LITERATUR REVIEW AND PARAMETRIC STUDY: INDOOR PARTICLE RESUSPENSION BY HUMAN ACTIVITY

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ABSTRACT
Once an aerosol contaminant is introduced into an indoor environment, it can remain in the air, deposit on interior surfaces or attach to dust particles already present. Human activity, such as walking and cleaning, resuspends contaminated particles, regenerating airborne contaminants. This report is a literature review on the effects of human activity on particle re-suspension in indoor environment. A parametric investigation is also made on particle resuspension effects of potential mechanical, aerodynamic and electrostatic force components, due to human activity over the particle-containing reservoir. It is shown that combinations of mechanical-aero-electro forces from human activity, can lead to significant particle resuspension in indoor environment. Additional experimental and modeling work is recommended to quantify the influence of human activity on indoor particle resuspension.

INDEX TERMS
Resuspension, human activity, mechanical vibration, boundary drag force, electrostatic force

INTRODUCTION

Human beings spend most of their lifetime in indoor environments. Studies (Wallace 1996) have shown that personal exposure to micron-sized particulate matter (PM) is related to these environments. Human activity resuspends particulate contaminants from indoor reservoir surfaces. Aerosol concentrations from resuspension are generally much lower than those from direct release of aerosols; but due to the persistence of the contaminants in indoor environments and the continuous human activity disturbance, long term exposure to the resuspended contaminants can cause considerable human health effects. However, there is no generalized relationship between specific human activity and particle resuspension levels.

This review examines the literature relating indoor human activity with indoor particle resuspension. From the literature, it appears that resuspension forces contain three major

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components: mechanical vibration, aerodynamic and electrostatic force. The contributions of these components relative to resuspension are analyzed.

FIELD STUDIES ON PARTICLE RESUSPENSION BY INDOOR HUMAN ACTIVITY

Aside from activities such as smoking and cooking (Wallace 1996) that directly generate aerosols, human activities such as walking and cleaning are considered the main generating sources of indoor particle concentration. To describe the particle resuspension process, two resuspension terms are widely used: resuspension factor (RF) and resuspension rate (RR), as defined by Equation 1 and 2.

$$RF\ (m^{-1}) = \frac{airborne\ concentration, C\ (\mu g\ m^{-3})}{surface\ concentration, S\ (\mu g\ m^{-2})} \tag{1}$$

$$RR\ (s^{-1}) = \frac{surface\ concentration\ removal\ rate, R\ (\mu g\ m^{-2}\ s^{-1})}{surface\ concentration, S\ (\mu g\ m^{-2})} \tag{2}$$

The scientific and public concern for indoor particle resuspension was initiated by the concern with exposure to radioactive dusts during the decommissioning process of nuclear facility (Fish 1967). Sehmel (1984) has assembled a detailed summary of resuspension results from literature before 1980s for both indoor and outdoor particle resuspension. In Sehmel's work, the particle resuspension are mainly divided into two categories: mechanical resuspension and aerodynamic, wind, resuspension.

More recently, studies (Ferro et al. 2004, Karlsson et al. 1999, Karlsson et al. 1996, Thatcher and Layton 1995) were carried out on the particle resuspension effects of specific indoor human activity such as walking and vacuuming. These studies concluded that the resuspension rate must be carefully specified as a function of aerosol size, personal activity and floor material. After the anthrax attacks in 2001 there is interest in determining occupant risk caused by human activity in areas previously exposed to biological weapons (BW) released by primary aerosolization. However, there is no readily available study on BW resuspension due to indoor human activity.

The above indicates that human activity is important to particle resuspension in indoor environments. Different types and intensities of human activity can generate significant difference in particle resuspension. Particle resuspension processes can be investigated by examining a few parameters related to human activity. Major potential force components on surface-residing particles are shown in Figure 1. Mechanical vibration, aerodynamic and electrostatic components are particle resuspension forces, related to human activity. Gravity and adhesion forces prevent particles from resuspension.

