Energy and Buildings 127 (2016) 252–258

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Analysis of PM2.5 distribution and transfer characteristics in a car cabin

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ARTICLE INFO

Article history:
Received 19 January 2016
Received in revised form 10 May 2016
Accepted 1 June 2016
Available online 2 June 2016

Keywords:
Car cabin environment
PM2.5
I/O ratio
Transfer characteristic

ABSTRACT

To investigate the transfer characteristics of PM2.5 in a car cabin, several experiments were performed featuring real-time online monitoring of the concentration of PM2.5 and CO_2 in the cabin under different ventilation modes (circulation with outdoor air and recirculation without outdoor air), at a minimum of mechanical ventilation and matching experimental route conditions. We analyzed the PM2.5 concentration distribution characteristics and the ratio of inside-to-outside PM2.5 concentration (I/O). The ventilation rate was determined by the CO_2 concentration change during the experiments, and it was used to analyze the transfer characteristics of PM2.5. The results showed that under the "circulation with outdoor air" condition, the average I/O was 0.6, while it was 0.25 under the "recirculation" condition. I/O value decreased with acceleration of driving speed. It could be concluded that the ventilation mode has a significant impact on the concentration of PM2.5 in the cabin, and plays a decisive role in PM2.5 levels. The quantitative evaluation of PM2.5 transfer characteristics under the "circulation with outdoor air" condition showed that the contributions of ventilation, penetration, and deposition to the cabin PM2.5 concentration accounted for 69.3%, 22.8%, and 7.9%, respectively; while under the "recirculation" condition, penetration accounted for 72.0% and deposition accounted for 28.0%.

1. Introduction

At present, China has been facing a significant air pollution problem, especially regional air pollution composed of respirable particulate matter (PM10) and fine particulate matter (PM2.5). This has become increasingly prominent [1,2], and has a severe impact on people's health. Worldwide toxicological and epidemiological studies have associated higher airborne particulate matter (PM) concentrations with increased morbidity and mortality [3–5]. Recent studies have shown that short- and long-term exposure to extremely high levels of PM may cause acute respiratory system responses such as inflammations, allergies, and asthma [6,7], as well as numerous long-term health problems including lung cancer and cardiovascular diseases [8,9]. The fact that the outdoor atmosphere cannot, in the short-term, be effectively controlled makes it highly important to maintain a healthy indoor environment in such areas as our homes and cars and in airplanes.

In 2014, the vehicle amount reached 264 million in China, among which cars accounted for 50%; and the total number of people who drove a vehicle reached 300 million, including more than 246 million people driving cars [10]. A large amount of PM is emitted by moving cars. In addition, due to the nature of the road environment, including a confined circulation space and the constant exhaust from surrounding vehicles, the resultant PM2.5 concentrations are much higher than in the ambient background [11,12]. As a result, drivers are exposed to far more PM 2.5 pollution in the road environment [13,14], which exceeds that of residential areas by 30% [15]. Karanasiou et al. also found that exposure to PM in cars is higher than in other modes of transport [16]. Experimental research into Los Angeles' roads showed that exposure to ultrafine particles from vehicles accounted for 33–45% of our total daily exposure [17]. Lee et al. also pointed out that 10–50% of the exposure to ultrafine particle in the car microenvironment occurs during commuting time of one hour a day [18]. Xu and Zhu analyzed the impact of ultrafine particles' inside-to-outside PM2.5 concentration (I/O ratio) factors using mass balance modeling [19]. Meanwhile, Hudda and Fruin established an empirical model to predict I/O ratio; the model's parameters included the vehicle's age, speed, volume, and ventilation mode setting [20]. It can be concluded that there are huge variations in exposure to PM2.5, both inside and outside cars, and in different countries and regions. Many studies have been carried out on exposure to PM from road vehicles. However,

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http://dx.doi.org/10.1016/j.enbuild.2016.06.004
0378-7788/

quantitative research on the factors influencing the concentration of PM2.5 in car cabins is very limited.

As it is impractical to measure either the pollution exposure or ventilation rate for large numbers of subjects' vehicles, as would be required in an epidemic study, we chose one car with which to perform experiments. This car is a private car. Our main objective was to highlight the importance of quantitative research into in-cabin PM2.5 dynamic processes (ventilation, penetration, deposition, and filtration) that is based on experimental data and the mass balance model. Our results were compared to related studies. Field measurements were conducted to record PM concentration; based on the experimental data, the temporal PM2.5 concentration characteristics and the I/O ratio were also studied.

2. Methods

In China, the problem of air pollution has become increasingly prominent, especially regional pollution from inhalable particulate matter (PM10) and fine particulate matter (PM2.5); this is epitomized by the north China area, including Tianjin [21]. A Chinese air quality-monitoring analysis platform indicated that particulate pollution was more serious from December to February in Tianjin. There was a 73.5% proportion of contamination status in winter 2014, with PM2.5 the primary pollutant [22].

