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Numerical study of particle motion near a charged collector

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ABSTRACT

The behavior of particles impacting the surface of a charged droplet involves adhesion, rebound, and submersion. In the present study, a numerical model for simulating particle impacts on charged droplets is presented that takes into account the various impact modes. With the droplet considered as a solid boundary, the criterion for rebounding is that the particle's impact angle is <85°. The simulated trajectories of the particles are verified by comparing with experimental data for low-velocity particles to assess the reliability of the model. For impact angles >85°, particles undergo three distinct modes depending on normal impact velocities. The critical velocity of adhesion/rebound and rebound/submersion is used to identify the mode that the particles are undergoing. The criteria are also verified by comparing with analytical data. The results show that the impact angle of particles increases with increasing Coulomb number and decreases dramatically with increasing Stokes number, both of which lead to a high probability for particle rebound.

Introduction

Particulates in air pollution are associated with adverse impacts on human health (WHO, 2011). Currently, about 80% of the global population resides in locations where particulate concentrations exceed the air quality guidelines of the World Health Organization. An estimated 3.2 million premature deaths each year are caused by particulates (Lim et al., 2013; Van Donkelaar et al., 2010). Controlling particulate emission is one of the most direct ways to improve air quality. The wet electrostatic scrubber is a type of efficient hybrid system for particle abatement, which combines advantages of electrostatic precipitators and inertial wet scrubbers, and overcomes many weaknesses of these systems operating independently (Jaworek, Balachandran, Krupa, Kulon, & Lackowski, 2006). The high efficiency of wet electrostatic deposition has been validated theoretically (Adamiak, Jaworek, & Krupa, 2001; Carotenuto, Di Natale, & Lancia, 2010; Dau, 1987; George & Poehlein, 1974; Jaworek, Krupa, & Adamiak, 1996; Jaworek, Adamiak, & Krupa, 1997; Jaworek et al., 2002; Kojevnikova & Zimmels, 2000; Nielsen & Hill, 1976; Pilat, Jaasund, & Sparks, 1974; Wang, Stukel, & Leong, 1986; Yang, Viswanathan, Balachandran, & Ray, 2003; Zhao & Zheng, 2008) or experimentally (Balachandran, Jaworek, Krupa, Kulon, & Lackowski, 2003; Jaworek, Krupa, & Adamiak, 1998; Jaworek, Balachandran, Lackowski, Kulon, & Krupa, 2006; Kraemer & Johnstone, 1955; Krupa et al., 2013; Metzler, Weiß, Büttner, & Ebert, 1997) in previous studies.

The interaction between charged droplets and particles in wet electrostatic scrubbing is usually considered as a two-phase system. Influenced by electrical forces, air drag, gravity, and other forces, particles are deposited onto the charged droplets. Particle capture undergoes two stages: a passage through air and an impact with the surface of a charged droplet. The trajectories of particles moving through the air were observed experimentally by Sumiyoshitani, Okada, Hara, and Akazaki (1984). They suspended a charged droplet over a capillary with particle-laden gas flowing upwards around it. Later, Jaworek, Adamiak, Krupa, and Castle (2001) improved the device by replacing the droplet with a brass ball as a collector to avoid the vibration of the liquid droplet. One benefit of this improvement was that a higher electrical potential can be applied to the collector. Hence, more detailed images were recorded of particle trajectories being influenced by the enhanced electrical forces. However, the behavior of the particle during impact with the liquid surface could not be obtained. Particle trajectories have been numerically simulated by several authors to better understand the wet electrostatic scrubbing process. Various approaches were developed such as assuming the particle-laden gas flow to be ideal (Nielsen & Hill, 1976; Pilat et al., 1974) or viscous and turbulent; treating the collector as stationary or accelerated (Adamiak et al., 2001; Jaworek et al., 1997, 1998; Wang et al., 1986);

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Nomenclature

a	Acceleration (m/s^2)
A	Fitting function
c	Velocity coefficient
C_c	Cunningham slip correction factor
C_D	Drag coefficient
d	Diameter (m)
E	Unit normal vector of surface
E	Electrical field intensity (V/m)
F	Force (N)
F	Force of per unit mass (N/kg)
f_D	Coefficient of drag
g	Gravitational acceleration (m/s^2)
Kc	Coulomb number
L	Wetted length (m)
m	Mass (kg)
n	Number of particles
p	Pressure (Pa)
Q	Charge (C)
R	Radius or distance (m)
T	Time (s)
u	Velocity (m/s)
U	Voltage (V)

