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Review

Walking-induced particle resuspension in indoor environments

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HIGHLIGHTS

- Studies on the resuspension of particles via human activities indoors are reviewed.
- Resuspension is compared with other indoor sources in terms of source strength.
- Resuspension estimates increase with particle size in the range of 0.7–10 μm.
- Fundamental mechanisms and factors of resuspension are reviewed.
- Future research directions are suggested under the framework of open questions.

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ABSTRACT

Resuspension of particles indoors increases the risk of consequent exposure through inhalation and non-dietary ingestion. Studies have been conducted to characterize indoor particle resuspension but results do not always agree, and there are still many open questions in this field. This paper reviews the recent research of indoor resuspension and summarizes findings to answer six critical questions: 1) *How does the resuspension sources compared to other indoor sources*; 2) How is resuspension determined and how does the resuspension measure change as a function of particle size; 3) *What are the primary resuspension mechanisms*; 4) *What are the factors affecting resuspension*; 5) *What are the knowledge gaps and future research directions in this area*; and 6) *How can what we know about resuspension guide better exposure mitigation strategies?* From synthesized results, we conclude that resuspension is an important source for indoor particulate matter, compared with other indoor sources. Among all existing quantification terms of resuspension, resuspension fraction has the least variation in its estimates by explicitly defining surface loading and walking frequency, and thus is recommended to be adopted in future research over other terms. Resuspension increases with particle size in the range of 0.7–10 μm, although differences exist in resuspension estimates by orders of magnitude. The primary mechanism of particle resuspension involves rolling detachment, and the adhesive forces can be greatly reduced by microscopic surface roughness. Particle resuspension is by nature complicated, affected by various factors and their interactions. There are still many open questions to be answered to achieve an understanding of resuspension fundamentals. Given the complex and multidisciplinary nature of resuspension, understanding indoor particle resuspension behavior requires cross-disciplinary participation from experts in aerosol science, textile science, surface chemistry, electrostatics, and fluid mechanics.

1. Introduction

Occupancy-associated particulate matter (PM) in indoor environments has drawn increased attention due to its significant contribution to human inhalation exposure (Yakovleva et al., 1999; Kopperud et al., 2004; Qian et al., 2012). Occupant activities in indoor environments are associated with elevated concentrations of inhalable particles, usually orders of magnitude higher than background concentrations (Thatcher and Layton, 1995; Ferro et al., 2004; Qian et al., 2008). The occupancy-associated particles can come from the human body itself (e.g., through skin shedding, breathing, coughing, sneezing) and from human activities (e.g., walking, sitting on upholstery) which aerosolize particles previously bound to indoor surfaces (e.g., flooring and furnishing). Resuspension refers to the detachment from surfaces and re-entrainment into the air of previously deposited particles.

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Disturbance of the air-surface boundary layer due to indoor activities can result in the bulk elevation of inhalable particles in the indoor environment.

The bulk elevation effect of resuspension has been ubiquitously observed in indoor environments. Personnel changing shifts and dry-mopping of the floor were found to increase the total particle count by up to 5 fold in a room (Lum and Graedel, 1973). Classroom activities also led to resuspension of mainly coarse particles, which greatly contribute to the mass of PM_{10} (particles with aerodynamic diameters less than 10 μm) (Branis et al., 2005). In small room settings, walking was found to be associated with higher personal inhalation exposure to PM than being sedentary (Brauer et al., 1999; Qian and Ferro, 2008). In a nonsmoking office, walking induced resuspension was estimated to explain 24–55% of the variation of 1–25 μm particle number concentrations (Luoma and Batterman, 2001).

The resuspension of particles from flooring alone is difficult to control, and can be a significant source (Yakovleva et al., 1999). The resuspended particle mass and number have been found to vary with particle size and many other factors such as surface concentration of particles, flooring type, activity type and intensity, walking style, ventilation configuration, and relative humidity (RH) (Thatcher and Layton, 1995; Ferro et al., 2004; Qian and Ferro, 2008; Rosati et al., 2008). Thus, mitigation of particle resuspension in indoor environments can be achieved through the change and control of certain factors, e.g., the selection of interior materials, ventilation configuration, and cleaning strategies. To determine the most effective control strategies, we need to achieve a better understanding of the mechanisms that affect particle resuspension as well as the knowledge gaps that connect fundamental understanding to the observed bulk concentration elevation effect.

