Dust collection simulation inside a wire-pipe type electrostatic precipitator system

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Abstract: The collection mechanism inside the Electrostatic Precipitator System (EPS) is determined by the electric field, the fluid flow and the particle motion. In this study, the collection phenomena inside a wire-pipe type EPS were simulated by coupling the Electrohydrodynamics (EHD) simulation with the particle dynamics. The presented numerical method was verified by comparing to the analytical solution for an electric field and to the available numerical results for a dust collection of wire-plate type EPS. From the present EHD simulation, the collection mechanism of the wire-pipe type EPS was investigated for various operating conditions.

Keywords: EHD; electrohydrodynamics; electrostatic precipitator; corona discharge; electric field; fluid flow; particle motion.


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1 Introduction

Dust pollutants arising from multi-storey buildings and tunnels have harmful health effects on the respiratory system of humans, and it can also cause various problems in the ventilation systems. Among several methods available to reduce these pollutant dust particles, the electrostatic precipitator has been widely used in the ventilation systems. The dust collection phenomenon due to corona discharge inside an electrostatic precipitator is a consequence of fluid flow and particle motion affected by the electric field. Hence, the understanding of these mechanisms is important to investigate the collection characteristics of the electrostatic precipitator.

To examine the dust collection phenomena inside the electrostatic precipitator, several studies have been carried out previously. Townsend (1914) analytically studied the unipolar corona phenomena in the cylindrical geometry. Janischewskyj and Gela (1979) proposed the analytical solution for the electric field between coaxial cylinders.
These analytical studies provided the exact solution of the electric field inside the electrostatic precipitator. However, these studies can be applied only to the simple geometry and have limited operating conditions.

For the complex geometry and diverse operating conditions of the electrostatic precipitator, various experimental studies have been performed. Jedrusik et al. (2001) experimentally analyzed the collection speed of the particle inside the electrostatic precipitator. Jedrusik et al. (2003) also studied the collection efficiency of the electrostatic precipitator with various types of discharge electrodes. Chang et al. (2006) performed the experiments on the fluid flow in the electric field around the cylinder-type discharge electrode applying the corona discharge. These experimental studies can be used to evaluate the overall performance of the specific precipitator. However, the experimental studies cannot provide the details of the dust collection mechanism, which is useful in designing the precipitator.

Recently, the development of CFD enables us to predict the dust collection phenomena by modeling the detailed physics and geometry of the precipitator. From the literature, several numerical studies can be found, which numerically analyzed the dust collection phenomena inside the electrostatic precipitator. Anagnostopoulos and Bergeles (2002) numerically analyzed the electric field due to the corona discharge with the wire-duct type electrostatic precipitator. Nikas et al. (2005) simulated the fluid flow and the particle motion inside the electrostatic precipitator with various types of the discharge electrode. Yamamoto et al. (2006) simulated the electric field and the fluid flow with point-type discharge electrode. Fujishima et al. (2004) analyzed the characteristics of the electrostatic precipitator with the spiked-type discharge electrode. In these previous numerical studies, no interaction between the electric field, the fluid flow and the particle motion has been considered for the dust collection phenomena because the interaction does not significantly affect the characteristics of the precipitator. However, the coupling of these physics can be considered to predict the dust collection phenomena more accurately. Although Choi and Fletcher (1998) and Skodras et al. (2006) proposed a numerical method for coupling these physics inside a wire-plate type electrostatic precipitator, they were not able to show the validity of their numerical results.

In this study, a numerical simulation on the Electrohydrodynamics (EHD) inside a wire-pipe type electrostatic precipitator was performed by coupling the electric field, the fluid flow and the particle motion. To validate this numerical method, the numerical results were compared with the analytical solution for electric field and with the available numerical results for dust collection. By the present validated numerical methodology, the dust collection phenomena were studied for various operating conditions.

2 Numerical analysis

2.1 Electrostatic precipitator

Figure 1 shows the geometry and the operating conditions of the electrostatic precipitator used in this study. This wire-pipe type electrostatic precipitator consists of the pipe-type collection electrode and the wire-type discharge electrode. By the Coulomb force, the corona discharge generated by the difference in the electric potential between the discharge and the collection electrodes, the electrostatic precipitator removes the dust particles from the air. This collection mechanism is determined by the fluid flow and the particle motion is affected by the electric field. Therefore, a numerical simulation needs to be performed by coupling these physics to study the characteristics of the electrostatic precipitator. In this study, a two-dimensional (2D) axi-symmetric simulation on EHD inside the electrostatic precipitator was performed using a commercial CFD program, STAR-CD V4.12 (2009), incorporated with users’ subroutines.

