Computational Fluid Dynamic Modelling of Particle Charging and Collection in a Wire-to-Plate Type Single-Stage Electrostatic Precipitator

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ABSTRACT

Electrostatic precipitators (ESPs) have been widely used to control particulate pollutants, which adversely affect human health. In this study, a computational fluid-dynamic model for turbulent flow, particle trajectory, and particle charging in ESPs is presented using a pre-developed corona discharge model (Kim et al., 2010), wherein electric field and space charge distributions in the plasma region are numerically calculated. The ESP under consideration is a wire-to-plate single-stage ESP, which consists of a series of discharge wires and two collecting plates. Two different kinds of particulates are considered in this study; fly ash and sucrose particles. Fly ash was selected because many ESPs have been utilized in coal-fired power plants to capture fly ash particles generated from combustion. Sucrose was selected to compare our numerical calculation results with experimental data found in literature. The electrical characteristics of the ESP, particle trajectories, particle charge numbers, and collection efficiencies under various operating conditions are demonstrated. For fly ash, the overall collection efficiencies based on particle mass are 61, 86, 95, and 99% at 45, 50, 55, and 60 kV, respectively, at a flow velocity of 1 m s⁻¹.

Keywords: Electrostatic precipitator; Corona discharge; Plasma region; Particle charge; PM₂.₅.

INTRODUCTION

Removal of particles smaller than 2.5 µm in diameter (PM₂.₅), which are considered as risk factors of diseases, has gained considerable attention (Wen et al., 2015). Electrostatic precipitators (ESPs) have been widely used to remove airborne particles in common industrial particulate control system owing to its high efficiency under low pressure drop (Huang and Chen, 2002; Lin and Tsai, 2010; Ruttanachot et al., 2011; Zhu et al., 2012). The potential of this technique has been established by industries; however, the technique exhibits certain limitations, including a low collection efficiency of submicron particles (Gouri et al., 2013).

In a wire-to-plate type single-stage ESP, space charges are formed by air ions generated as a result of corona discharge when a high voltage is applied between discharge wires and grounded collecting plates. The particles in the flowing gas are charged by the space charges and then collected on the ground plates by an electrostatic field. Because experimental investigation of ESPs is expensive (Adamiak, 2013), numerical analysis has been widely used for design and performance evaluation purposes. The electrostatic precipitation involves a complex interactive physical process among turbulent flow, electric field, space charge distribution and particle charging and motions. Modelling of corona discharge is complicated and challenging even for a straightforward electrode configuration (Adamiak, 2013). Talaie et al. (2001b) developed a corona discharge model based on the fact that increasing the applied voltage increases the plasma region, where ions are generated owing to electron-impact reactions around a discharge wire. Ion density values at the plasma boundary were calculated by empirical equations. Chen and Davidson (2002) numerically investigated the one-dimensional corona plasma region around a discharge wire by considering Kaptzov’s hypothesis. They reported that the ion densities remained relatively constant in the plasma region. In a study of our group (Kim et al., 2010), a computational methodology was proposed for calculating the plasma region thickness based on the study of Chen and Davison (2002). The ion densities were obtained using an analytical method and were defined both at the plasma boundary and within the plasma region. Kim et al. (2010) applied their methodology to wire-to-duct ESP, and the results were in reasonable agreement with experimental data of previous studies (Penney and Matick, 1960; MacDonald et al., 1977; Lawless and Spark, 1980; Ohkubo et al., 1986) with various geometries.

For analysis of particle charging and motion in the ESP, the Lagrangian approach has been widely used with corona
Gas Flow Field

For incompressible flow, the equations of continuity and momentum with electrical body force ($F_e$) can be expressed as follows:

$$\nabla \cdot \vec{u} = 0$$  \hspace{1cm} (1)

$$\rho \vec{u} \cdot \nabla \vec{u} = \nabla \left( -pI + \left( \mu + \mu_r \right) \left( \nabla \vec{u} + \left( \nabla \vec{u} \right)^T \right) \right) + F_e$$  \hspace{1cm} (2)

$$F_e = q \vec{E}$$  \hspace{1cm} (3)
corona discharge. The particle charge number \( n_p \) is estimated using diffusion and field charging theories (Reist, 1993):

\[
\frac{dn_d}{dt} = n_d + n_f
\]

\[
\frac{dn_f}{dt} = \pi K_b e Z / N_f \left( \frac{1}{n_f} \right)^2
\]

\[
\frac{dn_s}{dt} = 0
\]

\[
n_p = n_d + n_f
\]

\[
dn_d = \pi d^2 e Z / N_d \exp \left( -2n_f K_b e^2 \right)
\]

