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Insights into the role of particle space charge effects in particle precipitation processes in electrostatic precipitator

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ABSTRACT

Electrostatic precipitators (ESPs) are considered as cost-effective technology for separating the charged particle from flue gas. In this paper, a modified ESP model was developed to investigate the effects of charged particle on the electric field, ion density, particle charging and migration regarding various particle concentrations. Coupled processes of corona discharge, flow field, particle charging and transport were considered. Results showed that the particle space charge presented trajectory-dependent effects on the distributions of electric field and ion density in the gas flow direction. With the particle concentration increasing from 0 to 200 mg/m^3, the electric field strength on the electrode surface was inhibited from 1.32×10^6 to 1.24×10^6 V/m, while the electric field strength on the plate surface was raised from 7.1×10^5 to 8.3×10^5 V/m. By contrast, the ion density within the whole domain decreased when particle space charge considered, and it decreased by more than 40% when the particle concentration was 50 mg/m^3. The particle charging rate decreased due to particle space charge effects and consequently the overall particle charge decreased by 45.7% as particle concentration increased to 200 mg/m^3. The correlation between collection efficiency and corona current was discussed, and it showed that the two didn't vary synchronously with the increasing concentration. A criterion for efficiency deterioration, under corona suppression conditions, was first proposed for instructing ESP design and operation.

1. Introduction

Particulate matter pollution is one of the most important environmental concerns around the world [1–3]. Various technologies have been developed to eliminate particulate emissions, among which electrostatic precipitators (ESPs) are currently the most widespread technology in industries such as power plants, waste incineration, glass production and metallurgical industries [4–6]. However, the designing of ESP primarily relies on empirical approach because particle precipitation is influenced by several coupled processes and thus the designing represents much complexity [7].

Inside an ESP, the electrostatic field is established within the ESP channel, and the flue gas is ionized for particle charging. Afterwards, the charged particle is driven to the collection plate by electric force. Interactions among corona discharge, flow field, particle charging and migration make it difficult to predict the particle collection efficiency [8]. A variety of numerical and experimental studies have been carried out to investigate these processes in the past decades. Corona discharge is a fundamental process for ESPs, which is usually studied under particle free gas conditions [9–11]. Ionic space charge generated by corona discharge is of vital importance in particulate separation process [12]. Gas flow in ESPs is known as electrohydrodynamic (EHD), which is a result of interaction between flow field and ion transport. EHD flow characteristic can be obtained by the method of particle image velocimetry (PIV) [13,14] and analyzed by computational fluid dynamics (CFD) [15,16]. Electrode configuration [17,18] and gas temperature [19–21] are proven to have a substantial influence on EHD flow and the corresponding collection efficiency. As for particle charging and motion, various particle charging models have been developed and evaluated for simulating particle dynamics in ESPs [22], and recent researches mainly focus on fine particle charging and transport behaviors [23,24].

The abovementioned work mainly investigated the complicated processes under particle free conditions or by neglecting the charged particle effects. However, it has been observed in practical applications that the charged particle effects are of vital importance when the particle loading is high [7,25]. Severe current reduction was found when particles presenting in gas [26,27], which was typically called corona suppression or corona quenching. Our recent work indicated that not only corona discharge but also collection efficiency was inhibited with the increasing aerosol concentration [28]. Some researchers have

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Nomenclature

φ	electric potential, V
ρ_{ion}	ion space charge density, C/m^3
ρ_p	particle space charge density, C/m^3
ε_0	permittivity of free space, C/V/m
J	current density, A/m^2
k_{ion}	ion mobility, m^2/s/V
E	electric field strength, V/m
u	gas velocity, m/s
D_i	ion diffusion coefficient, m^2/s
Es	electric field strength on the electrode surface, V/m
E_0	breakdown electric field strength, V/m
m	dimensionless surface parameter
r_0	electrode radius, m
δ	relative gas density
ε_r	relative permittivity
d_p	particle diameter, m
q	particle charge, C
τ	time constant
k_B	Boltzmann constant
e	electronic charge, 1.6×10^{-19}C
T	gas temperature, K
α	model constant
e_{norm}	model constant
q_s	saturation particle charge, C
N_j	number of particles visiting the control volume
k	index of particle
$\Delta\tau$	particle residence time in the cell, s
m_p^k	mass flow rate, kg/s
V_c	cell volume, m^3
ρ_{gas}	gas density, kg/m^3
P	absolute pressure, Pa
μ_{eff}	effective gas viscosity, kg/m/s
m_p	particle mass, kg
u_p	particle velocity, m/s
C_d	drag coefficient
A_p	projected particle area, m^2
Re	Reynolds number
C_m	Cunningham correction factor
λ	mean free path, m
ω	particle migration velocity, m/s
E_p	electric field strength near collection plate, V/m
k_p	particle electrical mobility, m^2/s/V

