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The critical velocity of rebound determined for sub-micron silver particles with a variable nozzle area impactor

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ABSTRACT

The critical velocity of rebound was determined for spherical silver aerosol particles in the size range of 20–1000 nm. A novel instrument, a variable nozzle area impactor, was especially designed for measuring the particle–surface interaction as a function of the particle impact velocity. The experimental results were combined with a numerical model in order to obtain the impact velocities. The experiments were carried out using a plain aluminum collection substrate in the impactor. Our results show that the critical velocity of rebound decreases from 14 to 0.022 m/s as the particle size increases from 20 to 1000 nm. Furthermore, the critical velocity was found to be proportional to the power of −1.6 of the particle size, instead of the theoretical inverse proportionality. This result is in line with the previous studies for micron-sized particles. In the nanoparticle size range, the obtained values are approximately 3–10 times greater than the recent literature values. This discrepancy can most likely be explained by the different surface materials. All in all, our results give valuable information about the particle–surface interactions in the sub-micron size range.

1. Introduction

Particle rebound from a surface is a fundamental phenomenon. Recently, it has been of interest in several fields of aerosol physics, including atmospheric aerosols and aerosol synthesis. For example, Virtanen et al. (2010) found an amorphous solid state of biogenic SOA (secondary organic aerosol) particles by investigating the bounce behavior of the particles. The further development has led to some experimental methods capable of measuring the bounce probability of the SOA particles as a function of the relative humidity in specific low-pressure impactor systems (Bateman et al., 2014; Saukko et al., 2012). Within the field of engineered nanoparticles, the research of the particle–surface interaction has been focused on the fragmentation and binding energy of agglomerates (Froeschke et al., 2003; Ihalainen et al., 2014; Seipenbusch et al., 2007, 2010). However, the lack of knowledge of the fundamental bounce properties of ultrafine particles limits the reliability of these methods.

When a particle impacts on a firm surface, it may either stick to it or be reflected. The process is mainly affected by three factors: the adhesion, the energy loss mechanisms in the particle and the initial velocity of the particle. With low initial

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velocities, the energy losses dominate and the particle is captured by the surface. When the initial velocity increases up to a critical velocity, the kinetic energy, even when reduced by the energy losses, is sufficient to overcome the adhesion energy and the particle rebounds. According to theoretical knowledge, the critical velocity is inversely proportional to the particle size (Dahneke, 1971; Wang & Kasper, 1991; Weir & McGavin, 2008). Experimentally, the values of the critical velocity have been determined for different materials of micron-sized particles and substrates (Wall et al., 1990), and for silver and sodium chloride nanoparticles on a mica substrate in the size range of 10–80 nm (Rennecke & Weber, 2013a). Both the datasets show similar particle size dependency compared to the theories, but the critical velocity values have a difference of several orders of magnitude if extrapolated into the same size range.

The experimental challenges in measuring the particle rebound of nanoparticles are often related to low-pressure conditions required for the impaction and to the detection of the particles in these conditions. The experimental method used by Rennecke & Weber (2013a) was based on scanning the impact velocity by means of the impaction pressure. By continuously measuring the electrical current downstream and the particle concentration upstream, the penetration of the impactor could be defined as a function of the impaction pressure. The advantage of the electrical detection of particles in low-pressure conditions is its accuracy and a good time resolution. Optical detection of particles has also been used in the bounce and fragmentation studies of nanoparticles (Ihalainen et al., 2014; Saukko et al., 2012). Its advantage is that the possible charge transfer is not affecting the detection. However, the optical detection cannot practically be used continuously in low-pressure conditions.

Measurement of the impact velocity of a single particle can be performed for micron-sized particles with a laser Doppler velocimetry (Wall et al., 1990). Because of limitations in the optical detection, the same method cannot generally be exploited for nanoparticles. Reuter-Hack et al. (2007) have applied the laser Doppler velocimetry method for agglomerates with mobility diameters below 500 nm, but for spherical particles that would not be possible. The lack of experimental methods has led to the utilization of numerical methods and computational fluid dynamics (CFD) simulations in defining the impact velocity for nanoparticles (Ihalainen et al., 2014; Kuuluvainen et al., 2013; Rennecke & Weber, 2013a; Virtanen et al., 2011). These studies are mainly based on the previous work of modeling the impactor flow field and collection efficiency curves (Arffman et al., 2011; Rennecke & Weber, 2013b). According to the study by Arffman et al. (2012), the impactor geometry significantly affects the size resolution of an impactor. The best results were obtained with a slit type low-pressure impactor having a minimized nozzle throat length. The advantage of this type of an impactor is a very small deviation in the impact velocity of a certain particle size. This is also a great advantage in defining the critical velocity for nanoparticles.

This study presents a new method for measuring the critical velocity of nanoparticles using a variable nozzle area impactor, and reports the results for spherical silver particles in the size range of 20–1000 nm. The method is based on an impactor design, where the deviation of the impact velocities in a single measurement for a certain particle size is minimized, and the pressure conditions controlled. The impactor consists of a narrow slit with a short nozzle throat length, and the nozzle area can be varied by changing the slit length. By decreasing the slit length, the impact velocity of a particle increases. Furthermore, the impact velocities are calculated for different particle sizes and different slit lengths with numerical methods.

2. Theoretical background

The theory of aerosol particle rebound from a firm surface was first introduced by Dahneke (1971). The theory includes the effect of the adhesion, the energy loss mechanisms in a particle and the particle initial velocity. Assuming a spherical particle and an infinite firm surface, the adhesion energy between the particle and the surface can be written as

$$E_{\mathrm{adh}} = \frac{A_{\mathrm{H}} d_{\mathrm{p}}}{12 z_0}, \tag{1}$$

where d_p is the particle diameter, A_H is the Hamaker constant and z_0 is the separation distance, usually assumed to be 0.4 nm. The Hamaker constant arises from the van der Waals interaction of molecules and is dependent on both particle and surface materials.

The amount of energy loss in the collision is mainly dependent on the mode of deformation in the particle. Fully elastic deformation completely restores the kinetic energy of the particle, and the velocity after the rebound equals the initial velocity. Practically, this sort of collisions only takes place among molecules and atoms. Considering the collisions of aerosol particles and firm surfaces, plastic deformation is always present to some extent. Plastic and elastic behavior of aerosol particles during rebound was extensively studied first by Rogers & Reed (1984). Thereafter, Wang & Kasper (1991) and Weir & McGavin (2008) developed the theoretical approach for the elastic and plastic behavior, respectively.

Depending on the energy losses and adhesion energy, the particle may either rebound or stick to the surface. For the initial velocity, there is a certain capture limit v_{crit}, i.e. the critical velocity of rebound. The relation between the initial velocity of the particle, perpendicular to the surface, and the rebound velocity of the particle is called the coefficient of restitution C_R. Combining Eq. (1) and the definition of the coefficient of restitution, the critical velocity of rebound can be written as

$$v_{\mathrm{crit}} = \alpha d_{\mathrm{p}}^{\beta}, \tag{2}$$