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Human induced flow field and resultant particle resuspension and transport during gait cycle

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ABSTRACT

Particle resuspension from flooring is believed to be an important source of particulate matter (PM) in the indoor environment. It is hypothesized that the high speed airflow generated between the flooring and the foot during the gait cycle is the main cause of particle resuspension. The simulation results show that particles are detached from the substrate during the downward motion of the foot. Furthermore, during the upward motion of the foot, additional particles may also be resuspended because of the suction flow generated by lifting the foot. These resuspended particles are then dispersed in the room by the airflow turbulence.

In this study a combined experimental and computational studies were performed to shed light on the mechanisms of particle resuspension from flooring during the gait cycle. A mechanical foot experimental setup which mimics the human walking was developed and used to measure the rate of resuspension. In addition, to investigate the airflow field during walking, a three dimensional numerical model of a moving shoe during the gait cycle was generated using the ANSYS-FLUENT™ CFD package. A RANS approach with the RNG k-epsilon turbulence model was used for simulating the unsteady airflow field around and under the shoe. To include the shoe motion in the analysis, a user defined function (UDF) was developed and the dynamic mesh technique was used. A resuspension model was applied for the resuspension of pre-deposited particles from the flooring. The predicted particle resuspension were compared with the corresponding experimental results and good agreement was found.

1. Introduction

Particle resuspension is known to be an important source of particulate matter in the indoor environments [1]. Resuspension is defined as a process in which the pre-deposited particles on the floor are detached under the effects of fluid flow, surface acceleration, and/or electrostatic force and the particles enter the flow stream over the surface.

People spend approximately 90% of their time indoors [2]. The rise in occurrence of allergic diseases has been associated with the increased exposure to the indoor allergens including dust, pollen, viruses, bacteria, fungi and various chemical agents [3]. Several studied showed that indoor activities like vacuuming, walking, and using upholstered furniture can increase the PM concentration to orders of magnitude higher than the background level [4]. Among indoor activities, walking is recognized as a major contributor to the high PM concentration in indoor environments. Studies have shown that walking in a room can increase the concentration of particulate matter as much as 100% for submicron particles [1,5]. Walking also leads to even larger increase in indoor PM concentration for micron range particles, especially 5–10 μm particles [6,7].

Particle resuspension can be studied through both large-scale bulk resuspension and small-scale detailed mechanism [8]. Large-scale, or bulk, resuspension studies have expressed resuspension in terms of the resuspension factor (particle concentration in air divided by particle concentration on the surface), resuspension rate coefficient (flux of particles joining the flow field over the surface divided by particle concentration on the surface), or resuspension fraction (fraction of particles on the surface resuspended into the air per foot step). Large-scale resuspension studies are usually motivated for predicting the resulting bulk airborne PM concentrations and related human exposures [9]. On the other hand, small-scale resuspension studies include theoretical and experimental studies on the details of resuspension process and

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determining the removal mechanisms of particles under the effects of removal forces overcoming the adhesion forces. As discussed above, a number of numerical and experimental works were conducted during recent years to study the small-scale resuspension phenomenon [10–19]. Generally, micron and submicron sized particles in contact with a surface experience a strong van der Waals adhesion force. Several experimental studies [12,13,20–22] on removal and resuspension of particles from substrates showed that a shear velocity, on the order of 1 m/s or larger, is required to detach and resuspend the particles into the airflow field. This range of shear velocity is larger than that associated with the movement of the human body and shoe motion during the gait cycle far from the flooring. However, experimental studies [1,5,23] showed that human walking results in dust resuspension and a large increase in the indoor PM concentrations. Earlier efforts hypothesized that the high velocity jet ejected from the perimeter of an impacting object during descending movement causes the particle detachment and resuspension [24,25]. Madler and Koch [24,25] used a simplified model to describe the particle resuspension caused by the radial wall jet generated from an impacting disk to a dusty surface. Based on their work, several authors developed models for estimating the particle resuspension during gait cycle. Khalifa and Elhadidi [26] used an analytical solution for modeling unsteady flow resulting from the downward motion of a circular disk toward a seeded substrate. They also performed a computational fluid dynamics (CFD) analysis for the wall jet spreading radially outward of the disk perimeter and investigated the effects of airflow on detachment of spherical micron-sized particles.

