Colloids and Surfaces A: Physicochem. Eng. Aspects 481 (2015) 583–590

Contents lists available at ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

journal homepage: www.elsevier.com/locate/colsurfa

The role of electrostatic charge in the adhesion of spherical particles onto planar surfaces in atmospheric systems☆

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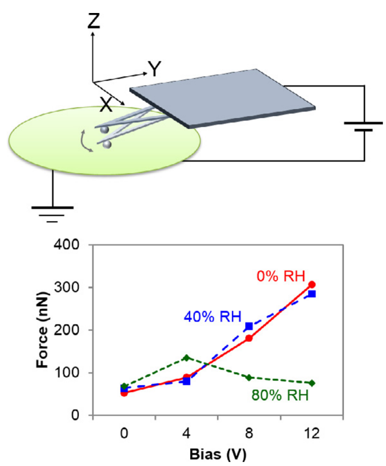
HIGHLIGHTS

- Surface charge and humidity play strong roles in the adhesion of two surfaces.
- Changes in adhesive force are greater for surfaces with higher charge densities.
- The role of capillary force in surface adhesion is stronger for larger particles.
- Humidity effects on the electrostatic force depend on surface hydrophobicity.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 February 2015
Received in revised form 29 April 2015
Accepted 15 June 2015
Available online 19 June 2015

Keywords:
Adhesive force
Electrostatic charge
Relative humidity
Particle adhesion

ABSTRACT

The influence of electrostatic charge on the adhesive force between spherical particles and planar surfaces in atmospheric systems was studied using atomic force microscopy. Electrical bias was applied to modify the surface charge, and it was found that application of a stronger positive bias to a particle induces a stronger total adhesive force. The sensitivity of the system to changes in the bias depended on the surface charge density. For larger-size particles, the contribution of the electrostatic force decreased, and the capillary force became the major contributor to the total adhesive force. The influence of water adsorption on the total adhesive force and, specifically, on the contribution of the electrostatic force depended on the hydrophobicity of interacting surfaces. For a hydrophilic surface, water adsorption either attenuated the surface charge or screened the effect of surface potential. An excessive amount of adsorbed water provided a path to surface charge leakage, which might cancel out the electrostatic force, leading to a reduction in the adhesive force. Theoretically calculated forces were comparable with measured adhesive forces except for mica which has a highly localized surface potential. The results of this study provide information on the behavior of charged colloidal particles in atmospheric systems.

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http://dx.doi.org/10.1016/j.colsurfa.2015.06.030

1. Introduction

Interfacial forces such as van der Waals, capillary, and electrostatic forces may play an important role in atmospheric transport of aerosol particles, especially when the particle size is in the micrometer range. Among these forces, the electrostatic force is a major contributor to the behavior of charged particles. Radioactive particles are a relevant example because they acquire surface charge through direct self-charging, as well as indirect charging processes [1–5]. Arising from surface charge, the electrostatic force leads to transport of radioactivity far from radioactive sources and accumulation of contamination on soil and plant surfaces [6]. Electrical household appliances are a significant source of ultrafine charged particles, which affect indoor air quality [7–11]. Electrostatic interactions may prevent the aggregation of charged aerosol particles and allow them to carry various air pollutants including microorganisms, dust, and sometimes radon progeny to long distances [6]. Since charged particles are stabilized with respect to aggregation, their surface charge can enhance the transport of air pollutants. The surface charge may also increase the concentration of pollutants on surfaces, such as computer displays, printers, and power cables [6,12].

Relative humidity (RH) is another variable that affects the behavior of particles in the atmosphere. As the RH is increased, more water molecules adsorb onto surfaces, and a water meniscus may form between the interacting surfaces. Adsorption of water molecules promotes the adhesion of particles due to the surface tension of water and the pressure difference across the meniscus [13,14]. Since water is a polar molecule, which can be attracted by a charged surface, the presence of surface charge considerably affects water adsorption onto surfaces. It has also been reported that water adsorption contributes to charge build-up [15,16], as well as dissipation of the charge by increasing the conductance of the material [16,17]. Thus, it is essential to consider not only the effects of surface charge and RH upon the adhesive force of micron- and submicron-size particles in atmospheric systems, but also the relationship between surface charge and RH.

