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A CFD SIMULATION OF PM1 AND CO AIR CONTAMINANTS IN A BUS PASSENGER COMPARTMENT

Noor Emilia Ahmad Shafie, Haslinda Mohamed Kamar*, Nazri Kamsah

Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

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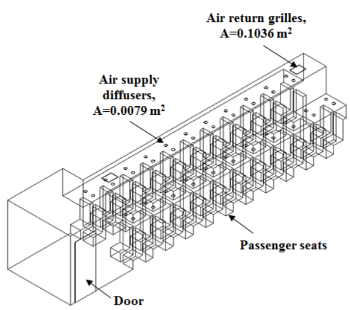
*Corresponding author
haslinda@mail.fkm.utm.my

Graphical abstract



Abstract

Air distribution systems inside a bus compartment are important for providing healthy and comfortable environment for passengers. Lack of ventilation inside the bus passenger compartment causes an increase level of air contaminants concentration. Particulate matters and carbon monoxide are indoor air contaminants which can affect the passenger's health such as respiratory problem and lung cancer. This article reports the results of a CFD simulation on transport of carbon monoxide and particulate matter 1 inside a passenger compartment of a university's shuttle bus. Fluent CFD software was used to develop a simplified three-dimensional model of the bus passenger compartment. Flow analysis was carried out using RNG k-ε turbulent model for air flow, discrete phase and species transport for the air contaminants. Four variations of ventilation system namely two mixing ventilation types, combined mixing with displacement ventilation and combined mixing ventilation with underfloor air distribution was examined. The CFD simulation results show that the use of the combined mixing and displacement ventilation and also the combined mixing and underfloor ventilation types are capable of reducing the concentration of carbon monoxide and particulate matter 1 inside the bus passenger compartment by 81% and 54%, respectively.

Keywords: Computational fluid dynamics, Indoor air contaminant, ventilation system, bus passenger compartment

1.0 INTRODUCTION

A bus passenger compartment requires a good ventilation system to distribute a clean and healthy air in the occupied zone. The efficiency of the ventilation system is reflected by a good indoor air quality (IAQ). The indoor air quality relates to the amounts of contaminants in the air. Good IAQ means the air has low amount of unwanted contaminants. Poor IAQ occurs when the amount of contaminants in the air exceeds the acceptable level. In IAQ studies two types of harmful air contaminants are usually investigated namely airborne particles and gas species. Particulate matter 1 (PM1) represents an airborne particles whereas carbon monoxide (CO) represents a gas species. Various diseases can adversely affect the health of the occupants because of these contaminants. Examples include respiratory problem and cardiovascular disease. Knowledge concerning the contaminants level is very important to prevent the harmful particles and gaseous inhaled by passengers when commuting in a bus. The ventilation system of the bus needs to be efficient to ensure a cleaner air and good health of the passengers.

Several factors influence the design and performance of a bus ventilation system such as size and type of the bus, air supply velocity, air supply temperature, layout of the air supply diffuser and layout of the air return grille. Ventilation strategies such as displacement ventilation (DV) and underfloor air distribution (UFAD) systems have been investigated in buildings. Ho *et al.* [1] compared the performance of two ventilation systems in an office building, which were an under-floor air distribution system and an overhead air distribution system, using a CFD simulation method. The under-floor distribution system was found to have a better performance compared to the overhead distribution system in removing air contaminants. Lin *et al*. [2] investigated the effectiveness of a displacement ventilation system in a public transport interchange using a CFD simulation. The system was found to be capable to provide adequate ventilation for the interchange. The DV and UFAD systems were able to reduce the air contaminants due to a phenomenon known as a perfect mixing.

At present, studies on reducing the air contaminants inside the bus compartment is quite limited especially those that use computational fluid dynamics (CFD) approach. CFD simulation is more convenient to do as compared to experimental method for analyzing the indoor air quality in occupied spaces. This article reports the findings of CFD simulation study to assess the concentration of air contaminants namely carbon monoxide and particulate matter 1 inside a passenger compartment of a university's shuttle bus. Fluent CFD software was used to develop a simplified three-dimensional model of the bus passenger compartment. Air flow analysis was carried out using RNG k-ε turbulent model while a discrete phase and species transport models were used to simulate transport air the contaminants. Four cases of ventilation strategy were investigated namely mixing ventilations (MV3 and MV4), a combine mixing and displacement ventilations (MV2+DV) and a combined mixing ventilation with under-floor air distribution (MV2+UFAD) system.

