CFD Simulation of Particulate Matters inside a Bus Passenger Compartment

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Abstract-- Passengers commuting in a public transport buses were exposed to indoor air contaminant such as particulate matter. Particulate matter can be found in enclosed spaces and could affect the passenger health in long and short terms duration. This paper presents the concentration levels of PM1, PM2.5 and PM10 against time and length of the passenger compartment. Field measurements were conducted in a university’s shuttle bus to validate the CFD model. The field measurement of concentration levels of PM1, PM2.5 and PM10 were conducted at the front of the passenger compartment at a level of 1.1 m from floor. CFD software was used to develop a simplified 3D model of a quarter section of a passenger compartment. Turbulent flow analysis was carried out using LES model for the air flow and DP model for the particles. It was found that the concentration levels of PM1, PM2.5 and PM10 were high at 200 sec, 600 sec, 800 sec and 1000 sec. This is due to outside particles enter the door during boarding and unboarding the passengers.

Index Term-- Indoor Air Contaminant, Particulate Matters, Concentration Level, Bus Passenger Compartment, Airborne Transmission Disease.

1. INTRODUCTION

Passengers are exposed to indoor air contaminant such as particulate matter inside a public transport buses. Ultrafine (PM<2.5) and large particle sizes (PM>2.5) are known as the types of particulate matters that can be found in enclosed spaces, for example inside the building or vehicles. Particulate matter is a mixture of solid particles and liquid droplets found in the air such as dust, dirt, soot and smoke [1]. Generally, the particle that less than 10 μm (PM10) in aerodynamic diameter tend to pose the greatest health concern because they can pass through the nose and throat and get deep into the lungs [2]. The particulate matters have a negative impact and affected the passenger’s health condition such as respiratory problem and cardiovascular diseases mortality diseases [3].

Previous researchers were conducted the field measurements of particulate matters contaminant. Different of cases and parameters were studied by previous researchers in order to measure and examined the concentration level of particle. For example the time and height of measuring, route type, short and long haul, bus age and bus engine. Wong et al., 2011 [4] were investigated the concentration level of PM10 of public transport buses in Hong Kong. The measurements were performed between suburban and urban areas in Hong Kong. The instrument was placed at the rear compartment and at the height of breathing level of passengers. The measurements were taken at the peak hours, which is 7.00 am to 12.00 pm. They found that the overall average of concentration level of PM10 was 169 μg/m³. Hsu et al., 2009 [5] were studied the concentration level of PM10 and PM2.5 inside the buses. The measurements were performed in highway road Taiwan. The total travelling distance was approximately 300 km, which normally took 4 hours to 5 hours, depending on the traffic and weather condition. The sampling instruments were placed in the middle of the passenger compartment and at the height of the breathing zone of the seated passengers. They revealed that the concentration level of PM10 and PM2.5 were 221 μg/m³ and 167 μg/m³, respectively.

Shengwei et al., 2010 [6] were examined the micro-environmental of particulate matter inside the public transport buses. The measurements were performed in Harvard University shuttle buses and without passenger during the field measurement. The bus engine was in idle condition and the air-conditioning system was operated as usual. All the windows and doors are fully closed during the field measurement. The measurements were performed at the front and rear locations of the passenger compartment. The instruments were placed in two mesh boxes and the measurements were conducted at a height of 0.6 m and 1.1 m from floor. The field measurements were started at 9.00 am until 16.30 pm with a lunch break around noon. The result shows that the concentration levels of PM2.5 and PM10 were 11 μg/m³ and 15 μg/m³, respectively.

Kadiylia et al., 2011 [7] were examined a concentration level of particulate matters in public transport buses in the city of Toledo. This study was carried out using a new bus under actual driving condition. The particulate matter was monitored for 24 hours a day by the three instruments of particle counter. The air was sampling at a rear seat of the buses to minimize the effects from outside air contaminant enters the door bus. The air sampling was placed at the height of breathing zone of the passenger bus. They found that the concentration levels of PM1, PM2.5 and PM10 were 200 μg/m³, 80 μg/m³ and 60 μg/m³, respectively. In line with this, (Rim et al., 2008) [8] were investigated the indoor air quality inside school buses in Central Texas. The measurements were performed using six school buses with different engine year in suburban Austin, Texas. The route distance was 42.4 km and required approximately 100 minutes to complete. Only research team members and driver were on-board buses during the field measurement. They revealed that PM2.5 was lower inside the school buses. Based on the previous studies they concluded that the concentration level of PM were influenced by the ventilation setting, air infiltration, heavy occupancy, peak hours, vehicle age, vehicle engine, vehicle speed, meteorology, boarding and unboarding passengers during the bus trips [2-8].

