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Penetration of charged particles through metallic tubes

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ABSTRACT

Several theoretical studies have shown that charged particles increased the particle deposition efficiency in cylindrical tubes by image force. Some experimental investigations have also found that the deposition loss increased with increasing aerosol charge. However, the amount of charges on the aerosols or the electrical mobility was relatively low in these previous experimental studies. In order to extend to higher aerosol charge, a TSI vibrating orifice monodisperse aerosol generator was modified to generate 1-μm DEHS aerosols with charge up to 24,000 elementary units. Metallic tubes were employed to exclude the effect of Coulombic force. Tube diameter, tube length, and average velocity in tubes were among the major operating parameters. Aerosol charge was monitored using a TSI electrometer, while a TSI aerodynamic particle sizer was utilized to measure both aerosol concentrations and size distributions upstream and downstream of the tubes. Aerosol deposition loss in the sampling train of the TSI electrometer was measured to back-calculate the average aerosol charge. A closed-form theoretical model, showing the deposition efficiency as a function of particle charge, was validated by the experimental data produced.

The aerosol deposition efficiency increased with increasing aerosol charge and tube length, due to stronger image force and longer retention time, respectively. The deposition efficiency decreased with increasing average velocity because of shorter retention time. Under the same average velocity, the deposition loss decreased with increasing tube diameter because the fraction of aerosols near the inner wall was higher for small-diameter tube than for large-diameter tube. The model developed from parabolic flow showed good agreement with most of the experimental data, except for data of highly charged particles. The discrepancy was probably due to the space charge effect.

1. Introduction

Coulombic and image forces are the two major electrostatic attraction mechanisms, by which a particle can deposit on a collector surface (Yu, 1977). Coulomb's law, describing the electrostatic interaction between electrically charged particle and collector, has been well studied, both theoretically and experimentally. Aerosol deposition by image force has been

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Table 1
Summary of studies on charged particles.

Year	Authors	Charging methods	Particle size (μm)	Elementary units of charge	Electrical mobility (m^2/V s)
1983	Melandri et al.	Corona charging	0.3	30	1.14×10^{-7}
			0.6	−230	4.34×10^{-7}
			1	142	1.61×10^{-7}
1985	Liu et al.	Diffision charging	0.03	1	3.93×10^{-8}
			0.05	2	4.69×10^{-8}
			0.1	3	3.47×10^{-8}
			0.3	10	3.79×10^{-8}
			0.5	17	3.85×10^{-8}
1998	Cohen et al.	DMA	0.02	1	5.92×10^{-8}
			0.125	1	9.22×10^{-9}
2007	Alonso et al.	Corona charging+DMA	0.025	3	1.42×10^{-7}
			0.065	3	5.93×10^{-8}
2008	Ali et al.	Corona charging	2.22	1700	6.41×10^{-7}
2009	Ali et al.	Electrolytic charging	2.7	−45	1.89×10^{-8}
			3.6	580	1.82×10^{-7}
2011	**Present study**	**Induction charging**	**1**	**24,000**	$\mathbf{2.72\times10^{-5}}$

investigated theoretically in several previous studies, which indicate that charged particles enhanced the particle deposition efficiency on a conducting surface (Ljepojevic & Balachandran, 1993; Mayya & Sapra, 2002; Yu & Diu, 1983).

Several experimental studies investigated the charge effect on deposition loss of inhaled aerosol particles in either cast replica or human subjects (Ali et al., 2009, 2008; Bailey, 1997, 1998). Increase in aerosol deposition in human airway was attributed to image force, since the human respiratory tract is conductive in nature. Aerosol deposition was found to be proportional to $(Bp^2)^{1/3}$, where B is the particle mechanical mobility, and p is the number of elementary charges (Melandri et al., 1983).

In general, the experimental data focusing on image force for particle deposition efficiency were rather limited. Moreover, the amount of charges carried by the particles was only about hundreds of elementary charges for micro-meter-sized particles. The electrical mobility of charged particles in those studies was estimated to be lower than 5×10^{-7} (m^2/V s), as summarized in Table 1. The low electrical mobility was apparently due to the limitations of aerosol charging methods, such as corona charging and/or diffusion charging, employed in these studies. In the present study, we adopted an induction method to generate aerosol particles with the amount of charges close to the Rayleigh limit. In addition to the experimental work, a closed-form theoretical model (Chen & Yu, 1993), showing the deposition efficiency as a function of particle charge, was also validated by the experimental data produced in the present study. In this model, the charge particle deposition efficiency (η_e) is expressed as $\eta_e=1-\exp[-(24\kappa)^{1/3}]$ for plug flow, and $\eta_e=\{1-\exp[-(4\sqrt{\kappa})^{1/1.74}]\}^{1.74}$ for parabolic flow, where κ is

$$\kappa=\frac{q^2LC_s}{48\pi^2\varepsilon_0\mu d_pR^3U}$$

in which q is the particle charge, R is the duct radius, r is the radial position of the particle, ε_0 is the permittivity, C_s is the slip factor, μ is the viscosity, d_p is the particle diameter, L is the duct length, and U is the average velocity in the duct.

The competition and interaction between the space charge force and the image force have been studied in detail (Yu, 1977). Fig. 1 shows space charge deposition efficiency vs. κ for $N_0R^3=1$, 10, 100, and 1000 and image charge deposition efficiency (Chen & Yu, 1993) for both parabolic and plug flows. The space charge force gives a larger fractional deposition than that obtained by the image force at N_0R^3 value exceeding 100, where N_0 is initial number of particles per unit volume. However, if the N_0R^3 value is smaller than 10, the image force is dominating.

2. Experimental materials and methods

A vibrating orifice monodisperse aerosol generator (VOMAG; model 3450, TSI, Inc., St. Paul, MN) was modified to generate monodisperse aerosols with uniform charge (Reischl et al., 1977). The VOMAG was modified by replacing the cap over the jet orifice with an insulated aluminum cap, which served as an induction electrode. The polarity and charges on aerosol particles were controlled using a DC power supply (TES 6220, TES Corp., Taipei, Taiwan). A small amount of nitric acid was added to the Di-2-ethylhexyl sebacate (DEHS)–ethanol solution to increase the conductivity, which was crucial to controlling the amount of charges carried by the aerosol particles. In this work, the negatively charged particles were used as the challenge aerosols. The main experimental apparatus was an L-type mixing chamber consisted of an aluminum tube with 100 cm height, 50 cm width and 7.8 cm inner diameter, as shown in Fig. 2. In order to ensure full development of the