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Experimental study of the effect of shoes on particle resuspension from indoor flooring materials

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ABSTRACT

Walking-induced resuspension is known to be a source of indoor particulate matter. The goal of this study is to investigate the effects of shoe type and shoe groove pattern on particle resuspension. This study is the first to investigate the shoe effect experimentally. The experiments were conducted in a controlled environmental chamber and a human participant performed prescribed stomping activity. Flooring samples were seeded with Ultrafine Arizona Test Dust prior to each experiment. Two shoe types, three groove patterns for the same shoe type, and two flooring types were tested. Resuspension fractions were estimated using a two-compartment mass balance model and normalized by contact area of the shoe with the flooring. Stomping-induced air velocity was measured at 6 locations along the edge of the shoe. Flat shoes enhanced particle resuspension fractions per contact area compared with high heels on tile, while no difference between the shoe types was observed on carpet. The no groove shoe was associated with higher resuspension fractions than grooved shoes for both flooring materials tested. Resuspension fractions, which increased with particle size, were found to be within the range of previous studies.

1. Introduction

Walking-induced resuspension of settled dust is known as a source of indoor particulate matter [7,20,23,25]. Shoe-to-floor contact in combination with the turbulent wake generated from a moving human body can detach and re-entrain micron-size dust particles into the air [7,23]. Depending on the composition of the dust, inhalation of resuspended dust particles can lead to adverse health outcomes, such as asthma. In addition, walking-induced resuspension can be an important pathway for disease transmission [16].

Resuspension caused by the shoe-floor contact is influenced by particle properties, flooring properties, environmental factors and human-related factors, including shoe type and walking style [20]. Previous research efforts have predominantly focused on the effects of the first three factors [2,7,19,21,24], while human related factors have received little attention. Only a few studies have discussed the role that human factors play in walking-induced resuspension [14,19,26]. Ref. [19] observed high variability in their chamber study of walking-induced resuspension with human participants, which was attributed to differences in walking styles, foot size and shoe type.

Regarding walking-induced resuspension, the removal forces include aerodynamic forces, vibration forces, and electrostatic forces. Although the role of electrostatic forces remains unclear [11], reported that aerodynamic forces dominate particle resuspension compared to vibration forces. A number of experimental and numerical studies have examined particle detachment under the effects of external forces from high speed airflow, although fluid flow studies specific to human-induced resuspension are limited. Previous experimental studies have shown that for micron-size particles, higher shear velocity is required to overcome adhesion forces and detach smaller particles from surfaces, consistent with the theoretical studies [1,8].

Ref. [14] simulated downward disk motion of a seeded substrate for the wall jet spreading radially outward of the disk perimeter [26]. mimicked the toe and heel parts by two circular disks. They also modeled the airflow outside the foot perimeter as wall jet. Other full size human CFD studies have ignored the effect of shoes [4,18]. The issue is further complicated by some features of real

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shoes, which are non-circular and often have grooves. Ref. [26] proposed a simplified model for grooves on the bottom of the shoe by modeling the integrated effect of the grooves as a gap size between the shoe and the floor. Ref. [26] modeled the heel-to-toe rotational motion of the foot on flat surface and stepping-induced airflow velocity at the shoe-floor interface. Their numerical simulation indicates that the estimated air velocity close to the flooring surface is very sensitive to the gap between the shoe and the flooring. Thus, the shoe groove depth is expected to have a substantial impact on particle resuspension.

Ref. [11] investigated particle resuspension inside experimental chamber with computer controlled air swirls and actuator-inducted mechanical vibration simulating airflow disturbances associated with walking. While the type of shoe affects airflow velocity at the vicinity of the floor, detailed description of shoe or shoe soles has seldom been reported in the resuspension literature [19,24].

While modeling and wind tunnel studies have investigated the effect of turbulent air on particle resuspension [3,5,10,12,13,22], validation of how observed vortices affect resuspension rate has still not been adequately addressed. A non-intrusive method, such as particle image velocimetry (PIV), can be used to characterize the velocity field induced by human walking. Ref. [15] employed a PIV system and visualization by an Argon laser sheet to study particle resuspension from a foot stepping down and up. They used an elongated plate and an indoor slipper, both with smooth bottom surfaces, in contact with the flooring. The wall jet and vortices were found to affect resuspension and re-entrainment of the particles. Ref. [6] covered the rubber-soled shoe with a sock as well as a Tyvek bootie to conduct their experiments. They also used a PIV system to measure airflow for a mechanical foot. They found that rotational foot motion contributes to particle re-entrainment and dispersion. While both studies using PIV had a clear objective to measure three-dimensional airflow effects from human walking, particle resuspension was not quantified.