Atomic force microscopy (AFM) has been used to study the interaction forces between micron-size particles and various substrate surfaces [18,19]. AFM is a suitable tool to study particle interaction forces in atmospheric systems because it enables simulation of the natural environment by controlling such variables as RH and surface potential. AFM has been used in our previous work for the study of micron- and submicron-size particles including a silicon nitride cantilever tip, spherical silica particles of varying diameter, and bacterial spores with various planar surfaces [20–22]. The contribution of the electrostatic force was identified by scanning surface potential microscopy (SSPM) measurements and through comparisons of AFM force measurements with calculated values using mathematical models for the van der Waals, capillary, and electrostatic forces [23,24]. Kweon et al. measured the interacting forces of a silicon nitride tip with a radioactive gold (^{198}Au) surface [22]. It was found that the electrostatic force arising from the surface potential of ^{198}Au contributes to the total adhesive force. In addition to radioactive particles, there are many examples in which the electrostatic force plays a critical role because aerosol particles can naturally or artificially acquire surface charge [6,7,12].

This study aims at investigating the contribution of the electrostatic charge and the influence of RH on the adhesive force of various materials. AFM was used to measure the adhesive force of silica and gold particles with various planar surfaces including mica, silica, and gold, which can be readily found in both natural and engineered environments. Mica and silica are insulating materials whereas gold is conductive, and mica can acquire a relatively higher surface charge density than silica does. In order to investigate the effect of particle size on the interaction forces, two different-size particles, 1 μm and 2.5 μm in diameter, were used. The interaction forces were also calculated using established models for the van der Waals, capillary, and electrostatic forces. Comparisons between experimental data and theoretical calculations in this work can be used to improve existing models.

2. Experimental and modeling methods

2.1. Surface preparation

Mica, silica (fused quartz), and gold foil were used as planar surfaces in this study. Prior to cleaning, mica and silica were mounted onto a magnetic disc that adjusts substrate surfaces onto the AFM stage using two-sided adhesive tape. In order to minimize surface contamination that could result in the modification of surface properties, mica was cleaved just before each force measurement. Silica was stored in concentrated sulfuric acid for more than 24 h and rinsed thoroughly with a large amount of deionized water. A pure gold foil of square shape was attached to the magnetic disc using silver paint, which enabled the application of electrical bias to the gold foil. The prepared gold kit was cleansed with ethanol and acetone, and rinsed thoroughly with a large amount of deionized water. Cleaned silica and gold surfaces were dried and stored in silica gel dehydrators for 3–5 days.

2.2. AFM probes

AFM probes of a spherical silica particle and a gold particle were prepared for interaction force measurements. A single spherical silica particle was attached at the end of a v-shaped tipless cantilever made of silicon nitride. A gold probe was prepared by coating a silica probe with gold. Particle attachment and gold coating were performed by Novascan Technologies (Ames, Iowa). The procedure involved handling of the particles with micro-manipulators and attachment of a single particle on each cantilever with a thin film of glue. A gold coating film enabled the application of an electrical bias to the particle. Two different particle sizes (1 μm and 2.5 μm) were used to prepare both probes of silica and gold particles.

2.3. AFM force measurements

The interaction force between three different substrate surfaces (mica, silica and gold) and the prepared particle probes was measured by using the AFM MultiMode V (Veeco Instruments, Plainview, New York) at room temperature (19–21 °C). Application of the electrical bias is allowed through the substrate surface and the particle probe. Since mica and silica are both electrically insulating materials, the electrical bias was introduced through the gold particle. For the system consisting of gold foil, electrical bias was applied through either the gold foil or the gold-coated particle. A silica particle probe was also used in the measurements with the gold foil. The magnitude of the electrical bias was controlled by changing one of the AFM operating parameters. The deflection of the particle probe due to the interaction forces between the probe and the surface was recorded in volts (V) and converted to force (nN) using Hooke's law: $F = k \times S \times \Delta V$, where F, k, S, and ΔV are the force, spring constant, photodiode sensitivity, and change in deflection signal, respectively. The relative humidity (RH) was controlled in a cylindrical glass chamber that completely covered the AFM head and scanner.

The normal load (F_n), adhesive force (F_{ad}), and total adhesive force (F_{tot}, i.e., the sum of normal load and adhesive force) can be estimated from the force-distance curve obtained by AFM. Fig. 1 shows a typical force-distance curve for two cases: interaction between a particle and a surface without a long-range attraction