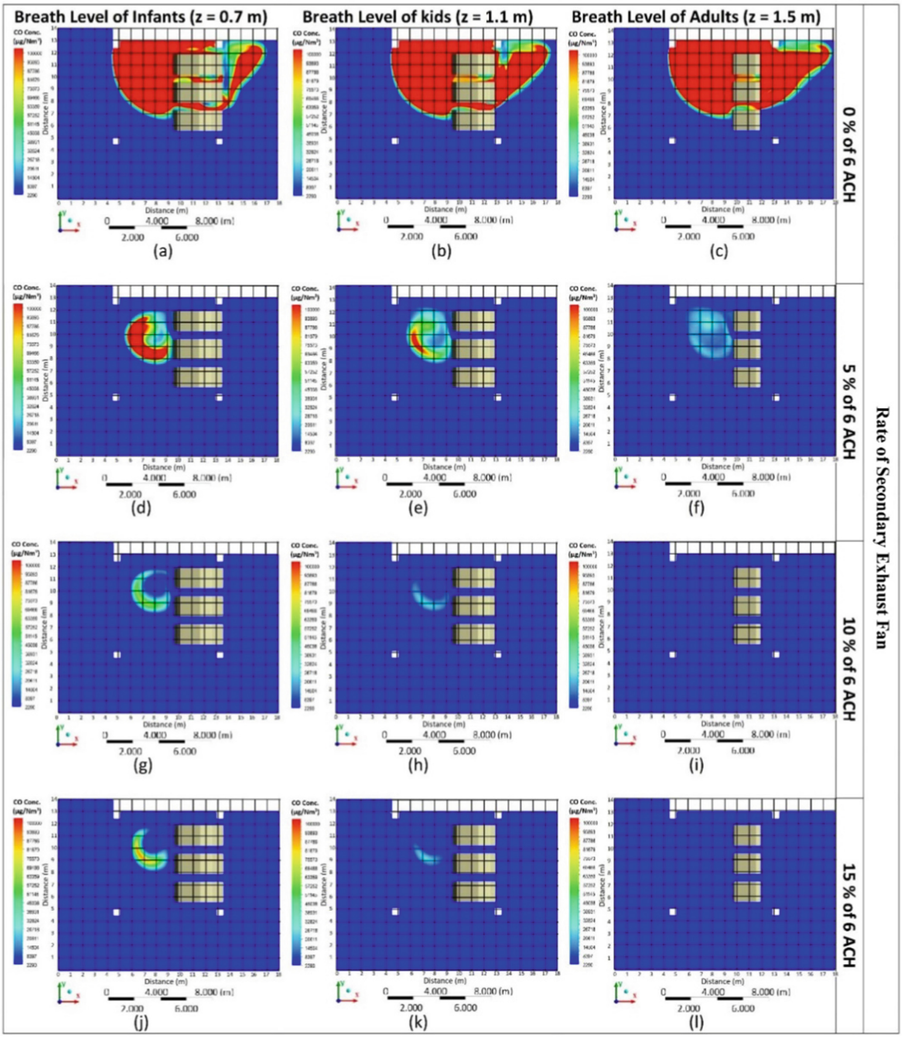

Fig. 7. CO concentration at each level compared to the environmental threshold (a) with no secondary exhaust fan at z = 0.7 m, (b) with no secondary exhaust fan at z = 1.1 m, (c) with no secondary exhaust fan at z = 1.5 m (d) Rate secondary exhaust fan = 5% of 6 ACH and located at z = 0.7 m (e) Rate secondary exhaust fan = 5% of 6 ACH and located at z = 1.1 m, (f) Rate secondary exhaust fan = 5% of 6 ACH and located at z = 1.5 m, (g) Rate secondary exhaust fan = 10% of 6 ACH and located at z = 0.7 m, (h) Rate secondary exhaust fan = 10% of 6 ACH and located at z = 1.1 m, (i) Rate secondary exhaust fan = 10% of 6 ACH and located at z = 1.5 m, (j) Rate secondary exhaust fan = 15% of 6 ACH and located at z = 0.7 m, (k) Rate secondary exhaust fan = 15% of 6 ACH and located at z = 1.1 m, (l) Rate secondary exhaust fan = 15% of 6 ACH and located at z = 1.5 m.

affected by the emission dispersion which is also affected by the pattern of air flow and the shape of any object inside the area of study.

4 Conclusion

This research follows two steps of CFD simulation, where the first step to determine the proper design of secondary exhaust fan which is integrated to wheel stopper. Meanwhile the second part to evaluate the effect of secondary exhaust fan to indoor air quality particularly for parameter of carbon monoxide (CO). The first step of research compares six designs os secondary exhaust fan and each design follows three simulation which each simulation has different rate of airflow (5%, 10%, and 15% of 6 air change rate per hour). Comparing to the all simulations, the design of E has the most uniform airflow through its holes and it is selected to be evaluated in the next step of research. The rate of airflow which flows through each hole can be seen in Fig. 5.

The selected secondary exhaust fan then evaluated by simulating its role to maintain the air pollutant concentration in a simple enclosed parking garage. This parking garage has maximum capacity of six cars. In these simulations, three cars are idling inside the parking garage and emitting high concentration of CO. This step evaluates four simulation of emission dispersion. Each simulation has different rate of air flow through the secondary exhaust fan. Based on the CFD simulations, the addition of secondary exhaust fan which is integrated to wheel stopper can significantly reduce the CO concentration. By comparing all the simulations, it can conclude that the CO concentration at breathing height of infants, kids and adults can be reduced by increasing the flow rate of secondary exhaust fan.

However, the secondary exhaust fan has limitation on its dimension. This exhaust fan can only adsorb the air with maximum of 15% of the requirement of minimum air flow of six Air Change per Hour (ACH). It recommends to continue the research, particularly for case of the moving cars. Generally, the moving car has much lower CO in its exhaust gas due to its engine and catalytic converter has attained an optimum condition. But the moving car is located more far away to the secondary exhaust fan and the rate of exhaust gas is also much higher than the idling condition.

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