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Glass particle resuspension from a contaminated (dirty) glass surface

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ABSTRACT

A wealth of adhesion force measurements between a variety of particle/surface pairs have been gathered via Atomic Force Microscopy (AFM) in the past years. However, these measurements deal mostly with clean surfaces and particles for reproducibility. It is therefore up for debate whether particle resuspension could be calculated using these measurements as surrogates for real outdoor particles and surfaces, which often carry both organic and inorganic contaminants ("urban grime"). Two components are necessary to investigate this question: (1) adhesion force measurements on both clean and contaminated surfaces and (2) estimation of particle resuspension from both surface types. In this work, AFM was used to measure the distribution of the adhesion force between a 5-µm clean glass particle and two glass surfaces: the first cleaned according to conventional laboratory standards and a second one left outdoors for six weeks in Albuquerque (New Mexico). The Rock 'n' Roll model was modified to use experimental adhesion force distributions of arbitrary shape and number of modes instead of a lognormal distribution, as in the original work Reeks & Hall (2001). The results of this analysis showed that the differences in the fraction of particles resuspended were small for a friction velocity of 0.5 m/s but increased for 1 and 2 m/s. For instance, for a friction velocity of 3 m/s, 71% of the original deposit was still on the surface after a day for the clean glass, while only 33% remained on the contaminated glass.

1. Introduction

Wind-driven particle resuspension occurs when particulates deposited on a surface become airborne because of wind gusts. Estimating the resuspension rate of harmful particles deposited on an outdoor surface is critical because particle reaerosolization may lead to a state of prolonged low-level secondary health hazard. In addition, especially in case of wind changing direction in time, the resuspended particles may be spread over an area wider than the initial deposit thus affecting a larger population and making cleanup efforts more difficult and expensive. There are a number of computational models in the literature that can assist in the estimation of particle resuspension. Broadly speaking, these models can be grouped into two classes: empirical models, derived from experimental data fitting, and mechanistic models, built on first principles. Empirical models include the main variables affecting resuspension, namely friction velocity, surface roughness, particle diameter and density, time, humidity, and the Hamaker constant (see for instance, Kim et al., 2016; Loosmore, 2003; Kim, Gidwani, Wyslouzil, & Sohn, 2010). The main issue with this approach s is that the

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existing models accept only mean values of the aforementioned parameters, while the shape and width of their distribution is also important. For instance, Braaten, Paw U, and Shaw (1988) showed that particle resuspension is often associated with ejections, which is a fluid motion characterized by a velocity higher than the average one. Mechanistic models are particularly appealing because grounded in the fundamental interactions, namely the adhesion force between the particle and the surface and the aerodynamic lift and drag forces applied to the particle by the wind. Among mechanistic models, two of great interest are the Rock ‘n’ Roll model (Reeks & Hall, 2001) and Guingo and Minier (2008) model because they both include probability density functions (PDF) to account for the stochastic nature of aerodynamic and adhesion forces and ultimately, of resuspension. For instance, in Reeks and Hall (2001), the adhesion force was captured with a lognormal distribution which parameters were derived from centrifuge experiments. The authors had to assume a distribution because the centrifuge technique could only provide average quantities, i.e., the mean adhesion force and its standard deviation. Nowadays, Atomic Force Microscopy (AFM) can provide the adhesion force distribution of a micron-scale particle interacting with a surface and there are numerous studies in the literature presenting such information for a variety of surface/particle pairs, some of which showed that distributions other than the lognormal are also possible, e.g., mono- and bi-modal Weibull distributions (Götzinger & Peukert, 2004). Indeed, AFM has been employed for many years to study surface roughness characteristics and adhesion force distribution. The issue with existing studies is that they oftentimes involve clean surfaces and particles for reproducibility, which may or may not be representative of real surfaces and in particular, of outdoor surfaces, usually covered in dust, pollen, and other pollutants, what Einfeld, Boucher, Tezak, Wilson, and Brown (2011) call “urban grime”. As a consequence, it is not obvious if standing adhesion force measurements between clean particles and surfaces are viable surrogates for real outdoor substrates when it comes to computing resuspension from measured adhesion force distributions. This work tries to answer this question in the following way. We used AFM to measure the adhesion force distribution for a clean glass particle interacting with two different glass surfaces: one cleaned according to common laboratory procedures and a second one left outdoors for six weeks in Albuquerque (New Mexico). We then modified the Rock ‘n’ Roll model so it could accept an experimental adhesion force distribution and computed the resuspension rate for both the clean and the dirty glass surface.