2.2 Particle charging

In the electrostatic precipitator, the dust particles can be diffracted and collected by the Coulomb force. The Coulomb force acting on the particle is determined by the electric field around the particle and the quantity of the particle charge. As the particle is exposed to the corona discharge, the particle charge $q_P$ is determined as follows:
\[
\frac{dq_i}{dt} = \begin{cases} 
\frac{1}{\tau q_{\text{max}}}(q_{\text{max}} - q_i)^2 & \text{if } q_i < q_{\text{max}} \\
0 & \text{if } q_i \geq q_{\text{max}} 
\end{cases}
\] (1)

\[q_{\text{max}} = q_{\text{sat}} = \frac{3\pi \varepsilon_0 E d_i^2}{e_r \rho_{\text{ion}} k_{\text{ion}}}, \quad \tau = \frac{4\varepsilon_0}{\rho_{\text{ion}} k_{\text{ion}}},\] (2)

where \(q_{\text{max}}\) denotes the saturation charge, \(\tau\) the time taken for the particle to reach half the saturation charge, \(e_r\) the permittivity of free space, \(e_i\) the relative permittivity of the gas, \(k_{\text{ion}}\) the ion mobility, \(d_i\) the particle diameter, \(E\) the electric strength and \(\rho_{\text{ion}}\) the ion charge density. The characteristic of particle charging is determined by the particle size and the electric field.

### 2.3 Electric field

The particle charging, the fluid flow and the particle motion inside the electrostatic precipitator are affected by the electric field. The electric field can be calculated with the interactions among the electric potential \(\phi\), the electric strength \(E\) and the ion charge density \(\rho_{\text{ion}}\) as follows:

\[
\frac{\partial^2 \phi}{\partial x_i^2} = -\frac{\rho_{\text{ion}} + \rho_{\text{pc}}}{e_0}
\] (3)

\[E_i = -\frac{\partial \phi}{\partial x_i},\] (4)

\[
\rho_{\text{ion}} = e_i \frac{\partial \rho_{\text{ion}}}{\partial x_i} \frac{\partial \phi}{\partial x_i},\] (5)

where \(\rho_{\text{pc}}\) is the particle charge density. The Eulerian value of particle charge density is calculated with the Lagrangian characteristics of particle motion as follows:

\[
\rho_{\text{ion}} = \frac{\sum_{n=1}^{N} \frac{\dot{m}_n^i}{m_p} q_n^i \Delta \tau}{V_i},
\] (6)

where \(\dot{m}_n^i\) is the mass flow rate, is the infection residence time in the cell and \(V_i\) is the cell volume.

### 2.4 Fluid flow

To analyse the fluid flow inside the electrostatic precipitator, the following continuity and momentum equations were solved:

\[
\frac{\partial}{\partial x_k} \rho U_k = 0
\] (7)

\[
\frac{\partial}{\partial x_k} \left[ \rho U_k (\mu + \mu_t) \frac{\partial U_k}{\partial x_k} \right] = -\frac{\partial p}{\partial x_k} + f_{\text{fr}} + \rho_{\text{ion}} E, \] (8)

where \(U_k\) denotes velocities vector in the Cartesian coordinates, \(p\) the pressure, \(\rho\) the density, \(\mu\) the viscosity, \(f_{\text{fr}}\) the drag force for particle motion and \(\rho_{\text{ion}}E\) the Coulomb force acting on the fluid.

### 2.5 Particle motion

The particle passing through the electrostatic precipitator is affected by the electric field and the fluid flow. The governing equations for the particle motion are as follows:

\[
\frac{dx}{dt} = V_{pi},\] (9)

\[\frac{m_p}{dt} V_{pi} = f_{\text{fr}} + m_p g_i \left(\frac{\rho_p - \rho}{\rho_p}\right) + q_i E_i,\] (10)

where \(V_{pi}\) denotes the particle velocity, \(g_i\) the gravity acceleration, \(\rho_p\) the particle density and \(q_i E_i\) the Coulomb force acting on the particle, respectively. The drag force \(f_{\text{fr}}\) is calculated as follows:

\[f_{\text{fr}} = \frac{1}{2} C_d \rho A_d \left|U_i - V_{pi}\right| \left(U_i - V_{pi}\right),\] (11)

where \(C_d\) denotes the drag coefficient and \(A_d\) the cross-sectional area of particle. The drag coefficient is calculated as follows:

\[
C_d = \begin{cases} 
24 \left(1 + 0.15 Re_i^{0.687}\right) / Re_d & \text{if } Re_d \leq 10^3 \\
0.44 & \text{if } Re_d > 10^3 
\end{cases}
\] (12)

\[Re_d = \frac{\rho \left|U_i - V_{pi}\right| D_d}{\mu},\] (13)

where \(D_d\) denotes the particle diameter. The Eulerian variable of particle density is also obtained as follows:

\[
\rho_p = \frac{\sum_{n=1}^{N} \dot{m}_n^i \Delta \tau}{V_i},
\] (14)