The CFD methods were used by previous researchers for simulated the air flow and particle concentration. Previous researchers were studied the air flow and particle concentration inside the building. For example the research was carried out inside a room and office. Therefore in this paper, we used and applied the building CFD method to 3D model of a quarter section of a bus passenger compartment. Tian et al., 2006 [9] were conducted the CFD study on particle concentration inside a room. LES and DP model were used to
simulate the air flow and particles. The particle density of PM1, PM2.5 and PM10 were 800 kg/m³. Their simulations revealed that LES model provided the best agreement with the experimental data. Lu et al., 1995 [10] were studied the particle distribution inside a room. The CFD method was used to simulate the particle distribution inside a room. Standard k-ε and DP models were used to simulate the air movement and particle. They found that the particle concentrations are mainly influenced by the airflow pattern and particle properties. The small particles such as PM1 and PM2.5 spend more time suspended in the ventilated spaces compared to PM10.

Beghein et al., 2005 [11] were investigated the particle motions in a room. The CFD method was used to model and simulate the particle motions. LES and DP model were used in their study in order to simulate the air flow and particle motions. They revealed that the air flow pattern was influenced the particle dispersion inside a room. From the investigation light particle follows the air flow and many particles were exhausted inside the room. However, heavier particles were deposit to the floor of the room. This is due to the air flow pattern inside the room. Chang et al., 2012 [12] also were studied the particulate matter inside a room. The CFD technique was used to simulate the particle concentration level. LES and DP model were used to simulate the air flow and particle dispersion. They revealed that PM1 and PM2.5 are more difficult to dilute than PM10 inside the room. The ventilation displacement produced less of particle mass concentration compared to the mixing ventilation method.

This paper presents the concentration levels of PM1, PM2.5 and PM10 against time and length of the passenger compartment. A CFD software was used to develop a simplified 3D model of a quarter section of a passenger compartment. Velocity and temperature boundary conditions were prescribed at air-conditioning diffusers and the door of the compartment, based on actual measured data. Turbulent flow analysis was carried out using LES model for the air flow and DP model for the particles. Field measurements were carried out inside the university shuttle bus. The field measurement of concentration levels of PM1, PM2.5 and PM10 were conducted at the front of the passenger compartment at a level 1.1 m from the floor. The CFD results were validated with field measurement results at a location x = 0.3 m, y = 1.1 m and z = 2 m against time. The prediction of particle concentration and velocity of PM1, PM2.5 and PM10 against length of the passenger compartment were examined in this study.

2. CFD SIMULATION

In this study a multi-purpose computational fluid dynamics (CFD) software (Fluent-R14) was employed to simulate the air-flow conditions inside the bus passenger compartment and examine the variation of concentrations of particulate matters (PM1, PM2.5 and PM10) at several locations inside the bus compartment, with time. The main steps of the simulation are briefly described below.

2.1. Computational Domain and Meshing

Fig. 1 shows the simplified model of the bus passenger compartment which was considered as the CFD computational domain. As seen from the figure, twelve of passenger seats were considered into the CFD model. There are twelve air inlet diffusers located on the upper board and one air exhaust opening located at the front side of the bus roof.

The computational domain was meshed using tetrahedral elements with a total of 77650 cells, as shown in Fig. 2. A mesh sensitivity analysis was performed in order to ensure that the meshing of the computational domain has no significant influence on the results of the CFD analysis. Table I shows detail dimension of the computational domain, the passenger seat, the air supply diffuser, the air exhaust opening, the door and the aisle.