Zhang et al. [27] studied the particle detachment, resuspension and transport due to human walking using analytical and computer simulation approaches. They modeled the stepping motion of the foot as a downward and upward motion. They simplified the shoe geometry with two circular disks for the toe and heel parts. They modeled the squeeze film flow between circular disks and the floor and evaluated the corresponding velocity field. They modeled the airflow outside the foot perimeter as a wall jet. For simulating the resuspended particle trajectories they used the Lagrangian approach. The dispersion of resuspended particle clouds were also included in their model. Kubota et al. [28] studied the human foot movement visually and through particle image velocimetry (PIV) measurements. Following Khalifa and Elhadidi [26] and Zhang et al. [27], they simplified the human walking motion with a disk moving normal to the floor downward and upward. Flow visualization of the resuspension of pre-deposited particles on the flooring showed particles are resuspended by both downward and upward motion of the disk. For both the downward and upward motions, the high speed wall jet emanating from the perimeter of the disk and flooring was determined as the cause for resuspension. They also determined that large scale ring vortex structures formed during both downward and upward motions. While these vortices may not contribute substantially to particle detachment process, they are certainly highly effective at dispersing and the resuspended particles away from the floor.

Using particle image velocimetry (PIV), Eisner et al. [29] studied the transport and dispersion of dust resuspended by a mechanical foot apparatus. They showed that during the motion of the shoe when the heel detaches and shoe rotates around a point in the ball of the foot, a draft corner flow develops, which carries the particles from the region heel to toe area. Oberoi et al. [30] modeled particle resuspension from the up and down motion of the foot using an Eulerian approach. Choi and Edwards [31,32] and Choi et al. [31,32] used the same procedure and modeled the removal of particles during gait cycle. Recently Kubota and Higuchi [33] experimentally investigated particle resuspension due to human foot motion focusing on aerodynamic effects using PIV.

Previous studies have reported important findings on resuspension during the walking process. Although a number of large-scale and small-scale studies have been reported, there is a gap between these two fields where current theoretical resuspension models do not directly predict the particle number concentration for an indoor activity, such as walking considering detail interaction of particle in contact with the substrate. In this study, a reliable model of particle resuspension during walking activity which is not available with details as yet was introduced. In this work, a combined experimental and computational study was performed to shed light on the mechanisms of particle detachment from flooring during the gait cycle and the corresponding resuspension and dispersion in indoor environment. A mechanical foot experimental setup was developed and used to measure the rate of resuspension for a range of conditions. The mechanical foot device mimics human walking and may be used to generate reproducible data for particle resuspension. In addition, a three dimensional numerical model of a shoe during heel-to-toe walking activity was generated using the ANSYS-Fluent computational fluid dynamic (CFD) package. The motion of the shoe was modeled using UDFs in the CFD software. The particle trajectories were analyzed using the Lagrangian approach including drag, lift and gravity forces. The Monte Carlo simulation model developed by Goldasteh et al. [10] was used for analyzing the detachment of particles from the floor. This new model takes into account the effects of dust particle irregularity, dust particle surface roughness, size distribution of particles and the spatial orientation of each dust particle on the flooring. With these modifications, the general model predicted the resuspension process during gait cycle more realistic than previous models which agreed well in compare to the experiments.

2. Experimental study

Experimental study of particle resuspension due to the gait cycle was conducted using a mechanical shoe resuspension apparatus, as shown in Fig. 1. This setup was designed to mimic the human foot step during walking. The resuspension apparatus consists of toe and heel plates controlled by two electric actuators. A men U.S. size ten tennis shoe was mounted on the resuspension apparatus and used in these experiments. Tian et al. [34] have reported that the resuspension apparatus provided consistent rotation motion, stepping frequency and pressure loading, which are comparable to human foot step. The mechanical show apparatus was housed in a

Fig. 1. Mechanical foot setup in the resuspension chamber.