The Influence of Air Flow Velocity and Particle Size on the Collection Efficiency of Passive Electrostatic Aerosol Samplers

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1. THEORETICAL BACKGROUND

Electrostatic precipitators (ESPs) use electrostatic forces to collect charged particles from an air stream (Hinds, 2012). Charging occurs as particles encounter an upstream corona discharge, imposed at a high curvature electrode. The corona, which can be negative or positive, ionizes surrounding air molecules and induces a charge transfer from charged air molecules to aerosol particles through an avalanche effect. A counter electrode forms the collector surface, imposing an electric field that causes the charged particles to migrate and be deposited. Several transport mechanisms occur in an ESP: acceleration of charged particles due to the electric field, Brownian motion, momentum transfer due to particle collisions and forced convection. The former and the latter are expected to dominate the other two in the context of aerosol sampling (Parker, 2003) and therefore only these will be addressed in this study.

Two electrical charging mechanisms affect the particles, field charging and diffusion charging. Field charging of particles occurs via unipolar ions in the presence of a strong electric field (Hinds, 2012). Ionized air molecules accelerated by the field colliding on their trajectory with aerosol particles, which locally deform the electric field in proportion to their relative dielectric constant ε. In the case of field charging, the amount of charge n(t) acquired over time in an electric field E can be estimated as:

$$n(t) = \left(\frac{3\varepsilon}{\varepsilon+2}\right)\left(\frac{Ed_p^2}{4K_e e}\right)\left(\frac{\pi K_E e Z_i N_i t}{1+\pi K_E e Z_i N_i t}\right) \qquad (1)$$

where the electric mobility of the ions is $Z_i \cong 150{*}10^{-6}$ $m^2/V{*}s$ and the relative dielectric constant ε is for instance >80 for salty water. The first two factors in Eq. S1 represent the saturation charge as a function of the dielectric constant, of the particle surface area and of the electric field strength. The last factor represents the charging level until saturation, with the charging rate

mostly depending on the ion concentration. Under a typical ion concentration of 10^{13}/m^3, the time constant is on the order of a few seconds.

Diffusion charging is the charging of particles via random collisions between ionized air molecules and aerosol particles due to Brownian motion and does not depend on the particle material (Hinds, 2012). The amount of charges n(t) acquired through diffusion charging over time t by a particle of diameter d_p can be estimated as:

$$n(t) = \frac{d_p kT}{2K_E e^2} \cdot ln\left(1 + \frac{\pi K_E d_p \bar{c_i} e^2 N_i t}{2kT}\right) \qquad (2)$$

where $\bar{c_i}$ is the the mean thermal speed of the ions, N_i is the concentration of ions and t is the charging time. The $N_i t$ parameters is typically larger than 10^{12} s/m^3 for particles of diameter 0.07 to 1.5 μm and larger than 10^{13} s/m^3 for particles of diameter 1.5 to 40 μm. Finally $K_E = \frac{1}{4\pi\epsilon_0} = 9 * 10^9$ N∗m^2/C^2 is a constant of proportionality, k is the Boltzmann constant, T is the temperature in Kelvin and e is the charge of the electron (Hinds, 2012).

Generally speaking, field charging is dominating for particles >1 μm, while diffusion charging is dominating for sizes <0.1 μm. A more complicated situation occurs for particles in the intermediate size range (0.1 μm < d_p < 1 μm), which acquire charges through both mechanisms.

One can also find an expression for the migration velocity (ω_{th}) of particles with respect to their charge and size as (Parker, 2003):

$$\omega_{th} = \frac{n^{inf}{}_E}{3\pi\eta d_p} * C_0 \approx \frac{E^2 * d_p C_0}{\eta} \qquad (3)$$

where η is the viscosity of the gas medium and $C_0 = 1 + 1.246 * \frac{2\lambda}{d_p} + 0.42 * 2\lambda d_p *$ $\exp(-0.87 d_p / 2\lambda)$ is the Cunningham correction factor for the Stokes drag of small particles, with λ the mean free path of the air molecules. An intrinsic limitation of ESPs is that ω_{th} passes through a minimum for particles size laying between regimes dominated by field and diffusion charging, from 0.1 to 1 μm.

2. REFERENCES

Hinds, W. (2012). Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles. Wiley.

Parker, K. (2003). Electrical Operation of Electrostatic Precipitators. Energy Engineering Series. Institution of Engineering and Technology.