![Fig. 1. Simplified CFD model of the bus passenger compartment](image)

![Fig. 2. The meshing of the CFD computational domain](image)

<table>
<thead>
<tr>
<th>Table I</th>
<th>Dimensions of the computational domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain (L x W x H)</td>
<td>3.92 m × 2.5 m × 2.4 m</td>
</tr>
<tr>
<td>Aisle</td>
<td>3.92 m × 0.9 m</td>
</tr>
<tr>
<td>Door</td>
<td>2.1 m × 0.82 m</td>
</tr>
</tbody>
</table>
| Diffusers | Diameter, 0.1 m  
Area, 0.0079 m² |
| Seats | 0.7 m × 0.4 m × 0.12 m  
0.7 m × 0.5 m × 0.12 m |
2.2. Boundary Conditions

The boundary conditions prescribed on the computational domain are shown in Fig. 3. The inwards air flow occurs at the cool-air supply diffuser and at the door. Hence air-flow velocity and air temperature boundary conditions were prescribed at these locations. In this study, it was assumed that the air-conditioning system of the bus is the main source of the air pollution inside the passenger compartment. Also, all windows and the bus door were assumed to be closed and there were no passengers inside the bus compartment. Based on these assumptions, the particulate matters were injected at all the cool-air supply diffusers only during the CFD simulations. In the particle tracking process, walls in the bus were set as the trap boundary. Trap boundary means that once a particle touches it, the particle is trapped, and particle tracking process would cease. Details on the boundary conditions and properties of the particles that are used in the CFD simulations are shown in Table II.

![Fig. 3. Velocity and temperature boundary conditions prescribed on the CFD model](image)

Table II

<table>
<thead>
<tr>
<th>Boundary condition and particle properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity inlet (diffuser)</td>
<td>3.1 m/s</td>
</tr>
<tr>
<td>Velocity inlet (door)</td>
<td>0.4 m/s</td>
</tr>
<tr>
<td>Mass flow rate (diffuser)</td>
<td>0.029 kg/s</td>
</tr>
<tr>
<td>Temperature inlet (diffuser)</td>
<td>23°C</td>
</tr>
<tr>
<td><strong>Volume</strong></td>
<td>18.43 m³</td>
</tr>
<tr>
<td><strong>ACH</strong></td>
<td>57.4</td>
</tr>
<tr>
<td><strong>Density of air</strong></td>
<td>1.18 kg/m³</td>
</tr>
<tr>
<td><strong>Density of particle</strong></td>
<td>800 kg/m³</td>
</tr>
<tr>
<td><strong>Viscosity</strong></td>
<td>1.721.72e-05 kg/ms</td>
</tr>
<tr>
<td><strong>Particle sizes</strong></td>
<td>1 μm, 2.5 μm and 10μm</td>
</tr>
</tbody>
</table>

2.3. Flow Analysis

The CFD simulation was carried out using ANSYS (Fluent V.14.0) software. Advanced solver technology, accurate CFD results, flexible moving, deforming meshes and superior parallel scalability is the advantages of using this tool [13]. Transient model was used to determine the concentration level of particle as a function time. For example, the particle concentration was simulated and recorded at 200 sec, 400 sec, 600 sec, 1000 sec, 1200 sec, 1400 sec, 1600 sec and 2000 sec, respectively. Two types of the CFD model were selected in the problem setup namely viscous and discrete phase model. Large Eddy Simulation was chosen from the viscous model. Large Eddy Simulation was used to simulate the turbulent flow inside the passenger compartment. Large Eddy Simulation directly calculates the time-dependent large eddy motion while resolving the more universally small-scale motion using subgrid scale modelling [14]. In order to simulate the turbulent flow inside passenger compartment the Smagorinsky-Lilly was selected from the subgrid scale modelling.

The discrete phase model was used to simulate the concentration level of the particle. The particles were assumed injected at the inlets of the air supply diffusers and door. This is to visualize the dispersion of particle concentration inside the domain. The types of the particle physical properties are Staffman lift force and Brownian motion [15]. The dispersion of the particulate matter was assumed trap inside the domain. Therefore, the wall boundary condition was selected in trap types. Table 2 shows the boundary condition and particle properties of this study.