2.0 METHODOLOGY

Fluent CFD software was used to develop the simplified model of the bus passenger compartment and to simulate the air flow and air contaminants transport inside the compartment. Air flow simulation was carried out using RNG k-ε turbulent model while discrete phase and species transport models were used to simulate the transport of the particulate matter 1 and carbon monoxide gas, respectively. Results of a field measurement carried out on an actual university's shuttle bus were used as a basis to validate the CFD model. The simplified model of the bus passenger compartment is shown in Figure 1. There are fourteen air supply diffusers which are placed on the ceiling mounted ducting and two air return grilles that are placed on the roof of the compartment. The currently used ventilation system for the bus is the mixing ventilation (MV).

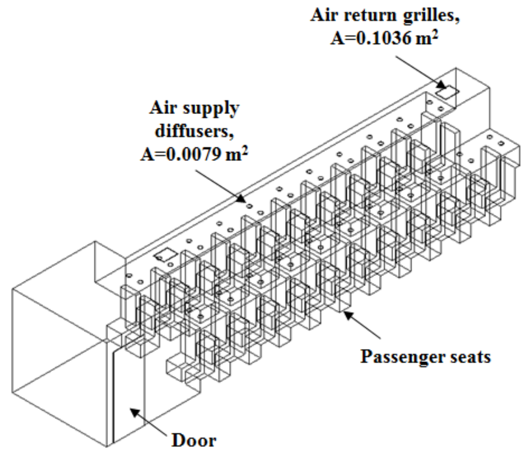


Figure 1 A simplified model of the bus passenger compartment

2.1 Field Measurement

Field measurements were conducted to quantify the contaminants concentration of CO and PM1 inside the passenger compartment of the bus. The bus travels along the routes in the university's campus for a total distance of about 12 km. The field measurements were carried out on an empty bus. Measurements of concentrations of the air contaminants were carried out at the front, middle and rear sections of the compartment. The concentration levels of CO gas and PM1 were continuously monitored during the trips and data were recorded at a time interval of 1 minute. A handheld particle counter (HPC300) and an indoor environmental quality (IEQ Bacharach) were used to measure the concentration of CO and PM1, respectively. A digital anemometer (model V816B) was used to measure the air velocity and temperature at the air supply diffusers. The indoor air quality instruments were placed at a height of 1.0 m from the floor of the passenger compartment, which is considered as a breathing level [3].

2.2 CFD Validation

The CFD model was validated by comparing the concentrations of contaminants obtained from the CFD simulations with the findings from the field measurements. The following assumptions were made during the CFD simulation:

- The RNG k-ε turbulence, discrete phase and species transport models were applicable for modeling the airflow, particle and gas transport, respectively.
- The door is in an open position and there are no passengers inside the bus.
- Initially there are no air contaminants inside the passenger compartment.
- The CO and PM1 air contaminants enter the passenger compartment through the opened front door.

2.2.1 Meshing of CFD Model

The computational domain was meshed using tetrahedron elements. This element type is suitable for use in complex geometry and it usually results in faster convergence [4]. The total numbers of elements were approximately 508057. The maximum and minimum sizes of the elements are 0.34 m and 0.002 m, respectively. Much finer elements were used at the door, air supply diffusers and the air return grilles. This is to ensure that the CFD results are not severely affected by the element size variation. Figure 2 shows the meshing of the passenger compartment.

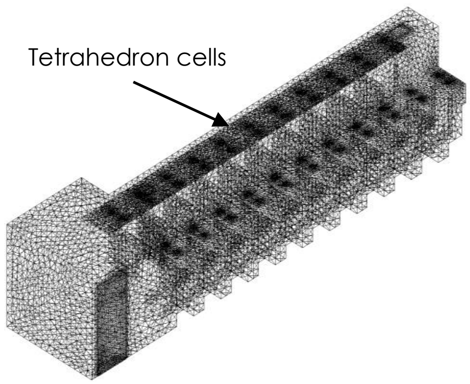


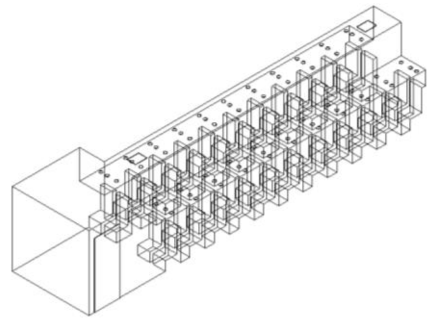
Figure 2 The meshing of the passenger compartment