attempted to investigate the charged particle effects on the flow pattern and the corresponding ESP performance by simulation methods [29–31]. Nevertheless, interactions among flow field, electric field, particle charging and migration are still not clearly understood when the particle diameter is small.

The presence of particles can contribute to the complexity of coupled processes in ESPs, and it can be more severe for ultrafine particles such as sulfuric acid mist even at much lower mass concentrations [25,32,33]. In this paper, we established a comprehensive model to simulate the coupled processes with trajectory-dependent particle space charge calculated by a combined charging model. Results were compared to account for the effects of charged particle on the electric filed and ion density distributions, and their influence on particle charging and migration in turn. Moreover, the correlation between collection efficiency and corona current was discussed under various concentrations and particle sizes. Based on the simulation data, a criterion for performance deterioration under corona suppression conditions, was first proposed for instructing ESP design and operation.

2. Simulation model

2.1. Corona discharge

Inside an ESP, electrostatic field is fundamental for particle separation from flue gas, which is governed by Poisson's equation. It can be numerically solved by calculating the distribution of electric potential and space charge density as follows:

$$\nabla^2\varphi = -\frac{\rho_{ion}+\rho_p}{\varepsilon_0} \tag{1}$$

The space charge density is composed of two components: ion space charge and particle space charge. Typically, the particle space charge density is much smaller than the ion space charge density, and thus many researchers neglect its effects to simplify the calculation as reviewed above. In the present model, the particle space charge is taken into consideration to determine the effects of charged particle on electric field and ion density. It is assumed that ions are produced in the active zone around the discharge electrode and transported towards the collection plates with the Coulomb force. The corona current density generated by ion motion is defined as:

$$J = \rho_{ion}k_{ion}E + \rho_{ion}u\text{-}D_i\nabla\rho_{ion} \tag{2}$$

In this work, the ion mobility of 1.9×10^{-4} m^2/s/V was used for the modelling. The electric field in Eq. (2) is represented by the negative gradient of the potential as follows:

$$E = -\nabla\varphi \tag{3}$$

The corona current is comprised of three parts, and they are drift current ($\rho_{ion}k_{ion}E$), convection current ($\rho_{ion}u$) and diffusion current ($D_i\nabla\rho_{ion}$). The drift effects with the Coulomb force dominate the generation of corona current, and the equation above can be simplified as:

$$J = \rho_{ion}k_{ion}E \tag{4}$$

The simulation is modelled under steady state conditions, and thus the current continuity is satisfied as follows:

$$\nabla J = \nabla(\rho_{ion}k_{ion}E) = 0 \tag{5}$$

The electric potential at the collection plate is set with zero since the plate is always well-grounded. To calculate the ion space charge, the electric field on the surface of discharge electrode is assumed to be constant after reaching the onset voltage, which can be determined by the empirical Peek's formula as shown in Eq. (6). Finally, the ion produced around the discharge electrode can be obtained by iterative procedures.

$$E_S = E_0 m\left(\delta + 0.0308\sqrt{\frac{\delta}{r_0}}\right) \tag{6}$$

2.2. Particle charging

As stated above, the charged particle contributes to the total space charge density. During the simulation, particles entering the ESP are assumed to be spherical and electrically neutral. As particles move through the ESP, they are charged because they are continuously exposed to the ion and electrostatic field. Particle charging can be expressed by two size-dependent charging mechanisms, which are field and diffusion charging. Since particles are simultaneously charged by the two mechanisms, it's complicated to obtain the exact value of the two parts by separated modelling. A combined charging model established by Lawless [34] was used in this study, which have been widely used by researchers [35]. Schmid [36,37] converted its