2.1. Equipment

A VW Passat private car aged four years was chosen as the experimental subject. The interior volume was about 3 m^3; the car was equipped with an automotive filter and air conditioning system. An integrated sensor was adopted to simultaneously measure the cabin's environmental parameters and the concentration of common pollutants including temperature, illumination, humidity, noise, CO_2 concentration, PM2.5 concentration, and Formaldehyde concentration. We paid most attention to the temperature, humidity, PM2.5 concentration, and CO_2 concentration, as these continuously varied in the car cabin. The integrated sensor was calibrated according to DUSTTRAK II 8530 for its relatively high accuracy and stability, and portability, with the sampling frequency set to 1/60 Hz. The measuring range of the PM2.5 sensor, which was installed in the sensor, was 10–900 $\mu g/m^3$. The accuracy of this sensor was $\pm 10\ \mu g/m^3 \pm 5\%$ of readings, and the measuring size was 1.0–2.5um. The measuring range of the device's CO_2 sensor was 0–5000 ppm; the measurement accuracy was ± 75 ppm $\pm 3\%$ of readings. The generated data could be accessed through Web in a mobile phone APP dynamically and in real time; the data packet was downloaded from the server of the sensor manufacture.

In addition, the car's filter was taken out to measure the efficiency of PM2.5 in the laboratory testing platform of the air filter. In this platform, the US Metone 2400 laser particle counter was applied. The sampling flow was 28.3 L/min. Six kinds of particle size channels, including <0.3 um, 0.3–0.5um, 0.5–1.0um, 1.0–3.0um, 3.0–5.0 um, and 50–10.0 um, were utilized simultaneously. The overlapping loss of the Metone 2400 was less than 5% per 400,000 particles/Ft^3.

2.2. Procedure

Our study investigated pollution exposure for commuters in Tianjin, a city in northern China with serious air contamination. The roads to be studied, which are located in the center of the city, were selected. Experiments were conducted from December 2014 to February 2015, and each experiment was performed almost simultaneously (from 17:00–19:00).

Fig. 1. Measuring platform and position.

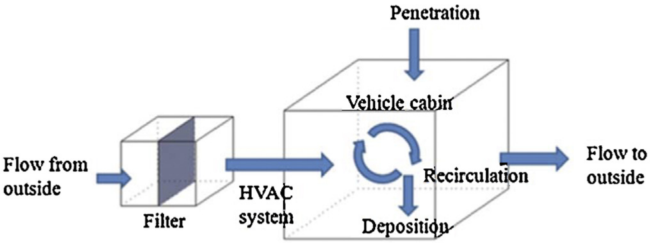

Fig. 2. Schematic of important processes: air flow through the vehicle cabin, ventilation, and air conditioning (HVAC) system.

The meteorological conditions of the indoor and outdoor environments and the various cases tested are summarized in Table 1; these include traffic conditions (vehicle speed), pollution degree, driver and passenger activities, and ventilation settings. The pollution degree is defined according to the range of PM2.5 concentration, good means below 35 $\mu g\, m^{-3}$, moderate means 36–75 $\mu g\, m^{-3}$, unhealthy for sensitive groups means 76–115 $\mu g\, m^{-3}$, unhealthy means 116–150 $\mu g\, m^{-3}$, very unhealthy means 151–250 $\mu g\, m^{-3}$, and hazardous means beyond 250 $\mu g\, m^{-3}$. A field measurement was conducted to assess particulate matter and carbon dioxide (CO2) concentration; from this, we could determine the quantitative evaluation. During the sampling period, the sampler was installed in the co-driver position of a bus that was nearly 1.2 m height, as shown in Fig. 1; this was because Joodatnia et al. had found that the distribution of the PM concentration is almost uniform in car cabins [23]. Two ventilation modes were adopted to conduct this experiment. Case 1 involved circulation with outdoor air (OA) and case 2 related to recirculation without outdoor air (RC). In order to ensure accuracy of the measurement, it only started when the ventilation in the car was steady, different routes were taken, and windows were closed for all runs. The measured mean values showed great variations in in-cabin PM2.5. The actual time spent on one-way journey depended on many factors including starting time, stop frequency, traffic density, and weather conditions. Due to the fact that vehicle was in a dynamic state, the outdoor concentration of PM2.5 was monitored before and after the in-cabin PM2.5 monitoring, and the concentration was determined as the average of the values of two phases.

2.3. Model application

2.3.1. Basic model postulate

Switzer and Ott [24] developed a mass balance model to simulate indoor and in-vehicle microenvironments. For our purposes, combined with the above research, a reformed model was derived, based on the schematic of the vehicle cabin and heating, ventilation, and air conditioning (HVAC) system [25], as shown in Fig. 2, to analyze the temporal PM2.5 concentration characteristics. The model was based on the following postulates: (a) the vehicle cabin is a well-mixed zone with a uniform PM2.5 concentration [23], (b) the negligible effect of temperature on in-cabin particle concentration was previously confirmed [26], (c) the filter removal efficiency of the HVAC system was constant, irrespective of time or parti-