The goal of this study is to investigate the effect of shoe type (high heel and leather shoe) and shoe groove pattern (transverse grooves, longitudinal grooves and no groove) on different flooring types (tile and carpet). The outcome of this study will lead to a better understanding of human-related factors in particle resuspension.

2. Experimental setup and materials

This study is primarily intended to investigate walking-induced resuspension as a function of particle size for different shoes and shoe groove patterns. The resuspension experiments consisted of two stages: (1) seeding and (2) stepping. The flooring materials were seeded with a known mass of test dust in the seeding chamber, following by stepping experiments in the resuspension chamber. Two flooring materials were chosen:tile and carpet.

2.1. Seeding

A seeding chamber with dimensions of 0.5 m (W) × 0.5 m (H) × 0.5 m (L) was built to reproducibly seed particles on the flooring samples based on the chamber described in Ref. [24]. Inside the chamber, four mixing fans, each pointed towards the chamber center, were mounted on the ceiling corners to achieve a well-mixed condition by creating turbulent flow. Compressed air at 276 kPa was supplied to a venturi mini-vacuum valve to break up aggregates and disperse the particles inside the chamber. The front side of the chamber could be opened for the placement and removal of the flooring samples. Ultrafine test dust (ISO 12103-1, Powder Technology Inc., Arden Hills, MN), with particles ranging from 1 to 10 μm in diameter, was selected to seed the flooring to represent the range of resuspended particles relevant to human health.

The target particle loading was 6 g m^{-2}, within the range of the 2–8 g m^{-2} loading levels used by Ref. [24]. Flooring samples were vacuumed before seeding. After cleaning, each sample was weighed using a high accuracy electronic balance (Series GS, Shinko, Japan) and recorded as M_1. Immediately after weighing, the samples were placed into the seeding chamber and the chamber door was sealed with duct tape. Mixing fans were turned on. After 5 min, test dust was fed to the venturi seeding system. The dust was then dispersed through a nozzle mounted at the top of the chamber. Following the dust injection, mixing fans continued to run for 5 min to maintain a well-mixed condition inside the chamber. Then, the fans were turned off and the chamber was left untouched for 4 h before the samples could be withdrawn, reweighed and recorded as M_2. M_2 - M_1 indicates how much test dust was deposited on the flooring sample. This weight difference divided by the area of flooring sample ($0.15 \times 0.30 = 0.045$ m^2) represents the surface dust loading, L in the unit of g m^{-2}.

The seeding method was validated by Ref. [24]; who reported the measured spatial variation of the dust on the bottom surface of the deposition chamber to be approximately 10%. The uniformity of the particle deposition was validated for the present study using nine tared coupons with dimension of 9 cm × 9 cm placed across the bottom of the deposition chamber. Three replicate seeding experiments were conducted, and the coefficient of variation (CV), the uniformity (U) and their standard errors, SE (CV) and SE (U), were estimated to be 0.24, 0.78, 0.023 and 0.018, respectively.

For carpet samples, a 6 kg steel roller was employed to roll forth and back over the carpet sample at a slow rate of 5 cm/s for about 30 strokes to embed the particles along the carpet fibers. This method is similar to that developed by Ref. [17] and adapted by Refs. [19] and [24]. According to [24]; dust lost on the roller during the embedding process was negligible (<1% error) for cut-pile carpet.

2.2. Stepping

All resuspension experiments were conducted in a full size, stainless steel chamber with dimensions of 2.25 m (W) × 2.25 m (H) × 2.2 m (L). The chamber is air conditioned with one supply and one return grill on the ceiling. When the air conditioning unit (A/C) was turned on, the air change rate was determined to be 6.0 h^{-1} by decay of carbon dioxide in the chamber following removal of the CO_2 source. The temperature and RH inside the chamber were observed to be fairly stable at 22 °C and 50–60% RH.

The resuspension chamber and tested shoe sole were vacuum cleaned before each experiment. A seeded flooring sample and an optical particle spectrometer (OPS, Model 3330, TSI, Shoreline, MN, USA) were placed as shown in Fig. 1. For the resuspension experiments, seven particle size ranges were analyzed, including 0.8–1.0 μm, 1.0–2.5 μm, 2.5–3.5 μm, 3.5–4.5 μm, 4.5–5.5 μm, 5.5–8.0 μm and 8.0–10 μm. The refractive index of the OPS was set to be 1.5 with particle density of 2.65, as reported by the test dust manufacturer. The interval of measurement was set to at 1 s and total measurement time at 720 s.

The experiment was divided into 3 stages and lasted 12 min in total. In the first stage, the participant stayed motionless in the chamber for 2 min and the OPS spectrometer recorded the background concentrations. In the second stage, the participant performed stomping by raising his right leg 20 cm above the flooring sample and lowering it on the floor sample at a frequency of 40 steps/minute for 1.5 min. In the final stage, the participant