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Development of a CFD model for simulating vehicle cabin indoor air quality

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ABSTRACT

As the level of CO_2 within the vehicle cabin increases, the risk of accidents as a result of driver drowsiness and a slowing of the reactions also increases. Accordingly, a CFD simulation model was developed in this study to explore the effects of outdoor air ventilation rate on vehicle cabin indoor air quality and the amount of outdoor air required for each person in a vehicle. The results show that using the outdoor air supply rate recommendations of ASHRAE Standard 62.1 (i.e. 2.5 l/s per person) the mean CO_2 concentrations in the cabin are around 2850 ppm. The results also show that using the outdoor air supply rate recommendations of 4.0 l/s per person for improved human wellbeing, the corresponding mean CO_2 concentrations in the cabin are around 1810 ppm. Moreover, the present study found that an outdoor fresh air flow rate of 9.2 l/s per passenger was sufficient to reduce the carbon dioxide concentration within the cabin to a safe value of 1000 ppm. Furthermore, an outdoor fresh air flow rate of 3.6 l/s per passenger resulted in a carbon dioxide concentration of around 2000 ppm.

1. Introduction

With changes in modern lifestyle, people spend an increasing amount of time in vehicles. Accordingly, various ventilation methods and devices have been developed in recent decades for providing a comfortable thermal environment for vehicle occupants while simultaneously reducing the energy demand. One of the most effective strategies for achieving both goals is to use an auto air-conditioning system (also known as an Energy Saving Airflow System), which automatically adjusts the ventilation mode and supply air speed depending on the number of occupants in the vehicle and the outdoor/indoor temperatures (Dwiggins, 2000). However, due to the high traffic load in city areas, most drivers tend to close the window completely to prevent the ingress of pollutants and then set the ventilation system to full recirculation mode. Previous studies (Zhu and Eiguren-Fernandez, 2007; Qi and Stanley, 2008) have shown that such an approach yields a substantial reduction in the concentration of particle pollutants in the cabin. However, it also results in an accumulation of carbon dioxide (CO_2), which can lead to drowsiness and a slowing of the reactions, and hence the risk of accidents increases. Consequently, maintaining a healthy IAQ (indoor air quality) is an essential issue for vehicle designers and IAQ researchers.

Most previous studies on IAQ focus on buildings. Olesen (2004) reviewed the development of international standards for the indoor thermal environment and IAQ. ASHRAE Standards 55 (ASHRAE, 2013a) and 62.1 (ASHRAE, 2013b) provide general guidelines on thermal environmental conditions for human occupancy. Ahmed (2003) found that improvements in the outdoor

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thermal environment result in an enhanced indoor thermal environment and a lower energy strain on indoor thermal control systems. Candido et al. (2010) investigated air movement acceptability limits in ventilated buildings in Brazil, and found that subjects preferred air velocities of at least 0.4 m/s for operational temperatures of 26 °C and 0.9 m/s (higher than the 0.8 m/s ASHRAE limit) for temperatures of 30 °C. Arens et al. (2009) reported that many indoor occupants prefer a greater air movement than that prescribed by existing thermal comfort standards. Noh et al. (2007) performed field measurements and numerical simulations to investigate the thermal comfort and IAQ in lecture rooms with different HVAC systems. Yau and Chew (2009) conducted a thermal comfort study of hospital workers in Malaysia, and found that a higher temperature was required for comfort than that specified in the ASHRAE standards. Wang et al. (2012) performed an extensive field evaluation of thermal comfort and IAQ for a hospital in a hot and humid climate. Wang et al. (2014) recently conducted an investigation into the retrofitting of a total heat exchanger system in an office building in a hot and humid climate. The results showed that the CO_2 concentration decreased and the thermal comfort increased after the installation of the total heat exchanger. However, the improvement in the IAQ and thermal comfort was obtained at the expense of a slightly higher power consumption.