### 2.6 Numerical procedure

In this study, the numerical simulation on EHD of the electrostatic precipitator was performed with the numerical procedure as shown in Figure 2. First, the fluid flow inside the precipitator was simulated. Next, the electric field such as the electric potential, the ion charge density and the electric strength were calculated, then the particle motion inside the precipitator was predicted. With these Lagrangian variables, the Eulerian variables, such as the particle concentration and the particle charge density, were calculated. This procedure was repeated to achieve typical converged solution.
Dust collection simulation inside a wire-pipe type electrostatic precipitator system

For the calculation of the governing equations, the boundary conditions were used as shown in Figure 1(c). The fluid and dust particles entered into the inlet of the precipitator with a specific inlet velocity. For the electric fields, the boundary conditions of the electric potential and the ion charge density were applied. At the collection electrode, the value of voltage and the gradient of ion charge density were set to zero. The value of the applied voltage was set at the discharge electrode. The value of ion charge density at the discharge electrode was updated as the computation proceeds by using the Peek law for a circular wire as follows:

$$E_{\text{Peek}} = 3 \times 10^6 \left[ 1 + 0.03 \left( \frac{\delta}{R} \right)^{1/2} \right], \quad \delta = \left( T_0 \Omega / TP_0 \right)$$  \hspace{1cm} (15)

$$\rho_{\text{ion}}^* = \left( 1 - \omega \right) \rho_{\text{ion}}^0 + \omega \rho_{\text{ion}}^*, \quad \rho_{\text{ion}}^* = \rho_{\text{ion}}^0 \left( E^* / E_{\text{Peek}} \right)^T,$$ \hspace{1cm} (16)

where $E_{\text{Peek}}$ is the critical value of the electric strength at the wire surface, $R$ is the wire radius and $\delta$ is the ambient condition. Using this critical value of electric strength, the value of ion charge density at the discharge electrode was modified with that of the electric strength at the neighbour cell and the relaxation factors. With this numerical procedure, it took nearly 1 day for a typical computation by 1 CPU of a Linux server with a 2.4-GHz-AMD Opteron 64-bit-processor.

3 Results and discussions

3.1 Validation of EHD simulation results

In this study, the electric field of numerical results was compared with the analytical solutions (Janischewskyj and Gela, 1979) to validate the electric field simulation prior to the EHD simulation of the electrostatic precipitator. Figure 3 shows the numerical results of the electric field in the wire-pipe type electrostatic precipitator with the variation of electric potential of 30–50 kV. Due to the difference in the electric potentials in the discharge and the collection electrodes, the electric potential distribution was generated in the space between the electrodes. The electric strength evaluated as the gradient of the electric potential is concentrated near the discharge electrode. When the value of the electric strength at the surface of the discharge electrode is greater than the critical value, the ion is generated at the discharge electrode and moves toward the collection electrode. These numerical results of the electric field in the electrostatic precipitator were compared with the available analytical solutions as shown in Figure 4. From the figures, it is seen that the present numerical results agree quite well with the analytical solutions. The discrepancy of the ion charge density between the numerical and the analytical results was attributed to the boundary conditions calculated by the Peeks law.

To verify the numerical method for dust collection phenomena, the behaviour of the dust particle inside the wire-plate type electrostatic precipitator system were computed and compared to the numerical results of Skodras et al. (2006). The wire-plate type electrostatic precipitator used in the previous study has three discharge electrodes between two parallel collection electrodes as shown in Figure 5. The electric potentials of 60–85 kV were applied to the discharge electrode. Figure 6 shows the particle motion inside the precipitator for various applied voltage with air inlet velocity of 1.0 m/s. In the electric field, the particles are affected by the Coulomb force due to corona discharge. When high voltage is applied at the discharge electrode, the particle affected by the high Coulomb force easily moves to the discharge electrode. With these particle motions, the dust particle can be collected and removed as shown in Figure 7. In the figure, it is shown that the present numerical results of collection performance are in a good agreement with the numerical results of Skodras et al. (2006).
Figure 3  Electric field of a wire-pipe type electrostatic precipitator with various applied voltage of discharge electrode: (a) electric potential [V] distribution; (b) electric strength [V/m] distribution and (c) ion charge density [C/m³] distribution (continued)

Figure 4  Comparison of the numerical results for the electric field with the analytical results: (a) electric potential distribution; (b) electric strength distribution and (c) ion charge density distribution

Figure 5  Geometry and operating conditions of a wire-plate type electrostatic precipitator for the validation of the present numerical method for dust collection with: (a) wire-pipe type electrostatic precipitator; (b) geometry of electrostatic precipitator and (c) operating conditions of electrostatic precipitator Source: Skodras et al. (2006)