\[
dn_f = \pi K_b e Z / N_f \left( \frac{1}{n_f} \right)^2
\]

\[
n_s = \frac{3e_p E d^2}{e_p + 2K_e e}
\]

where \( n_d \) is the number of charges on a particle by diffusion charging, \( n_f \) is the number of charges on a particle by filed charging, \( n_s \) is the saturation charge attained after sufficient time at a specified charging condition, \( K_b \) is the Boltzmann constant, \( T \) is the absolute temperature, \( K_e \) is the constant of proportionality = \( 1/4\pi e_0 \), \( e_0 \) is the permittivity of vacuum, \( c_i \) is the mean thermal speed of air ions (240 m s\(^{-1}\) at 298 K and 1 atm), \( N_f \) is the ion number concentration (assumed as \( N_f = q/e \)), \( t \) is the residence time, \( Z_i \) is the ion mobility (1.4 m\(^2\) V\(^{-1}\) s\(^{-1}\) of positive ions) and \( e_p \) is the relative permittivity of the particle.

**Electric Field and Space Charge Distributions**

The distributions of electric potential \( V \) and ionic current density \( j \) are governed by the Poisson equation and charge conservation equation as follows:

\[
\nabla^2 V = -\frac{q}{\varepsilon_0}
\]

\[
\nabla \cdot j = 0
\]

For a uniform temperature and by omitting the diffusion effect, the ionic current density is defined as follows:

\[
j = q \left( \bar{u} + Z_i \bar{E} \right) \approx qZ_i \bar{E}
\]

where \( \bar{E} = -\nabla V \). The flow velocity \( \bar{u} \) is omitted in this study as it is negligible (under 10 m s\(^{-1}\)) compared to the ion velocity \( Z_i \bar{E} \), in the order of \( 10^6 \) m s\(^{-1}\). Once \( j \) is obtained, the electric current can be calculated by integrating Eq. (15) over the area of the ground electrode.

**MODEL DESCRIPTION**

In order to validate the proposed CFD model, the electrodes configuration and experimental data of Lawless and Sparks (1980) were used. They performed experiments on a high-voltage corona wire-to-plate configuration in the absence of particles.

The geometry configuration and computational region of this study are illustrated in Fig. 1 (eight discharge wires and two collecting plates). The wire-to-plate distance \( S \), wire-to-wire distance \( D \), wire radius \( r_w \) and duct length \( L \) were 114.3 mm, 228.6 mm, 1.59 mm and 1.8288 m, respectively. The plasma boundary was located at distance \( r_p \) from the...
The radius \( r_p \) of the plasma region is defined such that the reduced electric field strength \( \frac{E}{N} = \frac{Td}{N} \) is higher than 120 Td \( (N \) is the neutral gas density, which can be obtained from the ideal gas law) (Grabarczyk, 2013). The computational region contained 37,392 meshes with a quadratic shape (See Fig. 2). The mesh located in the proximity of a wire was substantially refined to 25 µm owing to the large gradient of the electric potential in the proximity of the wire.

Boundary conditions used in this study are summarized in Table 1. \( v_a \) and \( V_a \) represent the inlet gas flow velocity and applied voltage on a wire, respectively. \( q_a \) is the charge density in the plasma region. The initial particle charge number was assumed to be zero.

The semi-implicit method for pressure-linked equations (SIMPLE) algorithm was used to specify pressure-velocity coupling in the equations of continuity and momentum. In order to solve the coupling of the Poisson equation and charge conservation equation for specified applied voltage, the discharge model presented by Kim et al. (2010) was used.

Two different particles were considered in this study; fly ash and sucrose particles. ‘Fly ash’ was selected because many ESPs have been utilized in coal-power plants to capture fly ash particles generated from combustion. ‘Sucrose’ was selected to compare our numerical calculation results with experimental data of Huang and Chen (2002). Huang and Chen (2002) carried out a controlled experimental study as part of their health and toxicological studies to understand the behaviour ultrafine particles (diameter < 100 nm) in ESPs.Sucrose aerosols of about \( 1.2 \times 10^5 \) numbers cm\(^{-3} \) in total number concentration, 42 nm of geometric mean diameter (GMD), and 1.8 of geometric standard deviation were generated with an electrospray aerosol generator. Using these sucrose aerosol particles, Huang and Chen (2002)...

