Journal of Aerosol Science 41 (2010) 859–868

Contents lists available at ScienceDirect

Journal of Aerosol Science

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

Ultrafine particle penetration through idealized vehicle cracks

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ARTICLE INFO

Article history:
Received 2 September 2009
Received in revised form
13 May 2010
Accepted 13 May 2010

Keywords:
Ultrafine particle
Penetration factor
In-cabin environment
Diesel exhaust particle
Electric charge

ABSTRACT

Understanding the in-cabin microenvironment of vehicles is important for assessing human exposure to ultrafine particles (UFPs, diameter <100 nm) of vehicular origin. UFP penetration through cracks on the vehicle envelope is one of the influencing processes that determine the in-cabin UFP concentrations. In this study, penetration factors, calculated as the ratio of the downstream to upstream UFP concentrations across seven idealized cracks, were characterized for different crack sizes under a range of different pressure drops across the cracks. Three types of UFPs (neutralized diesel exhaust particles, unneutralized diesel exhaust particles, and vehicle exhaust particles) were used to investigate the effects of electric charge on penetration factors. Crack length, crack height, and pressure drop across the cracks account for approximately 10%, 5% and 12% of the penetration factor change, respectively. A coefficient "*B*", which presents the ratio of the penetration factor for unneutralized to neutralized diesel particles, was introduced and successfully accounted for the electric charge effect on penetration factors.

1. Introduction

Epidemiological studies have associated the atmospheric particulate matter (PM) with adverse health effects (Pope, 2000; Pope et al., 2002; Pope & Dockery, 2006). Strong correlations between elevated PM levels and cardiovascular diseases (Delfino, Sioutas, & Malik, 2005; Kunzli & Tager, 2005) and respiratory tract disease (Li, Hao, Phalen, Hinds, & Nel 2003) were reported. Recent animal toxicology studies have shown that ultrafine particles (UFPs, diameter $<$ 100 nm) are more toxic than larger particles under the same mass concentration due to their distinctive composition and size (Kleinman, Araujo, Nel, Sioutas, & Campbell, 2008; Nemmar & Inuwa, 2008). High UFP concentrations were observed on and near interstate freeways (Westerdahl, Fruin, Sax, Fine, & Sioutas 2005; Zhu, Hinds, Kim, Shen, & Sioutas, 2002a; Zhu, Hinds, Kim, & Sioutas, 2002b; Zhu, Eiguren-Fernandez, Hinds, & Miguel, 2007) and urban roadways (Wang, Zhu, Salinas, Ramirez, & Karnae, 2008). Commuters and drivers are likely to be exposed to high levels of vehicle exhaust UFPs driving inside their vehicles.

Human exposure to vehicular UFPs depends substantially on how UFPs penetrate through the cracks on the vehicle envelope into the in-cabin environment. Recently, a theoretical model that calculates the in-cabin to on-roadway (I/O) UFP concentration ratios has been developed and key parameters that affect the I/O ratio have been analyzed (Xu & Zhu, 2009). Based on this modeling work, filtration efficiency of in-cabin filters, penetration factor across vehicle cracks, and particle deposition inside the vehicles were found to be important. While UFP deposition inside vehicles has been studied recently (Gong, Xu, & Zhu, 2009), there is no comparable study on UFP penetration through vehicle cracks. UFP penetration through