Discrete phase model also called Lagrangian simulation model are obtained from the integration of numerical following three dimensional differential equations which include the gravitational force, drag force, Staffman lift force and Brownian motion force. The equation below shows the Lagrangian model which are used in simulation process [15]. The Lagrangian model is mathematically expressed by:

\[
\frac{1}{6} \pi \rho_p d^3 p \frac{dU_j^p}{dt} = F_g + F_d + F_s + F_b
\]

i.e.

\[
\frac{1}{6} \pi \rho_p d^3 p \frac{dU_j^p}{dt} = \frac{1}{6} \pi \rho d^3 (\rho_p - \rho) g i \delta i 3 - \frac{1}{6} \pi \rho_p d^3 p \frac{1}{\tau} (U_j^p - U_i) - \frac{1}{6} \pi \rho_p d^3 p \frac{5.188 \rho^{1/2} d_{ij}}{5 d_p (d_{ij} - d_{ij})^{5/2} (U_j^p - U_i)} + \frac{1}{6} \pi \rho_p d^3 p G_i \sqrt{\frac{\pi \delta_i}{3\tau}}
\]
where $F_g$ is the gravitational force, $F_d$ is the drag force, $F_s$ is the Staffman lift force, $F_b$ is the Brownian motion force, $U_i$ is the fluid velocity, $U_i^p$ is the particle velocity, $\rho$ is fluid density, $x_i$ is a coordinate of particle, $t$ is a particle time, $dp$ is particle diameter, $S$ is density ratio between particle and adjacent fluid, $S$ is a function of delta, $\tau$ is the relaxation of the particle and $dij$ is $[(Uij + Uji) / 2]$ is the deformation rate tensor. The concentration levels of PM1, PM2.5 and PM10 were obtained from the numerical average particle concentration equation which is known as $C$. $M_s$ is the total mass of suspended particle ($\mu g$) and $V$ is the volume of the bus compartment ($m^3$) as given in equation (3).

$$C = \frac{M_s}{V}$$  \hspace{1cm} (3)

A semi-implicit method for pressure-linked equations (SIMPLE) algorithm was used for handling the coupling between pressure and velocity [9]. A second order implicit of transient model was used to determine the pattern changes of particle concentration over time inside passenger compartment.

2.4. Field Measurement

A field measurement was conducted to investigate the variation of concentration of particulate matters (PM1, PM2.5 and PM10) inside the passenger cabin of a university’s shuttle bus that ferries students from their hostels to the university’s campus. However, the measurements were performed when the bus was empty. Detail description of the bus is given in Table III. The bus was stopped at several locations along the selected route and the door of the bus was opened for several minutes and then closed back during these stopages to simulate the conditions when students are boarding and unboarding the bus. The in-campus route followed by the bus during the entire period of the field measurement is shown in Fig. 4. The total distance travelled by the bus was about 12 km.

The measurements were conducted at the front section of the bus passenger cabin. The concentrations of PM1, PM2.5 and PM10 were continuously monitored during the trips and data were recorded at several time intervals, at the steady-state conditions.

<table>
<thead>
<tr>
<th>Description of the bus used for the field measurements</th>
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<tbody>
<tr>
<td><strong>Description of bus</strong></td>
</tr>
<tr>
<td>Model</td>
</tr>
<tr>
<td>Hino (RKJJSK-14045)</td>
</tr>
<tr>
<td>Engine</td>
</tr>
<tr>
<td>JO8C-F EURO 1</td>
</tr>
<tr>
<td>Year</td>
</tr>
<tr>
<td>2011</td>
</tr>
<tr>
<td>Bus compartment</td>
</tr>
<tr>
<td>Length, 11.4 m</td>
</tr>
<tr>
<td>Width, 2.5 m</td>
</tr>
<tr>
<td>Height, 2.4 m</td>
</tr>
<tr>
<td>Bus door</td>
</tr>
<tr>
<td>Width, 0.82 m</td>
</tr>
<tr>
<td>Height, 2.1 m</td>
</tr>
</tbody>
</table>

A handheld particle counter instrument (model HPC300) was used to measure the concentrations of particulate matters PM1, PM2.5 and PM10 inside the bus passenger cabin. A digital anemometer (model V816B) was employed to measure the air velocity and temperature at the cool air supply diffusers. For stability reason, the instrument was attached onto a tripod during the data measurement, as shown in Fig. 5. The particle counter instrument was placed at the height of 1.1 m from the floor of the bus cabin, which is considered as the breathing level of the passengers. The air velocity and temperature at the cool air supply diffuser were maintained as much as possible at 3.1 m/s and 23°C, respectively during the field measurement period.