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**Table 1. Boundary conditions.**

<table>
<thead>
<tr>
<th>Equations</th>
<th>Inlet</th>
<th>Outlet</th>
<th>Symmetric</th>
<th>Discharging wire</th>
<th>Collecting plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuity and Momentum</td>
<td>( u = u_a )</td>
<td>( p = 1 ) atm</td>
<td>( \frac{\partial}{\partial y} u = 0 )</td>
<td>( u = 0 )</td>
<td>( u = 0 )</td>
</tr>
<tr>
<td>Poisson</td>
<td>( \frac{\partial}{\partial x} V = 0 )</td>
<td>( \frac{\partial}{\partial x} V = 0 )</td>
<td>( \frac{\partial}{\partial y} V = 0 )</td>
<td>( V = V_a )</td>
<td>( V = 0 )</td>
</tr>
<tr>
<td></td>
<td>( \frac{\partial}{\partial x} q = 0 )</td>
<td>( \frac{\partial}{\partial x} q = 0 )</td>
<td>( \frac{\partial}{\partial y} q = 0 )</td>
<td>( q = q_a )</td>
<td>( \frac{\partial}{\partial y} q = 0 ) (In the plasma region)</td>
</tr>
<tr>
<td>Charge conservation</td>
<td>( \frac{\partial}{\partial x} V = 0 )</td>
<td>( \frac{\partial}{\partial x} V = 0 )</td>
<td>( \frac{\partial}{\partial y} V = 0 )</td>
<td>( V = V_a )</td>
<td>( V = 0 )</td>
</tr>
<tr>
<td></td>
<td>( \frac{\partial}{\partial x} q = 0 )</td>
<td>( \frac{\partial}{\partial x} q = 0 )</td>
<td>( \frac{\partial}{\partial y} q = 0 )</td>
<td>( q = q_a )</td>
<td>( \frac{\partial}{\partial y} q = 0 ) (In the plasma region)</td>
</tr>
<tr>
<td>Motion of particle</td>
<td>( u_p = 0 )</td>
<td>( u_p = 0 )</td>
<td>( \frac{\partial}{\partial y} u_p = 0 )</td>
<td>( u_p = 0 )</td>
<td>( u_p = 0 )</td>
</tr>
</tbody>
</table>

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**Fig. 2.** Computational domain: (a) Meshes in total domain; (b) Meshes in a single wire domain.
carried out performance tests of their Lab-made ESPs. The relative permittivity ($\varepsilon_r$) and the mass density of sucrose particles were assumed as 3.3 and 1.59 g cm$^{-3}$, respectively. The geometric mean diameter of fly ash particles was assumed as 0.1 µm based on the experimental results of Strand et al. (2002). The relative permittivity and the mass density of fly ash particles were assumed as 3.0 (Baoyi et al., 2012) and 2 g cm$^{-3}$ (Ghosal and Self, 1995), respectively.

The number distribution of particles of size $d_p$ that enter the ESP was assumed to be a log-normal distribution:

$$df_s = \frac{1}{\sqrt{2\pi} \ln \sigma_g} \exp \left( -\frac{(\ln d_p - \ln \text{GMD})^2}{2(\ln \sigma_g)^2} \right) d\ln d_p \tag{16}$$

where $\sigma_g$ is the geometric standard deviation, which was assumed to be 2.0 (Ghosal and Self, 1995). The number distribution was also converted into the mass distribution using the following equation:

$$df_m = \frac{m_i}{M} df_s \tag{17}$$

where $m_i$ is the total mass of the particles in group $i$, and $M$ is the total mass of all the groups ($= \sum m_i$).

RESULTS AND DISCUSSION

Numerical calculations were conducted for various applied voltages in the range of 45–60 kV and various duct flow velocities in the range of 0–8 m s$^{-1}$. The temperature and pressure were 293 K and 1 atm, respectively. For each flow velocity, the spatial distributions of voltage and electric field between the eight discharging wires and a collecting plate were obtained by solving the Poisson equation (Eq. (3)) as well as the Laplace equation ($q = 0$ in Eq. (3)). The spatial distributions of voltage are illustrated in Figs. 3(a) and 3(b), respectively, for distributions of voltage are illustrated in Figs. 3(a) and 3(b), respectively. The relative permittivity and the mass density of fly ash particles were assumed as 3.0 (Baoyi et al., 2012) and 2 g cm$^{-3}$ (Ghosal and Self, 1995), respectively.

The phenomenon occurs in the presence of space charges as the net electric field formed at any location is equal to the vector sum of ± Y direction fields produced by all the space charges (Superposition principle). The results presented in Fig. 3(d) were in reasonable agreement with those of previous studies (Sekar and Stomberg, 1981; McLean, 1988).

The charge density ($q$) distribution when the applied voltage was 60 kV is presented in Fig. 4(a). The variation of charge densities at $X = 0$ along the Y-axis under various voltages is illustrated in Fig. 4(b). The current densities at the collecting plates were also calculated for various applied voltages (see Fig. 5). The results were in agreement with the experimental data of Lawless and Sparks (1980), which was also verified by Kim et al. (2010).