2.2.2 Boundary Condition

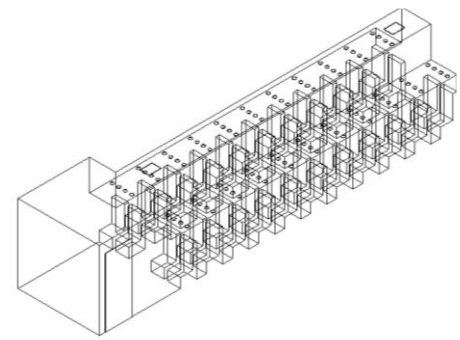
Temperature and velocity of the air leaving the air supply diffusers were set at 23°C and 3 m/s, respectively, based on the field measurement values. The wall temperature of the bus was set at 26°C. The concentrations of CO gas and PM1 at the front door were set at 7 ppm and 52 μg/m^3, respectively. These were applied for all cases of ventilation setup considered in this study. Turbulent intensity was set at 5%. A no slip condition was applied at the walls of the passenger compartment. The CFD simulations were performed as a steady-state condition with pressure-based segregated solver with the SIMPLE, second order upwind discretization scheme. The convergence criterion for all the equations was set at 10^{-4} except for the energy equation, which was set at 10^{-6} [6].

2.3 Parametric Study

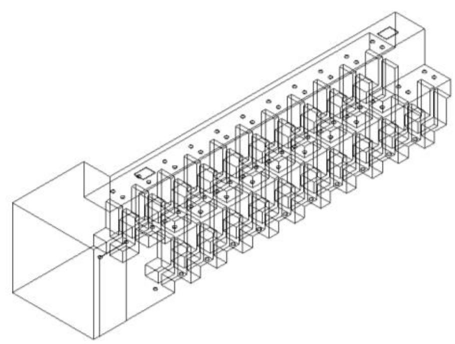
Four cases of ventilation setup were considered in this study. These are illustrated in Figure 3. In case 1 (MV3), three air supply diffusers are placed on the ceiling mounted ducting. In case 2 (MV4), four air supply diffusers are placed on the ceiling mounted ducting. In case 3 (MV2 + DV), two air supply diffusers are placed on the ceiling mounted ducting and one air supply diffuser is placed on the side walls, adjacent to the rows of seats. Finally in case 4 (MV2 + UFAD), two air supply diffusers are placed on the ceiling mounted ducting and one air supply diffuser is placed on the floor, in front of each seat.



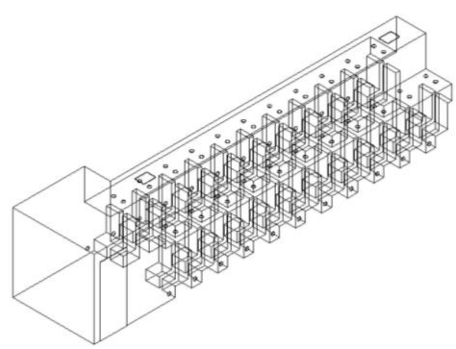
(a)



(b)



(c)



(d)

Figure 3 Various cases of ventilation setup: (a) MV3, (b) MV4, (c) MV2+DV and (d) MV2+UFAD

3.0 RESULTS AND DISCUSSION

Figure 4 shows a variation of CO gas concentration along the height of the passenger compartment, for various cases of ventilation setup. It can be seen that the concentration of CO gas is about 7 ppm up to the height of 1.1 m from the floor. The CO concentration decreases to about 3 ppm at the height of 1.3 m. At the height of 1.5 m from the floor, the CO gas concentration is almost 0 ppm. These are true for nearly all types of ventilation setup. However, when the combined mixed ventilation and under-floor air diffusers were used, the CO gas concentration is about 6 ppm up to the height of 0.7 m from the floor. Then the CO concentration reading reaches about 7 ppm at the height of 1.1 m.