![Fig. 4. The in-campus route followed during the field measurement](image1)

![Fig. 5. A HPC300 handheld particle counter instrument.](image2)

3. RESULTS AND DISCUSSIONS

3.1. Concentration Levels of PM1, PM2.5 and PM10 as a Function of Time

Fig. 6 shows the variation of particle concentration of PM1 with time. The particle concentrations were measured at the location, \( x = 0.3 \text{ m}, y = 1.1 \text{ m} \) and \( z = 2 \text{ m} \) inside the bus passenger compartment as shown in Fig. 7. The x-direction is a width, y is a height and z is a length of the bus passenger compartment. The locations were chosen at the height of the breathing zone of passengers and kept away from the bus main entrances and air supply diffusers. This is to prevent the error during measuring the particle concentration inside the passenger compartment. It can be seen that the simulated results of PM1 shows a good agreement with the field measurement. LES model combining with the Lagrangian model provides reasonable prediction of the particle concentration of PM1 inside the bus passenger compartment. The results can be observed that at 200 sec the particle concentration was high and low at 400 sec. However, at 600 sec to 1000 sec the particle concentrations were high again. Then, at 1200 sec to 2000 sec the particle concentrations were decreased inside the bus passenger compartment. The result shows that the trends of the PM1 were decreased when measured at the long duration time (2000 sec). The concentration level of PM1 was higher at 200 sec, 600 sec, 800 sec and 1000 sec due to inadequate ventilation of the bus, loading and unloading passengers at the bus stop [6]. The ventilation system of the bus could not eliminate the particles when the door was widely open. However, the concentration level of PM1 was lower at 1200 sec, 1400 sec, 1600 sec and 2000 sec. The particle concentration level of PM1 was lower at that time due to sufficient ventilation and least of unloading passengers. The highest and lowest particle concentration levels of PM1 were 62 \( \mu \text{g/m}^3 \) and 8 \( \mu \text{g/m}^3 \), respectively. The particle concentration levels of PM1 were exceeded the allowable limit recommended by the World Health Organization (WHO). The allowable limit of concentration level for PM1 should not exceed 25 \( \mu \text{g/m}^3 \) [14]. The trends of the particle concentration of PM1 show similar with the previous studies findings [12].

Fig. 7 shows the variation of particle concentration of PM2.5 with time. The PM2.5 were measured at the location, \( x = 0.3 \text{ m}, y = 1.1 \text{ m} \) and \( z = 2 \text{ m} \) inside the bus passenger compartment as shown in Fig. 9. The x-direction is a width, y-direction is a height and z-direction is a length of the bus passenger compartment. The locations were chosen at a level of breathing zone of the passengers and kept away from the door and air supply diffusers. This is to prevent the error during measurement. It can be seen that the numerical simulation results of PM2.5 shows a good agreement with field measurement. LES model combining with the Lagrangian model provides reasonable prediction of the particle concentration of PM2.5 inside the bus passenger compartment. It can be observed that at 200 sec the particle concentration was increased and decreased at 400 sec. At 600 sec to 1000 sec the particle concentrations were increased again. Then, at 1200 sec to 2000 sec the particle concentrations were decreased again inside the bus passenger compartment. As shown in Fig. 8 the trends of the particle concentration levels were decreased when measured at the long duration time (2000 sec). The concentration level of PM1 was higher at 200 sec, 600 sec, 800 sec and 1000 sec due to
lack of ventilation and during loading and unloading occupants [6]. The ventilation system of the bus could not remove the PM2.5 when the door was widely open. However, the concentration level of PM2.5 was lower at 1200 sec, 1400 sec, 1600 sec and 2000 sec. This is due to sufficient ventilation and least of unloading passengers. The highest and lowest particle concentration levels of PM2.5 were 62 μg/m³ and 8 μg/m³, respectively. The particle concentration levels of PM2.5 were exceeded the allowable limit recommended by the World Health Organization (WHO). The allowable limit of concentration level for PM1 should not exceed 25 μg/m³ [14]. The trends of the particle concentration of PM2.5 were closely same with the previous studies finding [12].