To serve this purpose, we evaluated literature on particle resuspension via human walking. Generally, resuspension research focuses on either (1) bulk elevation of particle concentration due to resuspension, or (2) the physical processes that govern the particle resuspension. Literature in both areas is still relatively thin at this stage, and very few studies have endeavored to link the particle-substrate physical processes to the bulk elevation effect of resuspension. This study focuses on the identification of current knowledge gaps based on synthesized findings from the most current research, and discusses research directions that would improve our understanding of indoor resuspension.

2. Methods

This review study focuses on particle resuspension from flooring by human walking indoors. However, most experimental results of walking induced resuspension also include direct skin shedding and resuspension from clothes other than floorings. Resuspension from contaminated clothing can play an important role in elevations of particle concentrations in the breathing zone, especially for particles of occupational origin (Bloor and Dinsdale, 1962; Bohne and Cohen, 1985; McDonagh and Byrne, 2014). We assume that, in non-occupational environments, skin shedding and resuspension from daily clothing are small compared to the resuspension from flooring, as observed in a study which compared monitored particle indoor/outdoor ratios for uncovered flooring vs. flooring covered with a clean sheet in a classroom (Hospodsky et al., 2012). Many other movements besides walking have also been observed to resuspend particles. Such activities include moving papers (Karlsson et al., 1999), dusting, vacuum cleaning and general cleaning (Thatcher and Layton, 1995; Long et al., 2000; Corsi et al., 2008), pushing a vacuum cleaner with it on or off (Ferro et al., 1999; Corsi et al., 2008), and even sitting on upholstered furniture (Ferro et al., 2004). Such activities can largely increase PM concentration especially in poor-ventilated occupational spaces, but are not the review focus of this study. For the fundamental surface–particle interactions for a variety of applications, readers should refer to review articles such as Ziskind et al. (1995), Reeks and Hall (2001), and Gradon (2009).

This paper reviews previous studies on indoor particle resuspension from flooring by walking, framed with the following questions: 1) *How does the resuspension sources compared to other indoor sources in terms of source strength*; 2) How is resuspension determined and how does the resuspension measure change as a function of particle size; 3) *What are the primary resuspension mechanisms*; 4) *What are the factors affecting resuspension*; 5) *What are the knowledge gaps and future research directions in this area*; *and* 6) *How can what we know about resuspension guide better mitigation strategies*?

A literature search was conducted using several online databases including ISI Web of Knowledge, ScienceDirect, and PubMed. The searched disciplinary fields include environmental science, engineering, physics, allergy, and public environmental occupational health. For the initial keywords searching, we used "indoor " AND "particle" AND "human activities" AND "resuspension" (or its equivalent "re-suspension", "re-entrainment", and "re-aerosolization"). The search result was refined to studies relevant to answer the framed questions directly or indirectly. Backward and forward searches were also used to identify key scholars in this field and the relevance of their other publications were evaluated. The process results in 13 key studies of resuspension which meet the following criteria: experiments are clearly described; resuspension is quantitatively estimated either as a source term or a rate, or a quantitative estimation of resuspension can be derived from the reported experimental data, to answer question 2. An additional 96 studies were also reviewed to answer the remaining framed questions.

3. Results and discussion

Table 1 lists the 13 key studies of resuspension quantification, their experimental methods and major findings. The first eight studies listed used dust particles and the remaining five studies used specific biological particles to investigate resuspension.

3.1. Resuspension as an indoor source

Indoor resuspension results in increased inhalation exposure to a wide range of contaminants. The resuspended particles may contain polycyclic aromatic hydrocarbons (PAHs), pesticides, phthalates, flame retardants and other endocrine-disrupting compounds, bacterial and fungal pollutants, viruses, dust mite, cockroach allergen and animal dander (Maertens et al., 2004; Rudel et al., 2003; Montoya and Hildemann, 2005; Raja et al., 2010; Qian et al., 2012). The components of resuspended particles depend on the indoor environment settings as well as the occupants' habits.

To have a better understanding on how resuspension contributes to inhalation exposure as an indoor source, we compare the emission rates of several common indoor particle sources from a number of studies, including walking (Ferro et al., 2004; Qian and Ferro, 2008; Tian et al., submitted for publication), vacuum cleaning (Knibbs et al., 2012), and frying, candle burning, smoking and incense burning (Glytsos et al., 2010). Fig. 1 shows the emission rates of particles from these activities. It should be kept in mind that the particle size distribution varies with particle sources (see legend for the reported size ranges). Fig. 1a shows that the mass emission rate of walking-induced resuspension is mainly