Fig. 6 illustrates trajectories of fly ash particles under various applied voltages when the flow velocity was 1 m s$^{-1}$. Three particles each of size 0.1 µm entered the ESP at three positions, namely position #0 ($Y = 0$), position #1 ($Y = 28.6$ mm) and position #2 ($Y = 57$ mm), respectively. Each trajectory of these three particles are represented as P0, P1, and P2, respectively. Each particle gradually acquired space charge as the particle advanced with the flow along the X-direction and approached the collecting electrode located at $Y = 114.3$ mm (see Fig. 2). The applied voltage was 45 kV, all the three particles finally escaped from the ESP; however, all of those particles were captured when the applied voltage increased to 60 kV.

Fig. 7 illustrates that these three particles gradually acquired space charges when they advanced along the X-direction. The particle migrating in the proximity of the discharging wire (injected at position #0) carried a higher charge than the other two particles (injected at positions #1 and #2) owing to the stronger electric field (~5 MV m$^{-1}$; see Fig. 3(d)) and higher charge density (see Fig. 4(b)). The charge numbers of particles injected at positions #1 and #2 were approximately equal as these two particles passed through regions which had similar electric fields; for example, when the applied voltage was 60 kV, the electric field in 40 mm < $Y$ < 114.3 mm varied from 0.38 MV m$^{-1}$ to 0.47 MV m$^{-1}$ (see Fig. 3(d) and Eq. (12)).

Fig. 8(a) presents the collection efficiency of ESP for 0.1 µm particles (fly ash) under various flow velocities and various applied voltages. The collection efficiency is defined as

$$\eta\% = \frac{N_t}{N_i} \times 100 \tag{19}$$

where $N_t$ and $N_i$ are the number of particles trapped on the collecting plate and the number of particles injected to the inlet, respectively. Two hundred particles were injected to calculate the collection efficiency. For any applied voltage, the collection efficiency decreased exponentially as the

density at 1 atm and 25°C. For the geometry configuration used in this study, Eq. (18) results in 5.49 MV m$^{-2}$, which is approximately equal to the calculated value (5.33 MV m$^{-2}$).

It is noteworthy that in Fig. 3(d), the electric field decreases in the proximity of the discharge wire and increases in the proximity of the collecting plate, when compared to Fig. 3(c).

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flow velocity increased. These results can be substantiated
with the Deutsch-Anderson equation (Hinds, 1999), which
is expressed as follows:

$$\eta = 1 - \exp \left( -\frac{2WL}{US} \right)$$ (20)

where \( U \) is the flow velocity. The electrical migration velocity
(\( W \)) is expressed as \( W = Z_pE \); here, \( Z_p \) is the electrical
mobility, which is defined as follows:

$$Z_p = \frac{n_e e C_i}{3\pi \mu d_p}$$ (21)

When the flow velocity increases, the residence time
decreases, and therefore, the charge number decreases (see
Eqs. (9)–(12)). The decrease in charge number results in
the decrease of electrical mobility, electrical migration
velocity and collection efficiency.

Fig. 8(b) presents the collection efficiencies of ESP for
various fly ash particle sizes and various applied voltages
at flow velocity of 1 m s\(^{-1}\). The collection efficiency trend
followed that in literatures (McLean, 1988; Yoo \textit{et al}., 1997;
Ylätalo and Hautanen, 1998; Huang and Chen, 2002). The
efficiency was the minimum for particle sizes of 0.2–0.3 µm
regardless of the applied voltage. For example, when the
applied voltage was 60 kV, 0.1 µm particles and 0.5 µm
particles had highly similar collection efficiencies, 72% and

Fig. 3. Electrical characteristics: (a) Voltage distribution solved by Laplace equation at 60 kV of applied voltage;
(b) Voltage distribution solved by Poisson equation at 60 kV of applied voltage; (c) Variations of electric field solved by
Laplace equation along Y-axis for various applied voltages; (d) Variations of electric field solved by Poisson equation
along Y-axis for various applied voltages.
68%, respectively, notwithstanding the significantly dissimilar charge numbers, 4.17 and 44.24, respectively. However, it is interesting to note that the 0.1 µm particles and 0.5 µm particles had highly similar electrical mobilities ($Z_p$) of 115 µm² V⁻¹ s⁻¹ and 109 µm² V⁻¹ s⁻¹, respectively.