Fig. 8. Variation of PM2.5 concentration with time

![Fig. 8. Variation of PM2.5 concentration with time](image)

Fig. 9. Location measurements

![Fig. 9. Location measurements](image)

Fig. 10 shows the variation of particle concentration of PM10 with time. The particle concentrations were measured at the location, 0 ≤ x ≤ 3 m, 0 ≤ y ≤ 1.1 m and 2 m ≤ z ≤ 3.92 m inside the bus passenger compartment as shown in Fig. 11. The x-direction is a width, y-direction is a height and z-direction is a length of the bus passenger compartment. The locations were chosen at the height of the breathing zone of passengers and kept away from the bus main entrances and air supply diffusers. This is to prevent the error during measuring the particle concentration inside the passenger compartment. The simulated result of PM10 shows a good agreement with field measurement as shown in Fig. 10. LES model combining with the Lagrangian model provides reasonable prediction of the particle concentration of PM10 inside the bus passenger compartment. It can be observed that at 200 sec the particle concentration was high at 400 sec. However, at 600 sec to 1000 sec the particle concentrations were high again. Then, at 1200 sec to 2000 sec the particle concentrations were decrease again inside the bus passenger compartment. The trends of the particle concentration levels were decreased when measured in the long duration time (2000 sec) as shown in Fig. 10. The concentration level of PM10 was higher at 200 sec, 600 sec, 800 sec and 1000 sec due to insufficient ventilation of the bus, loading and unloading passengers [6]. The ventilation system of the bus could not eliminate the particles when the door was widely open. However, the concentration level of PM10 was lower at 1200 sec, 1400 sec, 1600 sec and 2000 sec. The particle concentration level of PM10 was lower at that time due to sufficient ventilation and least of unloading passengers. The highest and lowest particle concentration levels of PM10 were 60 μg/m³ and 7 μg/m³, respectively. The particle concentration levels of PM10 were exceeded the allowable limit recommended by the World Health Organization (WHO). The allowable limit of concentration level for PM10 should not exceed 50 μg/m³ [14]. The trends of the particle concentration of PM10 show similar with the previous studies findings [12]. As compared in Fig. 6, Fig. 8 and Fig. 10 the concentration levels of PM1 and PM2.5 were higher than PM10. This is due to the outside particle enters the door during boarding and unboarding passengers. Infiltration and lack of ventilation are the factor that increases the PM1 and PM2.5 inside the bus passenger compartment. PM1, PM2.5 and PM10 are known as coarse particles and produced from the vehicle emissions and dusts. PM10 is easy to remove out from the passenger compartment compared to PM1 and PM2.5.

Fig. 10. Variation of PM10 concentration with time

![Fig. 10. Variation of PM10 concentration with time](image)
3.2. Prediction of Dispersion of Concentration Level inside the Passenger Compartment

Fig. 12 shows the prediction of dispersion of concentration levels of PM1, PM2.5 and PM10 inside the bus passenger compartment. The highest dispersion of concentration level for PM1, PM2.5 and PM10 were illustrated in red colour as shown in Fig. 12(a), Fig. 12(b) and Fig. 12(c). The highest dispersions of concentration level of PM1 can be seen at the 1st and 2nd rows of the passenger seats and the door location. For PM2.5 the largest dispersion of concentration level can be seen at 1st and 3rd rows of the passenger seats. However, the highest dispersion of concentration level of PM10 can be seen at the 1st, 2nd and 3rd rows of the passenger seats. The highest and lowest of particle concentration levels of PM1, PM2.5 and PM10 were 100 μg/m$^3$ and 1 μg/m$^3$, respectively. The result shows that the passenger seat and door location were the highest dispersion of concentration level for all PMs. This is due to the effects of ventilation system and cabin geometry. However, the dispersion of PM1 was also high at the door location. This could be due to the effects of air velocity at the door location and the air supply diffuser. Lack of air velocity could increase the particle concentration level inside the bus passenger compartment.

