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Technical note

The influence of electric charge on minimum particle scavenging efficiency particle size during below-cloud scavenging processes

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ABSTRACT

Below-cloud wet deposition scavenging processes are important for removing coarse and very fine particles from the atmosphere. This study investigated the influence of electric charge on particle deposition and estimated the scavenging gap particle size (the most penetrating particle size) along with the corresponding minimum collection efficiency and minimum scavenging coefficient particle size by using equations for below-cloud scavenging processes. A harmonic mean type approximation was used for calculations and the Cunningham correction factor was applied to include the slip effect of nuclei mode particles. Results based on the analytically approximated solution compared well with the numerically calculated results and previous studies that did not consider electric charging effects. The results showed that charge effects play an important role in determining the most penetrating particle size. This study also showed that use of the Cunningham correction factor may increase the most penetrating particle size under certain conditions. Subsequently, these results indicate that consideration of the electric charge effect with a Cunningham correction factor is important for estimating the most penetrating particle size.

1. Introduction

Removal of particles by wet deposition is one of the most efficient particle sinks in the atmosphere. For modeling purposes, wet deposition is divided into in-cloud and below-cloud scavenging processes. The below-cloud scavenging process is important for the removal of coarse and very fine particles from the boundary layer (Andronache, 2003).

One practical problem in scavenging studies is to determine the minimum scavenging efficiency particle size (most penetrating particle size) and the corresponding minimum collection efficiency. Generally, an increase in particle size will induce an increase in the collection efficiency as a result of interception and inertial impaction mechanisms. However, a reduction in particle size increases the collection efficiency due to Brownian diffusion. Therefore, there is a range of intermediate particle sizes where two or more mechanisms may operate simultaneously and no one mechanism predominates. This intermediate range is the region where penetration of particles through the collector is maximized

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and collection efficiency is minimized. The minimum collection efficiency diameter of the scavenging gap can be numerically calculated by differentiation of the collection efficiency.

Numerous investigations of particle removal by scavenging processes have estimated the scavenging gap or most penetrating particle size. Lee (1981) obtained the most penetrating particle size for solid granular filtration when diffusion, interception, and gravitation were accounted for. Later Jung & Lee (2007) derived the most penetrating particle size for multiple fluid collectors and those results showed similar tendencies to results obtained for the solid collector by Lee (1981). The concept of most penetrating particle size has also been used in studies of granular media filtration processes for critical suspended particles in water (Qi, 1998; Jung & Lee, 2006). Jung et al. (2011) calculated an approximate analytical solution for determining the scavenging gap particle size. They considered only Brownian diffusion, interception, and impaction. According to Bae et al. (2009, 2010), other mechanisms such as thermophoresis, diffusiophoresis, and electric charge effects might also affect the below-cloud scavenging process, especially for particles with a diameter of about $0.01<d_p<1$ μm (Horn et al., 1988; Sparmacher et al., 1993).

Below-cloud scavenging coefficients can increase by almost one order of magnitude when a charge on raindrops and particles is present, especially for particles with diameters in the range $0.01<d_p<0.1$ μm. Andronache (2004) showed that diffusion and electric charge primarily affected the below-cloud wet removal of aerosols with $d_p<0.1$ μm. Thus, it is important to consider phoretic and electric effects when determining the minimum collection efficiency and most penetrating particle size.

Although Andronache (2004) described the scavenging coefficient considering the electric charge effects, the quantitative results for the scavenging gap diameter (most penetrating particle size) have not been driven either. As pointed in several modeling and experimental studies (see, for example, Tinsley et al., 2000; Zhang & Vet, 2006; Henzing et al., 2006; Bae et al., 2010; Jung et al., 2013), conventional wet deposition expressions in which electric charge effect is not considered, do not perform well. The various studies report different boundaries for the size range of the MPPS or Greenfield gap (Andronache et al., 2006; Henzing et al., 2006). Tinsley et al. (2000) suggested that thermophoresis and electrical charge may enhance the scavenging particles in the Greenfield gap. Thus, including electric charge effect and verifying its validity are important in the fundamental understanding of the process and in real world calculation of the collection efficiency of wet particle removal systems.

In this study, we expanded upon the mathematical expression that was used for determining the below-cloud scavenging coefficient and collection efficiency in Jung et al. (2011) to account for electric charging effects. An approximate analytical solution for the scavenging gap particle size (the most penetrating particle size) with corresponding minimum collection efficiency and minimum scavenging coefficient particle size was estimated by use of a harmonic mean type approximation. The Cunningham correction factor was applied to include the slip effect of nuclei mode particles. The obtained solution was then compared to numerically calculated results and previous studies that did not consider electric charging effects.

2. Minimum collection efficiency and most penetrating particle size of below-cloud scavenging processes

The collection efficiency is the ratio of the total number of collected particles by rain droplets to the total number of raindrops in the droplet's effective cross-sectional area (Seinfeld & Pandis, 1998). Fine particles can be collected via Brownian diffusion. The collection efficiency due to the diffusion mechanism decreases rapidly with increasing particle size. The collection efficiency is assumed to be equal with the collision efficiency (Slinn, 1983; Andronache, 2003; Tost et al., 2006). Thus, diffusion is expected to be the most important mechanism of particle scavenging by wet deposition for particle diameters less than 0.1 μm. For larger particles, interception, impaction, and electrical charging become important.

Lastly, the charging effect on collection efficiency (E_{el}) is given as follows (Andronache et al., 2006):

$$E_{el}=\frac{16KCcQq}{3\pi\mu_a U(D_d)D_d^2 d_p} \tag{1}$$

where $U(D_d)$, the fall velocity of a raindrop with its diameter D_d in cm s^{-1}; Cc, the Cunningham correction factor; d_p, the particle diameter in cm. $K=9\times10^{18}$ g cm^3 C^{-2} s^{-2}, $Q=a_{el}dD_d^2$, $q=a_{el}dd_p^2$, $a_{el}=0.83\times10^{-10}$, and d is an empirical parameter in the relations. In several field and experimental studies, the range of Q is in the range of $5.0\times10^{-2}\sim400$ pC (Christian et al., 1980; Chauzy & Despiau, 1980; Marshall & Winn, 1982; Dye et al., 1986; Byrne & Jennings, 1993). The value of d can vary between 0 for neutral and ~7 for highly electrified aerosols and raindrops based on the measurements (Pruppacher & Klett, 1997; Andronache et al., 2004, 2006). The parameter $d\sim2$ for average conditions of strongly electrified clouds (Pruppacher & Klett, 1997). Andronache (2004) compared his model's calculated collection efficiency with the experiments. He showed good agreement between the measured and calculated collection efficiency.

The Cunningham correction factor is approximated as (Lee & Liu, 1982):

$$Cc=1+2.493\frac{\lambda}{d_p}+0.84\frac{\lambda}{d_p}\exp\left(-0.435\frac{d_p}{\lambda}\right)\cong1+\frac{3.34\lambda}{d_p} \tag{2}$$