The Development and Application of Kinetic Models for the Resuspension of Small Particles in Turbulent Boundary Layers

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This presentation is about the way submicron size particles attached to a solid substrate are resuspended by a turbulent flow. Fundamentally it is a study of the adhesive forces that hold a particle onto a surface and the aerodynamic removal forces. Our particular concern here is how this process can be quantified by a rate constant for the removal of particles from a surface that reflects its statistical nature. The particles are small enough that only the intermolecular van der Walls forces and elastic restoring forces are responsible for the particle surface adhesion (gravity plays no part). The aerodynamic forces are generated in the turbulent boundary layer close to the surface and have both drag and lift components. Both component forces have a fluctuating as well as a steady mean components due to the turbulence in the near substrate region.

The traditional force balance view supposes that particles are removed from a surface when the lift force exceeds the force of adhesion. However particles are not removed instantaneously: whilst some particles are removed on timescales which are very short (on the timescale of the turbulence itself) there are some remaining that are removed on much longer timescales; there is a distinction between short and long term resuspension and this in principle is due to the scale of the turbulent fluctuations and the distribution of adhesive forces. What we describe here is an attempt to quantify these processes in a variety of situations from monolayer to multilayer coverages particles.

Our focus is on kinetic models[1] which encapsulate the resuspension by a primary rate constant that is similar to the rate constant p for the desorption of molecules from a surface and given by

$$p = n \exp - Q/2\langle PE \rangle$$

,where Q is the height of the surfaces adhesive potential well over which the adhering particles must overcome through the rotational energy they receive from the turbulent fluctuations in the aerodynamic removal force. The rate constant formula is precisely analogous to the rate at which molecules are desorbed from a surface, Q being the activation energy and $\langle PE \rangle$ the equivalent thermal energy. There is an important difference here reflected in the frequency n, typical of the motion of the particle-surface deformation- namely the process of resonant energy transfer when n is typical of the natural frequency of the particle surface deformation and the forcing frequency when n is off resonance driven by external aerodynamic removal forces. We show how when particles attached to a rough surface where there is a distribution of a adhesive forces caused by particle surface asperities how this greatly reduces particle–surface contact/adhesion and increases resuspension and leads to two types of resuspension: short term resuspension typical of the timescale of particle motion in the surface adhesive potential well, and a much longer term resuspension in which the rate of decay of particles on the surface varies almost inversely as the time. We show how some important early experiments indicated that resuspension by resonant energy transfer is negligible and that the most likely motion occurs quasi-statically where the adhesion is balance by the removal force at each instant of time. Furthermore removal was caused by particles rolling before they were lifted off. This lead to a new kinetic model for resuspension referred to as the rock 'n' roll model in which a particle in contact with a surface rocks about surface asperities, In this way the drag force plays a much more important role in initiating rolling and eventual removal than that of the lift force.

We show how this simple model assuming a log-normal distribution of adhesive forces was used to analyse the resuspension measurements of a series of experiments reported in the literature and derive empirical correlations for the geometric mean and spread of the adhesive force as a function of particle size, indicating that adhesion is much less than that for smooth contact.

We describe how significant improvements have been made to the rock 'n' roll model by extending its applicability to non-Gaussian removal forces taking into account the contribution of the highly intermittent non Gaussian sweeping and bursting events in the boundary layer, based on measurements of the streamwise fluid velocity and acceleration close to the wall obtained from a DNS of turbulent channel flow.[2]

We conclude with a brief description of how this basic kinetic model for particle resuspension of less than a monolayer coverage of particles has been extended to deal with the resuspension from multilayers coverages of particles[3]

[1]Reeks, M.W., & Hall, D. (2001). Kinetic models for particle resuspension in turbulent flows J. Aerosol Sci., 32, 1–31.
[2]Zhang, F., Reeks, M., Kissane, M. (2013). Particle resuspension in turbulent boundary layers and the influence of non-Gaussian removal forces. J. Aerosol Sci., 58, 103–128
[3]Zhang, F. Reeks, M. Kissane, M (2013) Resuspension from Multilayer Deposits J Aerosol Sci. 66, 31-61