According to the ASHRAE standard [5], the safe level of CO gas concentration in an occupied space is below 10 ppm. Hence it is safe to say that the level of CO gas concentration inside the passenger compartment of the shuttle bus is within a safe limit. In a combined mixing ventilation with under-floor air distribution setup cool air is supplied from the floor level in front of each passenger seat. This promotes temperature variation from the lower to the upper level of zone in which the passengers are seating. The resulting air flow pattern helps provide cleaner air to the passengers [1].

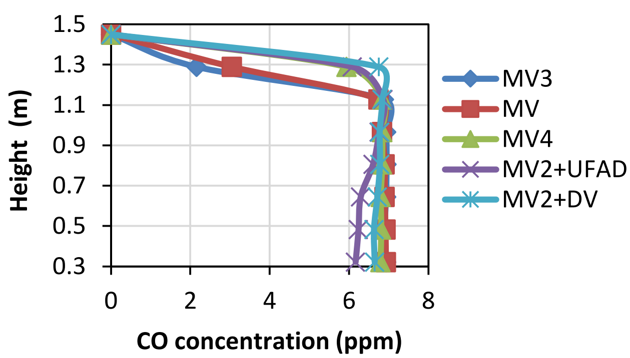


Figure 4 Comparison of CO gas concentration for different cases of ventilation strategy

Figure 5 shows the variation of PM1 concentration along the height of the bus passenger compartment, for various cases of ventilation setup. With the presently used mixed ventilation, the PM1 concentration is about 34 μg/m³ up to a height of 1.1 m from the floor. The PM1 concentration level reduces to a much smaller value above this height. The corresponding PM1 concentration level are about 22 μg/m³ for mixed ventilation with 3 air supply diffusers, 18 μg/m³ for mixed ventilation with 4 air supply diffusers, respectively. When the combined mixed ventilation with under-floor air distribution was used, the PM1 concentration is about 16 μg/m³ up to the height of 1.1 m from the floor. The concentration level decreases to almost zero value at the height of 1.5 m from the floor. Finally, with the use of combined mixing with displacement ventilation setup, the PM1 concentration is about 6 μg/m³ up to the height of 1.1 m from the floor level. The concentration reduces to a negligible level at the height up to 1.5 m from the floor.

According to the ASHRAE standard [5], the safe level of PM1 concentration in an occupied space is below 25 μg/m³. Hence the presently used mixing ventilation setup is not quit capable of providing a clean air inside the passenger compartment. The use of combined mixed ventilation with under-floor air distribution is capable of reducing the PM1 concentration by about 54%. The level of PM1 concentration could be reduced by 81% if the combined mixing with displacement ventilation setup is employed.

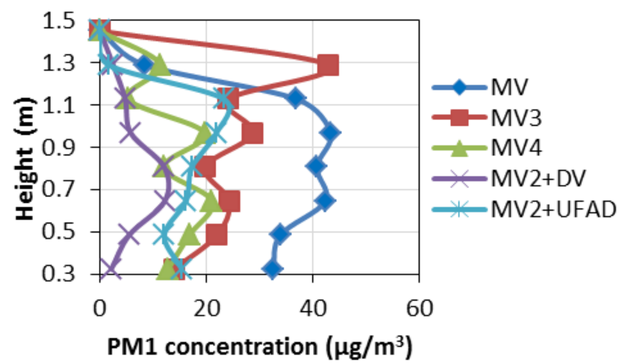


Figure 5 Comparison of PM1 concentration for different cases of ventilation strategy

4.0 CONCLUSION

A CFD simulation approach was used to simulate air flow and air contaminants transport in a passenger compartment of a university's shuttle bus. Two types of air contaminants were considered namely particulate matter 1 and carbon monoxide gas. The distributions of contaminants concentration inside the passenger compartment for four ventilation strategies were obtained from the simulations. The simulation results indicate that the combined mixed and displacement ventilation system has no significant effects in reducing the concentration of the carbon monoxide gas but is capable of reducing the level of particulate matter 1 inside the passenger compartment by about 81%. The combined mixed ventilation and under-floor air distribution system meanwhile is capable of reducing the concentration of carbon monoxide gas by about 2% and the concentration of particulate matters 1 by about 54% compared to the presently used mixing ventilation strategy.

Acknowledgement

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