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Original Research Paper

Numerical simulation on the fine particle charging and transport behaviors in a wire-plate electrostatic precipitator

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ABSTRACT

In this work, an integrated numerical model is presented and validated to investigate the particle charging and transport behaviors in a wire-plate electrostatic precipitator (ESP). Calculations of gas flow, electrostatics field and particle motions are coupled in the model, and the influences of electro-hydrodynamics (EHD) flows are also taken into account. The dynamic charging process of particles was treated with separate field and diffusion charging rates, and the trajectories of particles in the ESP were tracked with a Lagrangian-type method. Numerical results show that electric field strengths and charging ion densities varied largely in the computational domain, and inlet particles were initially charged primarily by diffusion charging mechanism. The particles were then charged to a near-saturation state in the discharging zone, while their transverse velocities showed considerable fluctuations along the trajectories. Numerical results indicate that particles with diameter between 0.2 and 1 μm normally exhibited lowest average transverse velocities, and longer residential time could slightly improve the transverse velocities for all sizes of particles. Moreover, increasing voltages could greatly improve the acquired charges and collecting performances for particles larger than 1 μm, while higher ion current value was more effective in achieving higher collection efficiencies for sub-micron particles.

1. Introduction

Particulate matter, usually described as airborne dispersed solid or liquid particles, is commonly generated in all kinds of industries, such as material processing, power generation and mass transport applications. Along with the rapid industrial and urban developments in many cities in the world, particulate emissions are definitely among the most serious environment problems, which may also cause great health hazards to people, especially for the children and the elderly [1]. Over the years, several kinds of systems and processes have been used for the control of particulate emissions, of which the electrostatic precipitators (ESPs) are most widely used in industries for removing particulate matters from flue gases, mainly due to its higher efficiency, lower resistance and wider adaptability to different kinds of dust particles. However, with increasingly stricter regulations on fine particulate (e.g. $PM_{2.5}$) emission in all industrial applications, the performances of existing ESPs are in great need to be improved, and the charging and collection mechanisms of fine particles in ESPs also need further investigation.

In ESPs, the precipitation process basically involves three highly-coupled fields of gas flow, corona-electrostatics field and particle motions [2]. Due to its complexity, conventional analysis on particle collection process was largely based on simplified theories and empirical correlations, for example, the Deutsch-Anderson equation [3] and the models of Cooperman [4], Leonard et al. [5], and Ortiz et al. [6]. However, with the developments of various numerical techniques, more comprehensive models have been proposed and developed to evaluate the performances of ESPs. McDonald et al. [7] developed one of the first numerical technique on solving the corona-electrostatic field in the precipitators, and Kim [8] presented a numerical model which included a coupled simulation of gas flow and electrostatic fields, and predicted the collection performance of an electrostatic precipitator for polydisperse particles. Later, Nikas et al. [9] and Skodras et al. [10] developed the numerical models with the considering of particle charging dynamics, and analyzed the collection performances of ESPs under certain conditions. Zhang et al. [11] studied the particle-wall collisions between charged particles and collecting plate in an electrostatic precipitator, and a criterion for particle

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adhesion to the collecting plate was proposed. Most recently, Adamiak and Atten [12] presented a coupled numerical model on the simulation of secondary EHD flows caused by corona discharge and charged particles, and Farnoosh et al. [13–16] made detailed investigations on the effects of charged particles and EHD turbulent flow on the gas flow patterns in a spike-plate electrostatic precipitator. Lancereau et al. [17] also studied the influence of secondary EHD flows on the collection efficiency of a cylindrical electrostatic precipitator using a population balance method, while Guo et al. [18,19] further investigated the effects of gas temperature and discharge electrode geometry on the collection performance and electric fields of electrostatic precipitators.

Of previous works, however, most researchers focused on the overall collection efficiencies of relatively large particles, as well as the apparent effects of temperature and secondary EHD flows on the collection performance of electrostatic precipitators. However, more knowledge on the detailed charging and transport behaviors of fine particles in the ESPs, especially those with diameter less than 2.5 μm, are still highly in need. In this paper, a numerical model is presented and validated to systematically investigate and predict the distribution of the corona-electrostatic field, the charging and transport behaviors of fine particles in a wire-plate ESP, as well as the effects of gas velocities, applied voltage and current on the collection efficiencies of particles with different diameters. It is expected that present model could help us to a better understanding of the charging and collection mechanisms of fine particles in the ESPs, and accordingly, could be used to evaluate and facilitate the future designs with more restrictive particle emission control.