For particles smaller than 0.2 µm, diffusion charging is the predominant mechanism even in the presence of electrostatic fields. Moreover, the particle charge ($n_p$) is proportional to $d_p \ln(1 + \alpha d_p)$, where $\alpha$ is the constant related to ion-particle collisions. Considering that the Cunningham correction factor can be approximated as $3.69 (\lambda/d_p)^{1/2}$ for the intermediate range of $\lambda/d_p$ (Lee and Liu, 1980), the particle
mobility ($Z_p$) is proportional to $d_p^{-1/2}$ for $d_p < \sim 200$ nm, and therefore, $\eta$ decreases as $d_p$ increases. For particles larger than approximately 200 nm in diameter, field charging is the dominant mechanism, and $n_p \sim d_p^2$. Therefore, the particle mobility is proportional to $d_p^{1/2}$ for $d_p > \sim 200$ nm, and hence, $\eta$ increases as $d_p$ increases. As the applied voltage increases, the collection efficiencies also increase notwithstanding the sizes of particles because of the higher particle charging.

The correlations between the electrical mobility and collection efficiency at various applied voltages are illustrated in Fig. 9. A linear correlation was obtained for each applied voltage. For $|2WL/US| \ll 1$ ($\sim 10^{-6}$ in this study), the Deutsch-Anderson equation (Eq. (20)) is expressed as follows, from the Tayler series;

$$\eta \approx \frac{2L}{US} W = \frac{2L}{US} Z_p E$$

(22)

Therefore, the collection efficiency increased linearly with electrical mobility under constant applied voltage. The rate of increase becomes higher with applied voltage.

Fig. 10 illustrates the effect of ESP on fly ash particle number and mass distributions under various applied voltages at flow velocity of 1 m s$^{-1}$. The overall collection efficiencies based on particle number were 30, 54, 75 and 90% at applied voltages of 45, 50, 55 and 60 kV, respectively. At the
downstream, the proportion of 0.2–0.3 µm particles increased owing to their low collection efficiency. As the emission regulations of PM are typically based on mass, the particle number distribution was converted into mass distribution. Then, the mode diameter of the upstream particles was shifted to 3 µm. The overall collection efficiencies based on particle mass were 61, 86, 95 and 99% at 45, 50, 55 and 60 kV, respectively. Similar plots could be prepared for the various flow velocities.

So far, our CFD model for turbulent flow, particle trajectory, and particle charging was applied to a wire-to-plate type single-stage ESP which consisted of a series of eight discharge wires and two collecting plates. With fly ash particles having a log-normal size distribution (GMD = 0.1 µm, geometric standard deviation = 2.0), the electrical characteristics of the ESP, particle trajectories, particle charge numbers, and collection efficiencies under various operating conditions were demonstrated.

Our CFD model was also applied to another wire-to-plate type single-stage ESP (three discharge wires and two collecting plates) which was used in an experimental study of Huang and Chen (2002). In their study, sucrose aerosols having a log-normal size distribution (GMD = 42 nm, geometric standard deviation = 1.8) were used. The wire-to-plate distance ($S$), wire-to-wire distance ($D$), wire radius ($r_w$) and length of collecting plate ($L$) were 60 mm, 42 mm,
Fig. 10. Particle distributions of fly ash particles under various applied voltages at upstream and downstream of the ESP at flow velocity 1 m s\(^{-1}\); (a) Number; (b) Mass.

Fig. 11. Calculated and experimental collection efficiencies for different particle diameters under different applied voltages. 0.3 mm and 300 mm, respectively. The air flow rate and the applied voltage were 100 L min\(^{-1}\) and 26.4 kV, respectively. Fig. 11 shows experimental data of the upstream and downstream size distributions of sucrose aerosols as well as collection efficiencies for different particle sizes. Fig. 11 also shows that our CFD calculation results were in good agreements with the experimental data of Huang and Chen (2002).

It should be noted that the effect of humidity (water vapour concentration) on corona discharge was not considered in our CFD model. In a real situation, the corona onset voltage decreases with the increase of water vapour concentration. Therefore, a correction function of water vapour concentration should be added to a conventional Peek formula (Wang and You, 2013).

CONCLUSIONS

A CFD model for turbulent flow, particle trajectory, and particle charging was developed and applied to two different wire-to-plate single-stage ESPs. Particle trajectories, particle charging, and collection efficiencies were simulated for various flow velocities, particle sizes, and applied voltages. The results were in reasonable agreement with those of previous studies. Two kinds of particulates were considered in this study; fly ash and sucrose, which possess different surface properties and carry different levels of charges. The differences in size, density, and relative permittivity affected particle charging, trajectories, and collection efficiencies. The proposed model can be used to design ESPs for removing or sampling particulate materials in the air.
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