Fig. 12. Prediction of dispersion of concentration level inside the passenger compartment (a) PM1, (b) PM2.5 and (c) PM10
3.3 Prediction of Concentration Levels of PM1, PM2.5 and PM10 as a Function Length

Fig. 13 shows the prediction of particle concentration levels of PM1, PM2.5 and PM10 with length of the passenger compartment. The prediction location were taken at x = 0.3 m, y = 1.1 m, z = 3.92 m. The x-direction is a width, y-direction is a height and z-direction is a length of the bus passenger compartment. The locations were chosen based on the height of the breathing zone of passengers and kept away from the bus main entrances and air supply diffusers. The prediction location of the particle concentration levels are illustrated in Fig. 14. The position of the passenger seat is 2 m to 3.92 m length inside the bus compartment. It can be observed that the particle concentration of PM1 was the highest compared to PM2.5 and PM10 at the 1.5 m to 3.92 m lengths. However, PM10 was slightly higher at the 3.2 m to 3.92 m length of the passenger compartment. This could be due to the effects of turbulent flow and the passenger seats and cabin geometry. All the PMs were lower at 0 m to 1.5 m length of the passenger compartment. PM1, PM2.5 and PM10 were lower at that length due to sufficient ventilation inside the passenger compartment.

Fig. 14. Location measurements

3.4 Prediction of Particle Velocity of PM1, PM2.5 and PM10 as a Function Length

Fig. 15 shows the prediction of particle velocity of PM1, PM2.5 and PM10 with length of the passenger compartment. The prediction location were taken at x = 0.3 m, y = 1.1 m, z = 3.92 m. The x-direction is a width, y-direction is a height and z-direction is a length of the bus passenger compartment. The locations were chosen based on the height of the breathing zone of passengers and kept away from the bus main entrances and air supply diffusers. The prediction locations of the particle velocity are shown in Fig. 16. It can be observed that the particle velocity of PM1 was lower compared to the PM2.5 and PM10. Particle velocity of PM1, PM2.5 and PM10 were higher at 0 m to 1.5 m length of the passenger compartment. At 0.5 m and 1 m length, the particle velocity of PM1, PM2.5 and PM10 were decreased inside the passenger compartment. However, all the particulate matters velocity was decreased again at 2 m to 3.92 m length. This could be due to the effects of air flow inside the passenger compartment. High of air velocity could reduce the particle concentration levels of PM1, PM2.5 and PM10 inside the passenger compartment [11]. Based on the previous studies the air flow pattern and particle properties were affected the particle concentration levels of PMs [11].

Fig. 15. Variation of particle velocity of PM1, PM2.5 and PM10 with length

Fig. 16. Location measurements
4. CONCLUSIONS

A field measurement was conducted to assess the levels of particle concentrations of PM1, PM2.5 and PM10 at the front section of a university’s shuttle bus. A CFD (Ansys Fluent, Version 14) software was used to develop a simplified 3D model of a quarter section of a bus passenger compartment. The CFD software was used to visualize and predict the concentration levels inside the passenger compartment. Particle concentration level and particle velocity as a function of time and length were examined in this study. The followings are major findings of this study:

a. The CFD results of particle concentrations of PM1, PM2.5 and PM10 were closely same with field measurement results.

b. Particle concentrations of PM1, PM2.5 and PM10 were found significantly higher at 200 sec, 600 sec, 800 sec and 1000 sec.

c. Particle concentrations were higher at 1.5 m to 3.92 m length of the bus passenger compartment.

d. Particle velocity of PM1, PM2.5 and PM10 were lower at 1.5 m to 3.92 m length of the bus passenger compartment.

e. The dispersion of particle concentrations of PM1, PM2.5 and PM10 were higher at the passenger seat areas.

f. The concentration levels of PM1 and PM2.5 were highest compared to PM10.

g. LES model combining with the Lagrangian model provides reasonable prediction of the particle concentration of PM1, PM2.5 and PM10 inside the bus passenger compartment.

h. Therefore, as an alternative ways, the air distribution method such as ventilation displacement may be needed inside the passenger compartment. The purpose is to increase the efficiency in removing the particle concentration levels of PM1, PM2.5 and PM10. Also, the displacement ventilation could provide a fresh air during the travelling.

The use of displacement ventilation could help reducing the level of particle concentrations inside the passenger compartment. Besides, could improve the air quality inside the passenger compartment.

ACKNOWLEDGEMENTS

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