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doi:10.1016/j.jaerosci.2010.05.005

vehicle cracks refers to the uncontrolled flow of air through cracks and leaks on the vehicle envelope. Previous laboratory particle penetration studies employing idealized smooth and rough building cracks have found a substantial proportion of particles passing through the cracks (Liu & Nazaroff, 2003). Similarly, studies conducted in actual buildings reported a substantial proportion of particles passing through the building envelopes (Thatcher & Layton, 1995; Long, Suh, Catalano, & Koutrakis 2001). Theoretical studies have been carried out to calculate penetration factors for various crack sizes (DeMarcus & Thomas, 1952). However, there are no accurate experimental data that quantify UFP penetration factors across vehicle cracks. Although indoor particle penetration has been studied to some extent (Liu & Nazaroff, 2001, 2003), the conclusions may not be directly applied to the in-cabin microenvironments where the crack size and particle type are different. In addition, existing theoretical studies do not account for the electrophoretic effect on particle penetration. Since particles emitted from engines usually carry electric charges (Maricq, 2006; Cruz et al., 2009), the theory developed based on neutralized particles (Eq. (1) in Section 2.3, DeMarcus & Thomas, 1952) may not apply to vehicular emitted UFPs.

In this study, seven idealized cracks were designed to simulate the actual cracks and leaks (e.g. cracks between frame and doors, cracks between doors and windows) through the vehicle envelope. The objective of this study is to investigate what parameters affect the penetration behavior of engine emitted UFPs. Penetration factors were measured using four crack sizes and under a range of differential pressures. Different types of UFPs (e.g. vehicle exhaust particles, diesel generator exhaust particles, neutralized diesel generator exhaust particles) were used to investigate the effect of electric charge on penetration factors. The theoretical equation reported by DeMarcus and Thomas (1952) was revised to extend its application to calculate the penetration factor for charged particles.

2. Methods

2.1. Crack apparatus

Seven cracks were designed with different materials (rubber, steel, and glass) and size dimensions (0.8 mm – height and 9.5 mm – length; 0.8 mm – height and 28.5 mm – length; 1.6 mm – height and 9.5 mm – length; and 1.6 mm – height and 28.5 mm – length) to simulate the textures and sizes of vehicle cracks. The crack dimensions were selected based on measurements conducted on real vehicle leakage paths. The length was measured as the thickness of the vehicle frame and doors. The height was measured by inserting a piece of silicone between doors and vehicle frame. The thickness of the silicone was then measured with a feeler gauge. The crack apparatus were designed to simulate the cracks through the vehicle envelope. Since there was no external charge field, the state of the substrate was assumed to be neutral. Table 1 summarizes the materials, sizes, and configurations of each test crack.

As shown in Fig. 1, two configurations of cracks (straight-through and double-bend) were designed to represent cracks commonly found on the vehicle envelope. A straight-through crack was used to represent the cracks between the door and the frame, and a double-bend crack was used to represent the cracks between the window and the door. The crack dimension parallel to the airflow is defined as crack length "z". The smallest dimension perpendicular to the airflow is defined as crack height "d". The third dimension of the crack is defined as crack width "w". Straight-through cracks were made using rubber–steel and rubber–rubber pairs. Cracks between the door and the frame were made using rubber–steel and rubber–rubber pairs. The double-bend crack was made using a glass–rubber pair to simulate the cracks between the window and the door.

2.2. Penetration measurements

The schematic experimental setup is illustrated in Fig. 2. A diesel generator (Red Hawk Diesel Generator DG4LE) was used as an UFP source. A Kr-85 neutralizer (TSI Model 3077) was used to neutralize the UFPs to a well characterized Boltzmann equilibrium charge distribution (Hummes et al., 1996). In order to investigate the effects of electric charge on the penetration factor, penetration factors were measured with and without diesel UFPs passing through the neutralizer. In addition, particles emitted from the tailpipe of an idling vehicle with gasoline direct injection engine (2005 Ford F-250) were also used in the study. For all three types of test aerosols, data collection started only after particle concentrations

Table 1
Materials, sizes, and configurations of idealized cracks.

Material	Size Height (mm); length (mm)	Configuration
Rubber–steel	0.8, 9.5	straight-through
	0.8, 28.5	straight-through
	1.6, 9.5	straight-through
	1.6, 28.5	straight-through
Rubber–rubber	0.8, 9.5	straight–through
	0.8, 28.5	straight-through
Rubber–glass	0.8, 28.5	double-bend