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Separating polydisperse particles using electrostatic precipitators with wire and spiked-wire discharge electrode design

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ABSTRACT

Numerical simulations of electrostatic precipitators featuring wire and spiked electrode designs were performed to determine particle behavior and separation efficiency. The applied-voltage mechanism that alters the flow structure of particles through ionic winds and mean electric fields are revealed. Numerical studies throughout the past years have shown these structures for channel and pipe configurations. However, less attention was given to field averaging for the $n_{i,\infty}t$-product and electric field. Our study focuses on this averaging and illustrates relevant differences between multidimensional setups concerning these fields. Turbulence was modeled using the Reynolds-averaged Navier–Stokes equations with a second-order Reynolds-stress-model closure. A high three-dimensionality of the ionic wind-induced turbulence is presented. This leads to an increase in the submicron-particle precipitation rate. The results confirm the dependence of separation efficiency on particle density and permittivity, thereby showing the advantages of spiked wires compared with wire-plate setups used in electrostatic precipitators.

Introduction

To reduce threats from environmental pollution, progressively constrictive legal obligations for fine-dust separation of PM_{10}, $PM_{2.5}$, and PM_1 are proposed. Electrostatic precipitators (ESPs) are highly efficient over the range of these particle sizes; they remove for instance fly ash during the cleaning of exhaust gases in industrial machinery such as lignite or bituminous coal-fired boilers and biomass combustion or coal-fired power plants (Dastoori, Makin, Kolhe, Des-Roseaux, & Conneely, 2013; Jedrusik, Swierczok, & Teisseyre, 2003; Lübbert, 2011; Prabhu, Kim, Khakpour, Serre, & Clack, 2012). In addition, the application of ESPs for filter cleaning in street sweepers has been investigated (Kaul & Schmidt, 2015). During the last few years, new insight into dust separation from exhaust gas using ESPs has covering aspects such as high gas temperatures, discharge electrode design, and quenching (e.g., Wen, Wang, Krichtafovitch, & Mamishev, 2015; Xiao et al., 2015).

The ESP dynamics depend on particle charging and field transport. Both phenomena exhibit a variation with local particle position, thus, leading to an effective field particles traverse (Lübbert, 2011). In industrial processes, an applied mathematical model describing the separation efficiency

$$\eta = 1 - \exp\left(-w_{\mathrm{th}}A/\dot{V}\right), \qquad (1)$$

was introduce in Deutsch (1922), where collection area A and flow rate $\dot{V}$ are process parameters. The theoretical migration velocity

$$w_{\mathrm{th}} = q_{\max}E\frac{\mathrm{Cu}}{3\pi\mu d_{\mathrm{p}}}, \qquad (2)$$

depends on the electric field E of the ESP, particle size d_{p}, and maximum particle charge

$$q_{\max} = \left[(1+2\mathrm{Kn})^2 + \frac{2}{(1+2Kn)}\frac{\varepsilon_{\mathrm{r}}-1}{\varepsilon_{\mathrm{r}}+2}\right]\pi\varepsilon_0 d_{\mathrm{p}}^2 E, \qquad (3)$$

where ε_0 is the vacuum permittivity, ε_{r} is the particle relative permittivity, Cu is the Cunningham correction factor and Kn is the Knudsen number.

Numerical models enable the tracking of particles through a channel exposed to an electrode-geometry specified electric field. The effect of different electrode geometry on the overall precipitation was demonstrated experimentally (Jedrusik et al., 2003; Podliński, Niewulis, & Mizeraczyk, 2009). Numerical simulations are usually limited to wire electrodes, as this geometry can be reduced to a 2D structure (Schmid, 2003). Being well studied, such electrodes are a good starting point for a comparison of different

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Nomenclature

A	Collection area (m^2)
b	Ion mobility ($m^2/(V\,s)$)
b	Fitting parameter ($A/(V\,m^2)$), used in Eq. (14)
b	Precipitator plate-to-plate width (m), as shown in Fig. 2
c'	Dimensionless charge
d	Diameter (m)
D	Diffusion coefficient (m^2/s)
e	Electron charge (C)
E	Electric field (V/m)
F	Force (N)
J	Ion flux (A/m^2)
k	Boltzmann constant (J/K)
m	Fitting parameter ($A/(V^2\,m^2)$)
n	Number concentration
q	Particle charge (C)
r	Radius (m)
s	Fitting parameter ($A\,s/(V^2\,m^2)$)
t	Time (s)
T	Temperature (K)
U	Velocity (m/s)
V	Voltage (V)
$\dot{V}$	Flow rate
w	Migration velocity (m/s)
w	Dimensionless charging number
x, y, z	Coordinate directions or length (m)

