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Numerical simulation of corona discharge and particle transport behavior with the particle space charge effect

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ABSTRACT

The corona discharge characteristics of an electrostatic precipitator are an important factor that affects particle charging and collection. The electrical characteristics of a wire-plate electrostatic precipitator and the particle transport behavior were studied by considering the electrohydrodynamics (EHD) and the effect of particle space charge through numerical simulation. Simulation results showed that the effect of particle space charge intensifies in extremely small particles, such as submicron particles. This condition significantly influences electric field, ionic charge density, and current. The electric field intensity and ionic charge concentration significantly decreased. The reduction in the minimum field intensity between the electrodes decreased to 50%, and the lowest concentration of the ionic charge tended to 0 when the particle size varied from 5 μm to 0.1 μm. When the applied voltage increased from 13 kV to 40 kV, the space charge ratio of the particles larger than 2 μm was reduced to almost 0 but remained at a high level for the particles less than 0.5 μm whose corresponding current was lower by 20% than that without particle condition. The ionic wind in the electrostatic field also weakened because the movement of ions was restricted for corona suppression, leading to decreased corona current. Furthermore, the particle transport behavior was compared considering the effect of particle space charge. Results indicated that the difference between the two conditions increased from 1.3% to 47.4% with decreasing particle size from 5 μm to 0.07 μm. In addition, the particle migration velocity of the 0.1 μm particles increased by 9.8%, from 0.2 to 0.1 μm, even if the drag force was reduced when considering the particle space charge. A modified I–V equation was provided, with fitting coefficient of 0.996, and is thus worthy of reference in practical application.

1. Introduction

In recent years, pollutant emissions have gained increasing attention due to industrial development worldwide. Particulate matter (PM) is often emitted through industrial production, material processing, and material transportation processes. PM, which is often suspended in the atmosphere after emission, can be inhaled into the lungs by humans and causes various respiratory diseases (Biswas & Wu, 2005; Davidson, Phalen, & Solomon, 2005). An electrostatic precipitator (ESP) is an effective technology used to remove particles and is widely used in tail gas treatments in industrial production facilities, such as in coal-fired power plants, due to its low pressure drop, high efficiency, and wide range of adaptability (Oglesby & Nichols, 1978; Parker, 1997). In an ESP, the removal of

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particles involves many complicated physical processes, namely, ionization of air and electron avalanche and the charging and transport of particles. Among these processes, the corona discharge characteristic is one of the main factors that affect PM removal. The electric field distribution and ionic charge density distribution in an electrostatic field directly affect the particle charge and migration. Therefore, the electric field strength and ionic charge density should be improved to enhance PM removal.

Corona discharge has been investigated by simulation and experimental methods in an electrostatic field. Kaci et al. (Jędrusik & Świerczok, 2013; Kaci, Said, & Laifaoui, 2015; Wang, Chang, & Xu, 2016) studied the influence of the electrode configuration on the stability and distribution uniformity of a corona current. Yan, Zheng, and Zhu (2016) presented the influence of gas electronegativity on corona discharge. The results showed that the high electronegativity gas had significant electron adsorption capability, which led to the decrease in the corona current. Ulrich Riebel et al. Riebel, Radtke, and Loos (2002) studied the corona discharge characteristics of ESP with glycerol aerosol. They found that the corona onset voltage increased and the corona current significantly decreased after the glycerol steam was injected into the system. A numerical simulation of the discharge characteristics and particle motion in the ESP was developed and prediction of the ESP removal efficiency was performed to further study the working conditions of an ESP (Guo, Su, & Yang, 2017; Kim, Park, & Lee, 2001; Lu, Yang, & Zheng, 2016; Luo, Li, & Zheng, 2015; Ortiz, Navarrete, & Cañadas, 2010). The simulation of an ESP was based on an empirical formula with many assumptions due to limited computing capabilities, which included the removal of the efficiency equation by Deutsch and the electric potential model and electric field developed by Cooperman (1963) (Hinds, 1998). With the development of improved computers and of related theories, some convenient and accurate calculation tools were used in the numerical simulation, including computational fluid dynamics (CFD), which is useful for the EHD model in the ESP (Guo, Yang, & Xing, 2013; Skodras, Kaldis, & Sofialidis, 2006). Talaie (2005); Talaie, Taheri, & Fathikaljahi (2001) studied the gas flow field and particle charging in an electrostatic field and proposed a variation law for the corona zone with voltage and particle concentrations. They further predicted the threshold of spark discharge while considering the expansion of the corona zone. Neimarlija, Demirdžić, and Muzaferija (2011) presented the influence of collecting plate configuration in the ESP on the related flow field and electric field distribution. Adamiak & Atten, (2009) (Farnoosh, Adamiak, & Castle, 2011) developed ESP models in two and three dimensions while considering EHD, which showed the variations in particle concentration in the vortex and in the flow field. The vortex further affected the particle charging and collection process. Guo & Yu (2014), Guo, Guo et al. (2014), Guo, Yang, & Su, 2016) carried out further studies on the influence of the temperature and the electrode configuration of an ESP on the electric field and particle removal efficiency.

However, the space charge density produced by the charged particles becomes extremely dense when the high concentration stream of small particles, such as sulfuric acid aerosol, was injected into the ESP. Thus, the original electrostatic field was distorted by the induced electric field of the particle space charge, thereby leading to a decrease in the corona current and the particle removal efficiency (Sproull, 1963). Most of the studies focused on the electrical characteristics in a low particle space charge and some superficial phenomena in the experimental research. Thus, the mechanism of the particle space charge effect cannot be interpreted in detail. Thus, the electrical characteristics and particle transport behavior under the condition of high particle space charge density should be studied through a numerical method. A modified model was developed by considering the particle space charge effect. The electric field distribution, ionic charge density distribution, ionic wind effect, and particle transport behavior in an electrostatic precipitator were investigated. The results revealed the effective mechanism of high concentration submicron particles on the corona discharge characteristics in an electrostatic precipitator. An empirical equation for I-V characteristics was obtained to predict the working state of the electrostatic precipitator under corona suppression conditions.

2. Numerical method

The numerical study was based on a simplified geometry model of a typical wire-plate ESP, and the geometry parameters are shown in Table 1. The theoretical analysis focused on the gas flow, electric field, space charge, and particle charging described by their governing equations.

2.1. Gas flow

The RNG k-ε model was used for a steady-state turbulent flow. The continuity and momentum equations are shown as follows:
Conservation of mass:

$$\nabla\cdot(\rho_f \overrightarrow{V_f}) = 0 \tag{1}$$

Conservation of momentum:

Table 1
Geometry parameters of the computational domain.

Length, l:	0.36 [m]
Wire-plate spacing, w-	0.06 [m]
Wire diameter, d:	0.002 [m]
Wire spacing, s:	0.09 [m]
Entrance/exit lengths:	0.09 [m]