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Nano-particle deposition in the presence of electric field

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ABSTRACT

The dispersion and deposition of nano-particles in laminar flows in the presence of an electric field were studied. The Eulerian-Lagrangian particle tracking method was used to simulate nano-particle motions under the one-way coupling assumption. For nano-particles in the size range of 5–200 nm, in addition to the Brownian excitation, the electrostatic and gravitational forces were included in the analysis. Different charging mechanisms including field and diffusion charging as well as the Boltzmann charge distributions were investigated. The simulation methodology was first validated for Brownian and electrostatic forces. For the combined field and diffusion charging, the simulation results showed that in the presence of an electric field of 10 kV/m, the electrostatic force dominates the Brownian effects. However, when the electric field was 1 kV/m, the Brownian motion strongly affected the particle dispersion and deposition processes. For the electric field intensity of 1 kV/m, for 10 nm and 100 nm particles, the deposition efficiencies for the combined effects of electrostatic and Brownian motion were, respectively, about 27% and 161.2% higher than the case in the absence of electric field. Furthermore, particles with the Boltzmann charge distribution had the maximum deposition for 20 nm particles.

1. Introduction

It is well-known that air pollutants have serious adverse health effects (Shy, Goldsmith, Hackney, Lebowitz, & Menzel, 1978). Particulate matter (PM), especially nano-particles, can infiltrate deep into the human lung and can cause cancer and other lung diseases (Cohen & Pope, 1995). Therefore, the development of air pollution control devices has attracted considerable attention in recent years (Talebizadeh et al., 2014). For PM removal from the emissions of various types of engines including air-breathing engines, there are a number of devices such as filters, cyclones, non-thermal plasma and electrostatic precipitators (Babaie et al., 2015; Takasaki et al., 2015; Tian & Ahmadi, 2007; Tu, Inthavong, & Ahmadi, 2012; Zheng, Reader, & Hawley, 2004; Zhou, Zhong, & Li, 2017). Gas turbine engines are a source of PM emissions with diameters less than 2.5 µm, which are subject to regulation under the National Ambient Air Quality Standards (George, Verssen, & Chass, 1969). Effective pollution control of gas turbine engines has been a major concern in the design of modern aircraft propulsion systems (Schnelle, Dunn, & Ternes, 2015).

Concerning nano-particles, Brownian diffusion is the main mechanism of particle dispersion and deposition (Guha, 2008; Talebizadeh et al., 2015; Zahmatkesh, 2008). The original model for simulating Brownian motion in the Lagrangian particle trajectory approach was introduced by Li & Ahmadi (1993a) and Ounis, Ahmadi, and McLaughlin (1993). Charged particles are affected

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Nomenclature

C_D	Drag coefficient
C_c	Cunningham correction factor
$\bar{c}_i$	the thermal mean velocity of ions
d_p	particle diameter
D	particle diffusivity
DE	deposition efficiency
e	electric charge unit
E	Electric field intensity
$F_{Coulomb}$	Drag force
F_D	Drag force
F_{Image}	Image force
F_g	Gravity force
h	duct half-width
H	Channel height
L	Channel length
k_B	Boltzmann constant
K_E	constant of proportionality
$\dot{m}_w$	mass deposition rate
$\dot{m}_{in}$	inlet mass flow rate of particles
n	number of electrical charges
N_i	concentration of ions
N_0	Number of injected particles
N_d	number of deposited particles
q	the amount of charge on particles
Q	air flow rate
Re_p	particle Reynolds number
S_0	spectral intensity function
T	absolute temperature
t_d	time duration
u	velocity
u_{av}	Mean fluid velocity
u_d	Deposition velocity
u_d^+	Non-dimensional deposition velocity
u_e^+	the variance of particle location under Brownian excitation
y	Distance from the centre
y_c	distance between the particle centre and the wall
u^*	shear velocity

Greek symbols

ε_0	electric permittivity of vacuum
τ	particle relaxation time
μ_f	fluid viscosity
ρ_f	fluid density
ρ_p	particle density
λ	the mean free path of air
ξ	zero-mean, unit-variance independent Gaussian random number
ν	kinematic viscosity
ε_{D0}	Dielectric constant of the particles
$\bar{\tau}_w$	wall shear stress
σ_s	sedimentation coefficient
$\sigma_y^2(t)$	the variance of particle location under Brownian excitation
Δt	time-step for particle integration

Subscripts

av	average
c	Centre
D	Drag
f	Fluid
P	Particle

Superscripts

—	Mean value

by different electrostatic forces in the presence of an electric field (He & Ahmadi, 1999; Kim et al., 2006; Malekian, Sajadi, Ahmadi, & Pirhadi, 2018; Mayya, Sapra, Khan, & Sunny, 2004). Therefore, the mechanisms of Brownian diffusion and electrophoresis are in competition for transport and deposition of charged nano-particles.

The deposition of charged particles in human airways during inhalation has been extensively studied, and it is shown that electrostatic forces increase particle deposition in human airways (Chan, Lippmann, Cohen, & Schlesinger, 1978; Melandri et al., 1983). Aerosol particles naturally carry a certain number of electronic units of charge according to the Boltzmann charge distribution. When aerosols carry a high level of charge, the electrostatic forces significantly affect the particle deposition rate (Bailey, Hashish, & Williams, 1998). Cohen, Xiong, Fang, and Li (1998) compared the deposition of charged aerosol particles in hollow-cast models of human airways due to the image force. They showed that the deposition rate of 20 nm particles that carry one electronic unit of charge was 3.4 times that of the same size particle that carry the average of Boltzmann charge distribution and 5.3 times the neutral 20 nm particles. Furthermore, many studies on the useful effect of electrostatic forces on deposition of charged particles with the aim of targeted drug delivery were reported in the literature (Koullapis, Kassinos, Bivolarova, & Melikov, 2016; Majid, Winker-Heil, Madl, Hofmann, & Alam, 2016; Ruzer & Harley, 2004).

Charged particle deposition and electrophoretic effects have been also studied extensively in other engineering applications including electrostatic precipitators and filters, particle separation devices and water purification (Besra & Liu, 2007; Jaworek, Marchewicz, Sobczyk, Krupa, & Czech, 2018; Tsai, Kim, Corrigan, Phaneuf, & Zachariah, 2005). In the filters, the electrostatic charging has been used to increase the collection efficiency of particles (Jaworek, Krupa, & Czech, 2007). In electrostatic precipitators, the electrostatic force is the main mechanism for particle removal from the exhaust gas (He, Dass, & Karthik, 2017). Goo and Lee (1997) studied particle deposition in a wire-plate electrostatic precipitator using the Lagrangian particle tracking method. Dixkens and Fissan (1999) studied particle deposition in electrostatic precipitators numerically and experimentally. They considered the effects of diffusion, electrostatic force, thermophoresis and sedimentation, and included the effects of field charging. Yu, Shih, Chen, and Yang (2017) studied deposition of submicron particles in an ionic air purifier experimentally ranging from 30 nm to 300 nm and showed higher deposition of nano-particles with higher dielectric constant. Tu, Song, and Yao (2017); Tu, Song, and Yao (2018) investigated experimentally and numerically particle removal from exhaust flue gas in a novel electrostatic filter using