Greek symbols

∇	Nabla operator
ε_0	Vacuum permittivity (F/m)
ε_r	Particle relative permittivity
η	Separation efficiency
μ	Dynamic viscosity (Pa s)
ρ_E	Space charge density ($A\,s/m^3$)
τ	Dimensionless time

Sub- and superscripts

b	Normal direction
c	Corona, critical
el	Electric
i	Cell indices
max	Maximum
p	Particle
plate	Plate

Dimensionless numbers

CFL	Courant–Friedrich–Levy number
Cu	Cunningham correction factor
Kn	Knudsen number

designs. In recent years, several authors began analyzing more complex geometry design extending their meshes to 3D configurations (Arif et al., 2016; Farnoosh, Adamiak, & Castle, 2010). However, the precipitation curves, e.g., those presented in Deutsch (1922), require the assumption that mean field values remain constant within the ESP, specifically the product $n_{i,\infty}t$ for nano-sized particles and electric field E in case of for micron-sized particles. With the precise tracking of the field data along the particle tracks, which yield charging and acceleration inside the field, the actual particle movement and separation are related to the mean field values and hence the separation efficiency inside the EPSs. The assumptions necessary for integral models can then be examined using numerical models.

Particle transport modeling is based on the Lagrangian movement formulation implemented in the OpenFOAM software (OpenFOAM, 2016). In ESPs, particles are subjected to an additional electric force that depends on their charge. Therein, a new model for particle charging and acceleration resulting from electric forces was implemented in OpenFOAM using the approach of Lawless (1996), involving a unipolar charging model that unites the previous approaches of diffusion and field charging.

Particle charging is governed by particle size and electric field strength. Particles become charged fast if they are either in a high electric field or their surfaces can accommodate many electrons e (high surface area and, therefore, diameters d_p). Fig. 1 shows a comparison of particles in an electric field E for dimensionless charging numbers of

$$w = \frac{\frac{d_p}{2}E}{\frac{kT}{e}}, \tag{4}$$

at a normal temperature $T = 21.5\,^{\circ}C$, where k is the Boltzmann constant. The dimensionless charge is calculated using

$$c' = \frac{ne^2}{2\pi\varepsilon_0 d_p kT}, \tag{5}$$

and the dimensionless time by

$$\tau = \frac{b\rho_E t}{\varepsilon_0}. \tag{6}$$

In principal both expressions are in agreement with simulations (Lawless, 1996). Initially, field charging is the dominant effect responsible for particle charging. At later times field charging becomes less important because surface charges on particles reduce the surrounding electric field and the electrons are more frequently diverted around the particles. For a better understanding of the mechanism, the upper and lower bounds of particle charging are also shown (Fig. 1). The lower bound is obtained assuming only dominant charging takes place. The sum of charges method assumes that diffusive and field charging as described in Lawless (1996) are additive. This solution differs only slightly from the simulation results in this work. When varying the permittivity assumed for particle charging, the saturation charge $3w$ must be recalculated with the quantity

$$1 + 2\frac{\varepsilon_r - 1}{\varepsilon_r + 2}. \tag{7}$$

This factor is a measure of the distortion of the electric field surrounding the particle.

Electrostatic precipitator design

The ESP of this study is a 0.3-m-high and 0.5-m-wide rectangular channel of length 1.2 m (see Fig. 2). The channel walls (top and bottom) are made of acrylic glass. The sides are grounded copper plates. Along the centerline at distances 0.3, 0.6 and 0.9 m from the inlet, three spray electrodes are positioned. This design covers a section of a real-size ESP, where multiple channels of the stated width are joined together to allow higher throughputs of exhaust gas. Stacks of these parallel channels are typically 20–60 times higher and their length varies by a factor of 10–20 to accommodate micron to nano-sized particle precipitation.

Numerical methods

Numerical modeling of the electric fields, charge transport, and retroactive effects on the continuous phase, so-called electric wind, have been performed and improved (Kaiser, 2013; Roghair, van den

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