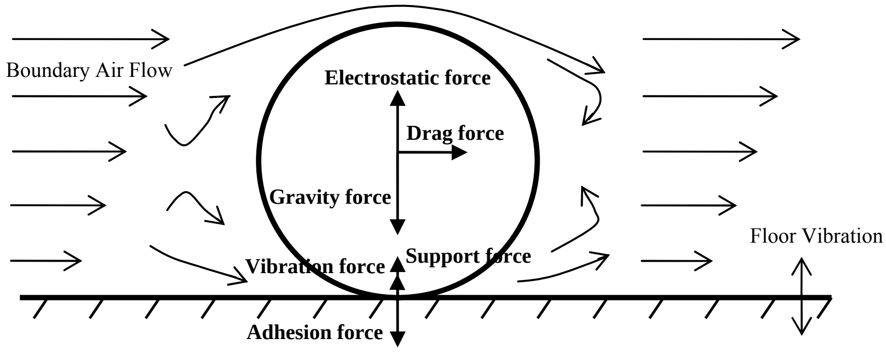

Figure 1. *Force analysis on surface residing particles*

ADHESION FORCE ON PARTICLES

Micron-sized aerosol particles may firmly adhere to the surface, with adhesion force exceeding the gravitational force by orders of magnitude (Hinds 1999). Thus adhesion force is the major force that prevents surface particles from resuspension. Main adhesion forces include van der Waals force, charge-induced electrostatic force, and surface tension induced by adsorbed liquid films. Van der Waals is usually the greatest in magnitude. Equation 3 (Hinds 1999) is commonly used to calculate the van der Waals force for initial contact between particles and a surface, without consideration of contact area flattening.

$$F_{adh} = \frac{Ad}{12x^2} \tag{3}$$

Where: F_{adh} is the adhesion force, N; A is the Hamaker constant, which depends on the materials involved and ranges from $6 \sim 150 \times 10^{-20} J$; d is the particle diameter, m; x is the separation distance between particle and substrate due to irregular contact surfaces, m.

When the effects of electrostatic force and surface tension are neglected, the adhesion force can be estimated by van der Waals force and compared with gravitational force, as shown in Figure 2.

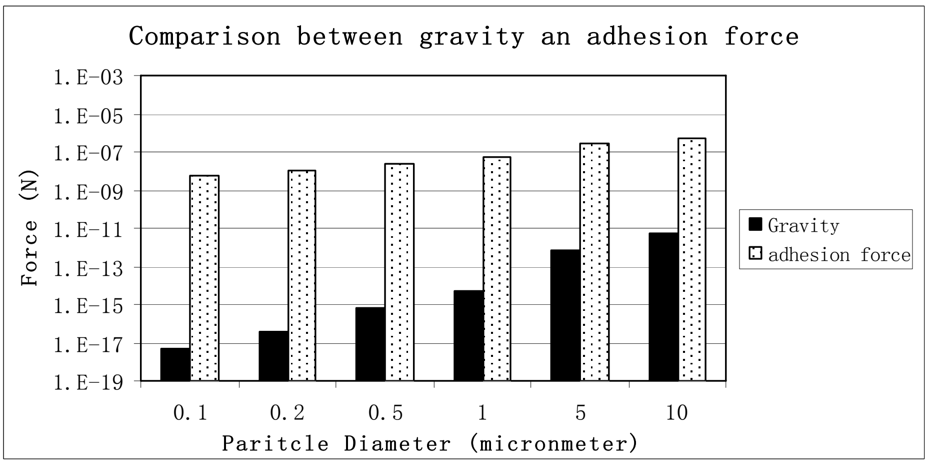

Figure 2. *Comparison between adhesion force and gravity force*

It can be seen that the adhesion force for micron particles can be orders of magnitude larger than the gravity. Contact time is an important factor that can influence particle adhesion force. As shown by experiments (Krishnan and Busnaina 1994, Tsai et al. 1991), after initial contact, the particle adhesion force can gradually deform the contact parts, decrease the separation distance and increase contact area until new force equilibrium is reached. In a recent study (Matsumoto 2003), researchers found that anthrax used in the attacks against the US 2001 were intelligently weaponized by using a layer of silicon bumps around the anthrax spores. The addition of these silicon bumps reduced the particle adhesion forces, thereby increasing the chance of particle resuspension.

ANALYSIS ON FORCE COMPONENTS CAUSING PARTICLE RESUSPENSION

Mechanical vibration force on particle resuspension

The floor vibration response due to human activities is the natural frequency or free vibration of the floor, a characteristic unique to each building and dependent on the structural properties. For a typical building, the vibration frequencies are 4~8 Hz. This vibration phenomenon can be modeled as a sinusoidal curve. The acceleration speed of floor surface vibration is defined by Equation 4.

$$a = 4\pi^2 f^2 A \sin(2\pi f t) \qquad (4)$$

Where: *a* is the acceleration speed, m²/s: *f* is the sinusoidal frequency, Hz; *A* is the sinusoidal amplitude; *t* is the time, sec.

Aerodynamic force on particle resuspension

In the indoor environment, air currents near the floor surface caused by human activity can add drag forces to the particles on the surface. For the surface residing particles, the drag force model in the boundary layer is shown by Equation 5 (Punjrath and Heldman 1972).

$$F_d = \left[\frac{\pi d^2}{4}\right]\left[C_{fx}\rho U^2 / 2\right] \qquad (5)$$

Where: C_{fx} is the local shear stress coefficient; ρ is the air density, kg/m^3; *U* is free-stream air flow velocity, m/s.

