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# Three-dimensional motion of particles in a shear flow near a rough wall

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ABSTRACT

A model is proposed for the three-dimensional motion of a small spherical particle entrained by the shear flow of a gas near a rough wall. On the basis of experimental results, the wall is modeled by an average small roughness and some much larger isolated peaks, which are yet smaller than the sphere radius. When encountering a high peak of roughness, the particle may be lifted if the aerodynamic force and torque take over the force and torque due to adhesion on the wall. The aerodynamics is treated using previous analytical results for the creeping flow around a particle near a wall. Values of the adhesion forces of a particle near a rough wall are obtained experimentally. When lifted from the wall, the particle follows a three-dimensional trajectory while rotating around the peak of roughness. Examples of calculated trajectories show that the particle may or may not reach the top of the peak, depending on the various physical parameters. Since the velocity of the particle when leaving the peak grows with its final distance from the wall, that velocity is essential for the subsequent particle resuspension by the ambient shear flow.

## 1. Introduction

In nuclear facilities, during normal operations in controlled areas, workers might be exposed to radioactive aerosols. Potential sources of airborne contamination are particles that are initially spread on the floor and later removed by walking workers. Particle resuspension by walking on a contaminated soil may be due either to the airflow blown by the shoe motion or to the mechanical action of the shoe. At present, studies on this topic are sparse and only empirical relationships are available (Jones & Pond, 1964; Brunskill, 1964; Boulaud et al., 2003). In order to assess occupational exposure and define the most appropriate protections for the workers, it is suitable to determine the particle resuspension rate for new situations. Empirical considerations may then not be sufficient and consequently modeling is needed (Mana, 2014).

Furthermore, there is a strong interest in the scientific community for this type of problem, especially in the framework of air quality in domestic environment (Gomes, Freihaut, & Bahnfleth, 2007; Qian & Ferro, 2008; Rosati, Thornburg, & Rodes,

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## Nomenclature

| | |
|---|---|
| $a$ | radius of spherical particle (m) |
| $\mathbf{C}$ | aerodynamic torque on particle (N.m) |
| $c$ | (with indices) friction factor for torque $\mathbf{C}$ (dimensionless) |
| $(\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3)$ | base vectors of the $(x_1, x_2, x_3)$ frame (dimensionless) |
| $E_1, E_2$ | Young moduli of materials 1, 2 (Pa) |
| $f$ | (with indices) friction factor for force $\mathbf{F}$ (dimensionless) |
| $\mathbf{F}$ | aerodynamic force on particle (N) |
| $H$ | center of circular region of contact of the spherical particle with the rough wall |
| $H'$ | projection of the sphere center $O$ onto the base plane |
| $\mathbf{H}$ | reaction force of rough wall onto particle at point $H$ (N) |
| $I$ | moment of inertia of particle (kg m$^2$) |
| $\mathcal{I}$ | impact factor (dimensionless) |
| $(\mathbf{i}, \mathbf{j}, \mathbf{k})$ | base vectors of $(x, y, z)$ frame (dimensionless) |
| $k_{\mathrm{q}}$ | constant coefficient of quadratic shear flow (m$^{-1}$ s$^{-1}$) |
| $k_{\mathrm{s}}$ | constant coefficient of linear shear flow (s$^{-1}$) |
| $\widetilde{k}_{\mathrm{q}}$ | normalized ratio $ak_{\mathrm{q}}/k_{\mathrm{s}}$ (dimensionless) |
| $\ell$ | distance between sphere center and base plane (m) |
| $m$ | mass of particle (kg) |
| $\mathbf{n}$ | unit vector normal to sphere at peak $P$ (dimensionless) |
| $O$ | sphere center |
| $P$ | peak of roughness |
| $P'$ | projection of $P$ onto base plane |
| $\mathbf{P}$ | reaction force of peak $P$ onto particle (N) |
| $r_c$ | contact radius of deformed elastic spherical particle |
| $\widetilde{r}_c$ | $r_c/a$ (dimensionless) |
| $\mathfrak{R}$ | Reynolds number (dimensionless) |
| $\mathrm{S_{tk}}$ | Stokes number (dimensionless) |
| $t$ | time (s) |
| $\widetilde{t}$ | dimensionless time $k_{\mathrm{s}}t$ |
| $\mathbf{U}$ | sphere translational velocity (m/s) |
| $U_x$ | $x$ component of $\mathbf{U}$ |
| $\widetilde{U}_x$ | $U_x/(ak_{\mathrm{s}})$ (dimensionless) |
| $\mathbf{v}_\infty$ | ambient flow velocity (m/s) |
| $V_s$ | stokes velocity of particle submitted to force $\mathbf{W}$ (m/s) |
| $\widetilde{V}_s$ | normalized Stokes velocity $V_s/(ak_{\mathrm{s}})$ (dimensionless) |
| $\mathbf{W}$ | weight plus adhesion force, normal to wall (N) |
| $\mathbf{W}_A$ | adhesion force (N) |
| $(x, y, z)$ | cartesian frame of coordinates attached to the wall and with origin specified in Section 5.2 (m) |
| $\mathbf{x}$ | position vector in frame $(x, y, z)$ (m) |
| $(x_1, x_2, x_3)$ | cartesian frame of coordinates attached to the wall and with origin at point $H'$ at time $t$ (m) |
| $(X, Y, Z)$ | coordinates of sphere center $O$ in frame $(x, y, z)$ (m) |