The paper is organized as follows: Section 2 describes the experimental settings; Section 3 presents the Reeks and Hall model (2001) and its extension to experimental adhesion force distributions; Section 4 presents and discusses the adhesion force measurements and the resuspension rate computed with the modified model; and finally, Section 5 presents our conclusions.

In the following, we will use the words “clean” and “contaminated” to distinguish between the classic laboratory surface, cleaned before use, from the sample that was left outdoors and therefore carried organic and inorganic contaminants on its surface.

2. Experimental method

Glass slides (63750, Electron Microscopy Sciences) were cleaned using piranha solution (70% H_2SO_4, Fisher Scientific, and 30% H_2O_2, 30% reagent grade, Fisher Scientific) for 30 min with 5 × rinse in de-ionized water. The samples were stored in de-ionized water until use and blown dry with nitrogen gas prior to imaging. Some of the glass slides were placed outdoors for six weeks (from 18 February 2015 to 01 April 2015) in an internal courtyard at the Center for Integrated Nanotechnologies in Albuquerque, New Mexico (lat: 35.060538°, lon: −106.534547°). The glass slides were placed flat on a surface, so that their face was pointing up at the sky. Fig. 1 shows Scanning Electron Microscope (SEM) images of some of the deposits that were found on the contaminated glass; both organic and inorganic compounds of diverse sizes were found. In this initial investigation, no attempt was made at characterizing the properties and nature of the debris beyond their roughness and adhesiveness.

Environmental conditions were gathered from the nearby Albuquerque International Sunport (lat: 35.0419°, lon: −106.6155°) as reported by the National Centers for Environmental Information (https://www.ncei.noaa.gov, last accesses on 18 December 2017). Fig. S1 shows the weather conditions during this period: winds were brisk during the entire time-frame, with one snow event in the second week. The contaminated samples were stored in closed containers after environmental exposure.

The adhesion force was measured on an MFP-3D atomic force microscope (Asylum Research) under ambient conditions (25 °C, RH ≤ 30%) in contact mode with a clean 5-μm diameter particle glued to a tipless cantilever (Fig. S2). Each adhesion force measurement involved an area of 10 × 10 μm (32 × 32 pixels) and both roughness and adhesion force were measured simultaneously. Since the humidity was below 30% during the measurements, only the van der Waals component of the adhesion force was present (Rabinovich et al., 2002; Wang, Qian, & Gao, 2009). See SI for a description of the colloid probe fabrication and nanoindentation measurements.

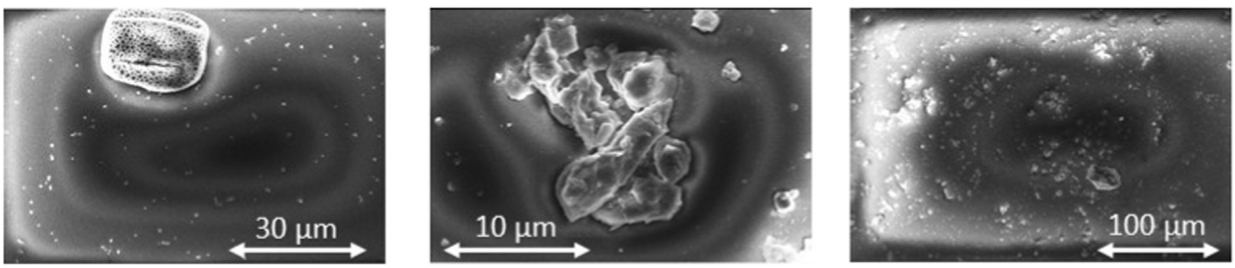

Fig. 1. SEM images of some deposits on the contaminated glass. On the left, a pollen grain; in the middle and on the right, inorganic debris.