Turbulence intensity of free stream can also influence the air drag force on the surface particles. Some studies (Punjrath and Heldman 1972, Schubauer and Skramstad 1947) found that the critical Reynolds number decreases as the intensity of turbulence in the free stream increases.

Electrostatic force on particle resuspension

Human activity can cause electrostatic charging between the human body and the indoor environment. Observing sparkles while taking off clothes and being shocked when touching a door knob are some of the common phenomena associated with indoor electrostatic discharge. The amount of static charge depends on the materials subjected to friction or separation, the amount of friction or separation and the relative humidity of the indoor environment. The friction of rubber shoes on the ground can increase the human static voltages to levels as high as 10,000 volts (Reade 1997). When such high voltage accumulates within the very short distance between a human foot and the floor, a high electrostatic field can be generated on the surface of the floor. Thus strong electronic force can act on the charged surface particles to contribute to the resuspension process. The induction particle charges under electrostatic field can be calculated by Equation 6. The electrostatic force on the charged particles can be calculated by Equation 7 (Cho 1964).

$$Q = 1.65 \times 4\pi\varepsilon_0 r^2 E \tag{6}$$

Where: ε_0 is dielectric constant of the air; r is the radius of the particle, m; E is the magnitude of electric field, v/m.

$$F_e = QE \tag{7}$$

Based on the above analysis, calculation can be carried out to compare the magnitude of particle resuspension force components with the gravitational force of micron-sized particles, as shown in Figure 3.

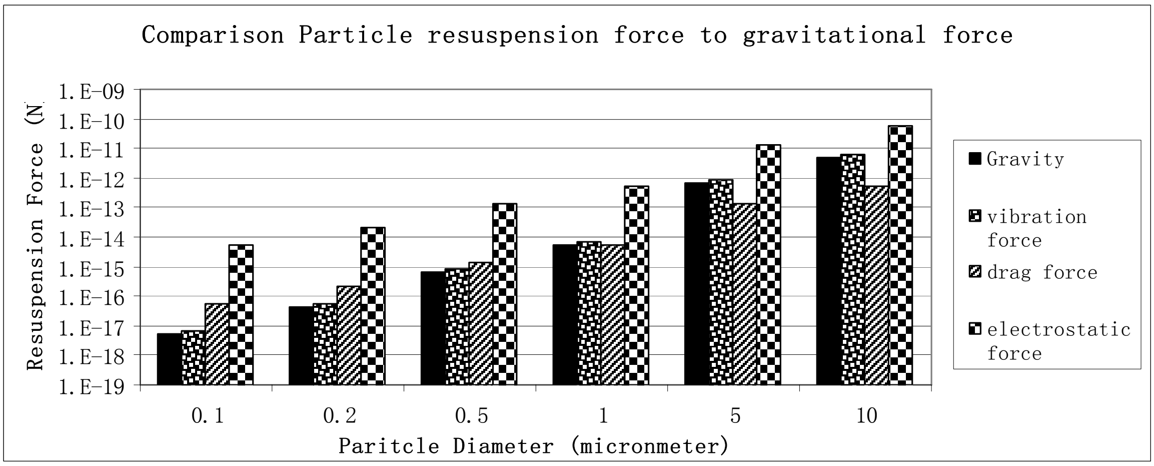

Figure 3. *Comparison of particle resuspension forces and gravity force*

In Figure 3, all the three resuspension force components are larger than the gravitation force of micron-sized particle. The electrostatic force has the largest magnitude for all the comparisons. As the particle diameter increases, the magnitude difference between aerodynamic force and gravity becomes smaller. This is also the trend shown between electrostatic force and gravity. For 10μm particle, the boundary air drag force is approximately the same as particle gravitational force. However, all these resuspension forces are much smaller than the theoretically calculated particle adhesion force as shown in Figure 2.

DISCUSSION

Although boundary layer air drag force is not large, the air drag force in free stream for suspended particles is much larger than the gravitational force. Once the particles move across the boundary layer, the free stream drag force can keep the particles in resuspension for a long time (Corn and Stein 1965).

Although resuspension forces induced by human activity are generally smaller than theoretically calculated particle adhesion force, particle resuspension phenomena are not unusual in indoor environment. This fact means that the real particle adhesion force can be much smaller than theoretical calculation due to imperfect contact between particles and surface. Thus experiments are recommended to quantify real particle adhesion force in indoor environment.

CONCLUSIONS

The studies from literature have shown that human activity can influence particle resuspension in indoor environment. The influence can mainly be decomposed into mechanical vibration, aerodynamic and electrostatic forces. Each force component shows a larger magnitude than the gravitational force of micron-sized particles. Additional experimental and modeling work needs to be carried out to quantify the activity induced force components and their influence on particle resuspension parameters.

This study also shows that the adhesion force between the particles and surface is the dominant force that prevents residing particles from resuspension. Experiments are recommended to quantify the real particle adhesion force in indoor environment.

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