Greek letters

α	Location angle of particle (°)
β	Advancing angle of particle (°)
γ	Impact angle of particle (°)
δ	Dimensionless number for predicting the impacting features of particle
ε_0	Permittivity of vacuum (F/m)
λ	Receding angle of particle (°)
μ	Viscosity (Pa s)
ρ	Density (kg/m^3)
σ	Coefficient of surface tension (N/m)
ϕ	Outer diameter of capillary (m)
Φ	Electrical potential (V)

Subscripts

0	Initial condition
c	Collector or critical condition
d	Droplet
e	Electrical mechanism
g	Gas phase
i	Particle index
n	Normal component
p	Particle
r	Rebound of particle
t	Tangential component
D	Drag
β	Advancing angle mechanism
σ	Surface tension mechanism

and simulating particles being attracted by a single collector or an array of collectors (Kojevnikova & Zimmels, 2000).

Nonetheless, from literature reports, the trajectories of the particles were deemed complete on impact with the charged collector; that is, particles were considered to be captured after collision. Indeed, not all particles are captured after impacting the liquid surface. Sumiyoshitani et al. (1984) directly observed that particles (lycopodium clavatum spore) of 32 μm diameter bounced off the surface of a charged droplet. Nevertheless, the criterion in distinguishing capture and rebound behavior after collision was not mentioned. Mikhailov, Vlasenko, Krämer, and Niessner (2001) found that the number concentrations of particles and droplets of diameter between 0.8 and 1.4 μm were increased during the scavenging process. They suggested that particles bouncing off the surface of droplets were responsible for significantly reducing the deposition efficiency of particles. The impact behavior of millimeter-sized particles at the water surface was revealed by Lee and Kim (2008) to be adhesion, rebound, or submersion. The mode that occurred depended on impact velocity. Wang, Song, and Yao (2015) numerically investigated the behavior of particles impacting on a liquid surface through a simplified Young–Laplace equation. Based on the analysis of energy conversion between particle motion and surface tension, criteria associated with the three modes of motion were presented. However, the results were based on normal impacts, and inclined collisions were not considered.

Inclination at impact is one of the most significant factors influencing the rebound. Empirically, rebounding of large spheres such as projectiles off water surface probably happen if the impact angle of the sphere falls below a critical angle $\theta_c = 18^\circ/\left(\rho_s/\rho\right)$ (Johnson & Reid, 1975), where ρ_s and ρ are the densities of the sphere and water, respectively. Clanet, Hersen, and Bocquet (2004) and Rosellini, Hersen, Clanet, and Bocquet (2005) studied skipping stones and found that the optimal impact angle of the stone is 20°. As reported in the literature, spheres bouncing off water surfaces do so predominantly at an inclined impact angle.

In the present study, a more complete numerical model for simulating the deposition of particles onto a charged droplet is presented that considers both normal and inclined impacts, as well as the three modes of motion: adhesion, rebound, and submersion.

Experimental

The experimental setup to study particle attraction using a charged droplet is shown schematically in Fig. 1(a). A syringe containing liquid was fixed in the chamber to generate droplets. A micrometer was mounted onto the syringe to control accurately the size of the droplet. The nozzle was made of a stainless steel plain-orifice capillary with a 0.51-mm outer diameter and connected to a high-voltage power supply with an output regulated up to 1 kV. In consequence, the diameter of the charged droplet was ~1.26 mm. A concave particle plate of curvature 0.5 mm was placed below the capillary to hold the particles and electrically grounded. Hollow glass beads (W.O # 216909, 900890, TSI, USA), of diameter 10 μm and density 1000 kg/m^3, were used in this study. Taking into account the droplet size, the distance from the capillary to the particle plate was set at ~2 mm. The whole apparatus was fixed onto a horizontal base. A high-speed digital camera (I-SPEED 3, Olympus, Japan) with a microscopic zoom lens (NAVITAR12X) was employed to observe the capture process of the particles attracted by the charged droplet. A point source of light (Olympus ILP-2) was used to accommodate the small field of focus.

Because of the electrostatic attraction, particles on the plate moved towards the droplet immediately as a 1-kV voltage was applied. Many particles bounced off the surface of the charged droplet after physical contact. Specifically, the probability of rebound is nearly 50% if the impact angle of the particles is <85° (the impact angle of the particle γ is indicated in Fig. 2). That is, the impact angle of 85° can be considered as a predictive criterion determining the inclined impact behavior of particles. This criterion is similar to that of large spheres (Johnson & Reid, 1975).

From Fig. 1, the distortion seen of the pendant droplet is not significant as the applied voltage is increased up to 1 kV. Thus, the liquid–gas interface can be approximated as an equipotential

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