*Greek letters*

| | |
|---|---|
| $\beta$ | distance of $P'$ from origin of $(x, y, z)$ frame |
| $\delta$ | distance of peak $P$ from base plane |
| $\Phi$ | value of angle $\phi$ for non-lifted sphere |
| $\varepsilon$ | gap between base plane and particle surface (dimensionless) |
| $\theta$ | angle between axes $x$ and $x_1$ |
| $\mu$ | gas dynamic viscosity (Pa s) |
| $\mu_s, \mu_d$ | static and dynamic solid friction factors (dimensionless) |
| $\nu$ | gas kinematic viscosity (m$^2$/s) |
| $\nu_1, \nu_2$ | Poisson coefficients of materials 1, 2 (dimensionless) |
| $\rho_a$ | air density (kg/m$^3$) |
| $\rho_p$ | particle density (kg/m$^3$) |
| $\tau_p$ | particle relaxation time (s) |
| $\phi$ | angle $\widehat{HOP}$ between center $H$ of contact region and peak $P$, as viewed from sphere center $O$ |
| $\psi$ | angle of rotation around axis $x_1$ |
| $\mathbf{\Omega}$ | sphere rotational velocity (s$^{-1}$) |
| $\Omega_y$ | $y$ component of $\mathbf{\Omega}$ (s$^{-1}$) |
| $\widetilde{\Omega}_y$ | $\Omega_y/k_{\mathrm{s}}$ (dimensionless) |

*Superscripts*

| | |
|---|---|
| $(\,)^{\mathrm{t}}$ | translation |
| $(\,)^{\mathrm{r}}$ | rotation |
| $(\,)^{\mathrm{s}}$ | linear shear flow |
| $(\,)^{\mathrm{q}}$ | quadratic shear flow |

*Subscripts*

| | |
|---|---|
| $O$ | refers to sphere center $O$ |
| $P$ | refers to peak $P$ |
| $(\,)_x, (\,)_y, (\,)_z$ | components in frame $(x, y, z)$ |
| $(\,)_1, (\,)_2, (\,)_3$ | components in frame $(x_1, x_2, x_3)$ |

2008; Oberoi et al., 2010; Choi, Edwards, Rosati, & Eisner, 2012; Kubota & Higuchi, 2013). All these studies show that obviously particle size is a critical parameter in the resuspension phenomenon and that soil characteristics (hard surface, roughness, new or worn carpet) are also relevant.

Analytical models describing the resuspension of micron-sized particles by an airflow generally consider that the characteristic scale of the surface roughness is small compared with the diameter of the particle (Reeks & Hall, 2001; Ibrahim, Dunn, & Brach, 2003; Goldasteh, Goodarz, & Ferro, 2013; Zhang, Reeks, & Kissane, 2013). In this case, the particle has several contact points with the asperities of the surface. The analysis of its motion is simplified by performing a balance of the moments of forces along two dimensions in a plane parallel to the direction of airflow. The role of surface roughness,