2. Numerical methods

This numerical study was based on the simplified geometry model of a typical wire-plate ESP, which is commonly used in industries, with negative high-voltage applied on the discharge electrodes. As the gravitation of the fine particle was considered to be very small order of magnitude in the ESPs, the computational domain was simplified to two dimensions, as shown in Table 1. In this paper, the velocity was set as 1 m/s, and specific collecting area was 13.3 $\text{m}^2/(\text{m}^3\ \text{s}^{-1})$.

2.1. Gas flow field

Due to the small pressure drop and temperature gradient in operation conditions, the air flow inside the ESP was normally treated as incompressible flow, which can be described with the conservation of mass and momentum equations, as Eqs. (1) and (2).

$$\frac{\partial}{\partial x_k}(\rho U_k) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_k}\left(\rho U_i U_k - (\mu + \mu_t)\frac{\partial U_i}{\partial x_k}\right) = -\frac{\partial P}{\partial x_i} + f_{Di} + \rho_{ion} E_i \tag{2}$$

where ρ is the mass density of the gas (kg/m^3), u_i and x_i are the gas velocity components (m/s) and the coordinate (m) at x and y directions, respectively, P is the mean static pressure (Pa), μ is the gas dynamic viscosity (N·s/m^2), f_D is the aerodynamic drag (N), E is the strength of the local electric field (V/m). Besides, due to the existence of space charges in the computational domain, the term of $\rho_{ion}E_i$ counts for the secondary electro-hydrodynamic flow caused by corona discharge and charged particles, and the turbulence kinetic viscosity μ_t was calculated with the RNG k–ε model.

Table 1
Geometry parameters of the computational domain.

Length, L	2000 [mm]
Width, D	300 [mm]
Wire spacing, s	250 [mm]
Wire diameter, d	4 [mm]
Entrance/exit length, L_e	375 [mm]
Specific collecting area, SCA	13.3 $[\text{m}^2/(\text{m}^3\ \text{s}^{-1})]$

2.2. Corona discharge model

The electrostatic field in the precipitator was numerically solved with Poisson's equation, which can be expressed in the terms of electric potential and space-charge density as,

$$\frac{\partial^2 \varphi}{x_k^2} = -\frac{\rho_{ion} + \rho_{pc}}{\varepsilon_0} \tag{3}$$

where φ is the electric potential (V), ρ_{ion} is the space charge density (C/m^3), ρ_{pc} is the charge density of particles (C/m^3), ε_0 is the permittivity of air (C/V·m). Meanwhile, the space charge density ρ_{ion} in Eq. (3) is calculated by the convection-diffusion equation as

$$E_k = -\frac{\partial \varphi}{\partial x_k} \tag{4}$$

$$\frac{\partial}{\partial x_k}\left[\rho_{ion}(k_{ion}E_k + u_k) - D_i\frac{\partial \rho_{ion}}{\partial x_k}\right] = 0 \tag{5}$$

where D_i is the ion diffusion coefficient (m^2/s), k_{ion} is the ion mobility ($\text{m}^2/\text{s·V}$), E_x and E_y are the local electric field strengths at x and y direction (V/m), respectively.

In order to solve these equations, the values of electric potential and space charge density are required to be specified at the boundaries. The electric potential on the electrode surface was assumed constant and equals to the set value, and a zero potential was set at the grounded collecting plates. The current value was used to calculate the ion density on the wire surface as below, and steady state diffusion was assumed on the collecting plates and other boundaries, as is shown in Table 2.

$$\rho_w = \frac{J}{\mu_i E_w} \tag{6}$$

where J is the ion current density on the wire (A/m), and E_w is the electric field strength at the wire surface (V/m).

2.3. Particle motion and charging models

A Lagrangian approach was adopted to calculate the particle trajectory and charging until collection or escape occured. Compared with Eulerian approach, the Lagrangian representation of particles could present a more accurate description on the particle motion and charging process, as well as the collection efficiencies of ESPs.

Under the influence of gas flow and electric field, particles were mainly subjected to both aerodynamics drag and electric forces, and the equation of the particle motion is expressed as,

Table 2
Boundary conditions for present numerical model.

	Gas velocity	Particle motion	Electric potential	Ion density
Inlet	u = 1 m/s	u = 1 m/s	$\frac{\partial \varphi}{\partial x} = 0$	$\frac{\partial \rho}{\partial x} = 0$
Outlet	Pressure outlet	Escape	$\frac{\partial \varphi}{\partial x} = 0$	$\frac{\partial \rho}{\partial x} = 0$
Collecting Plates	No slip	No slip	$\varphi = 0$	$\frac{\partial \rho}{\partial y} = 0$
Discharge wires	No slip	No slip	$\varphi = \varphi_0$	$\rho = \frac{J_0}{\mu_i E_w}$

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