As for buildings, the aim of HVAC vehicle systems is not only to achieve thermal comfort, but also to maintain a healthy cabin environment. Chan and Chung (2003) investigated the effects of the ventilation mode on the air quality in a vehicle cabin, and recommended the use of the full fresh air mode (i.e., 0% recirculation) when driving in countryside environments in order to exhaust the cabin indoor pollution gas. Katarzyna (2011) showed that in the cabin of a small passenger vehicle, the continuous use of the full recirculation mode can result in a CO_2 concentration of almost 4500 ppm, and may thus have significant adverse effects on driving safety. Jung (2013) developed a mathematical model for predicting the CO_2 concentration in vehicle cabins when using the air-recirculation ventilation mode. Thirumal et al. (2015) used Gray Relational Analysis (GRA) and Response Surface Methodology (RSM) techniques to optimize the IAQ characteristics (temperature, CO_2 level and relative humidity) of an air-conditioned car cabin over a specified range of input conditions. Chang et al. (2017) suggested that the total air leakage ventilation rate for a vehicle cabin comprises two components, namely (1) the car speed induced air leakage rate, and (2) the fan-supplied air speed induced air leakage rate. The authors further proposed a theoretical general equation for predicting the air leakage ventilation rate.

Each exhaled breath by an adult contains 35,000–50,000 ppm of CO_2 (ASHRAE, 2013b; Scott et al., 2009). For a vehicle, the indoor CO_2 concentration is directly related to the number of occupants in the cabin, the ventilation rate, and the CO_2 level of the outside air. As described above, an elevated CO_2 level poses a significant risk to driving safety. Consequently, evaluating the concentration and distribution of CO_2 in the vehicle cabin is an essential task for vehicle designers and IAQ researchers alike.

Vehicle road tests are expensive and time-consuming. Accordingly, the present study performs CFD simulations to evaluate the CO_2 concentration in a typical vehicle cabin given various outdoor fresh air supply rates and numbers of occupants in the cabin. The validity of the numerical model is confirmed by comparing the simulation results with the experimental data reported in the literature. The results provide a valuable insight into the minimum fresh air supply rate required to achieve the ASHRAE criterion of a CO_2 concentration of no more than 1000 ppm in the vehicle cabin.

2. Numerical model

2.1. Physical model

The present study considered a Mitsubishi Galant having a cabin with the dimensions shown in Fig. 1. The cabin is fitted with four inlets on the upper surface of the dashboard (I1-I4 in Fig. 2) and four return air outlets on the lower side of the dashboard (R1-R4 in Fig. 2). For evaluation purposes, the present study additionally designed two fresh air inlets at the front of the cabin (L1 and L2 in Fig. 2) and one direct outlet at the rear of the cabin (O1 in Fig. 2). To simplify the CAD model, rational simplifications were made to the cabin interior without affecting the simulation accuracy. For example, steering wheel was ignored in the CAD model.

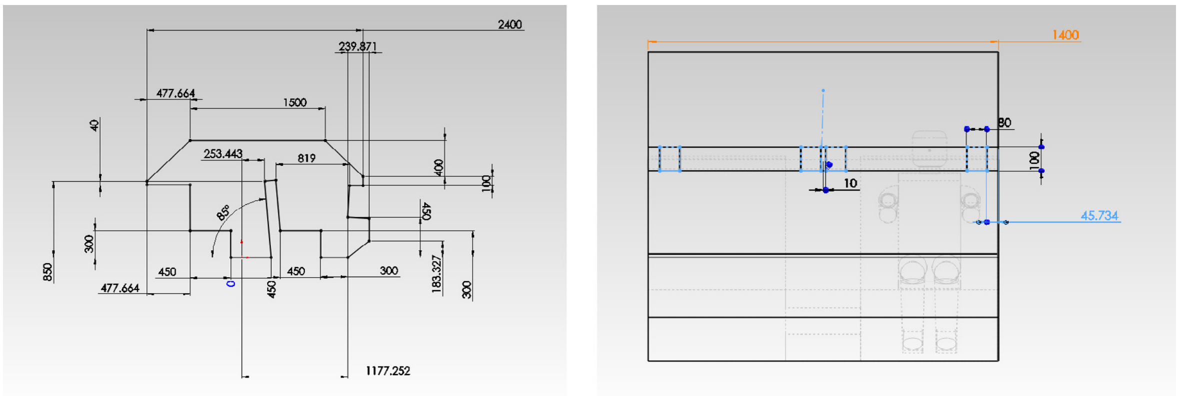

Fig. 1. Detailed dimensions of Mitsubishi Galant cabin.