Figure 6  Behaviours of dust particles with various applied voltages of discharge electrode inside a wire-plate type electrostatic precipitator: (a) applied voltage = 60 kV; (b) applied voltage = 65 kV; (c) applied voltage = 70 kV; (d) applied voltage = 75 kV and (e) applied voltage = 80 kV
3.2 Collection mechanism inside an electrostatic precipitator

With the present numerical method, the collection phenomena inside a wire-pipe type electrostatic precipitator were numerically predicted. Figure 8 shows the simulated the electric field, the flow velocity distribution and the resultant particle concentration distribution inside the electrostatic precipitator. For this base simulation, the dust particles of 2.0-µm-diameter are assumed to be entering the precipitator uniformly mixed with air at particle concentration of 0.0010 kg/m³. The air and the particle velocity at the inlet are both 1.0 m/s, and the applied voltage in the precipitator is 40 kV. By the difference in the electric potentials at the discharge and the collection electrodes, the electric field in the device was generated as shown in Figure 8(a)–(c). When the fluid flows and the particles move through the electric field, the Coulomb force affects the fluid flow and the particle movements. The axial and radial components of the flow velocity affected by the Coulomb force are shown in Figure 8(d) and (e), respectively. From the figure, it can be observed that the axial velocity becomes much slower near the discharge electrode due to strong radial force generated by the electric strength. Particle concentration is shown in Figure 8(f) where the particles move away from the discharge electrode and migrates toward the collection electrode.

The trajectories of dust particles affected by the Coulomb force were also predicted and shown in Figure 9. Since the particle trajectory is affected by the particle charging and the electric strength, the highly charged particles near the discharge electrode experiences higher forces toward the collection electrode and thus these particles are more diffracted as seen in the figure. These diffracted particles hit the collection electrode wall and adhere to this wall. Since the collection performance of the electrostatic precipitator is determined from the coupled physics of the electric field, the fluid flow and the particle motion, effects of various operation conditions, such as an electric strength, fluid velocity, particle concentration and size on the collection performance, are analysed and discussed in this study.

3.3 Effect of applied voltage

Since the electric field inside the electrostatic precipitator generates the driving force of particle movement, the fluid flow and the particle trajectory inside the precipitator strongly depend on the applied voltage. The numerical simulations were performed for applied
voltages of 35~50 kV while keeping other variables the same as in the base model.

Figure 10 shows the distribution of particle concentrations in the precipitator for various voltages applied at the discharge electrode. As the strength of applied voltage increases, the Coulomb force acting on the particle also increases. For this reason, the particles migrate toward the collection electrode with higher voltage. When 50 kV is applied, most particles adhere to the collection electrode and clean air leaves the precipitator in this case. Figure 11 shows the effect of applied voltages on dust collection performance. Horizontal axis denotes the location along the flow direction, and vertical axis denotes the cumulative dust collection amount along the flow direction. As previously explained, for the case of 50 kV, all the dust particles are collected and clean air leaves the precipitator so that the cumulative dust collection amount at the exit of the precipitator becomes 100% due to strong radial Coulomb force. Whereas the cumulative dust collection amount at the exit of the precipitator becomes about 25% when 30 kV is applied so that 75% of dust is not collected and leaves the precipitator.

3.4 Effect of inlet velocities

Since the particle motion is largely dependent on the fluid flow inside the electrostatic precipitator, the inlet velocity of the fluid flow is a dominant factor for the collection performance. To examine the effect of inlet velocities on the collection performance, simulations were performed for the range of inlet velocities 0.5~2.0 m/s while keeping other variables the same as in the base model.

Figure 12 shows the distribution of particle concentrations in the precipitator for various inlet velocities. As the inlet velocity of fluid flow increases, the particles are less diffracted and leave the precipitator uncollected. When inlet velocity is 0.5 m/s, most particles are collected and almost clean air leaves the precipitator due to relatively higher Coulomb force in radial direction than the flow inertia in the axial direction. The effect of inlet velocities on dust collection performance is shown in Figure 13. The effect of flow inertia is clearly shown from the figure such that at high inlet velocity of 2.0 m/s, only about 20% of the particles are collected and 80% leaves the precipitator uncollected.
3.5 Effect of particle concentrations

The particle concentration inside the electrostatic precipitator affects the electric potential as shown in Equation (3). The collection performance of a precipitator can be changed by the variation of electric potential affected by the particle concentration. The effect of the particle concentration on the collection performance was analysed with the variation of the particle concentration of 0.0005 – 0.0020 kg/m³ while keeping other variables the same as in the base model.

Figure 14 shows the distribution of particle concentrations in the precipitator for various inlet particle concentrations. For the range of variables considered in this study, the particle concentration distribution inside the precipitator is not very sensitive to the inlet particle concentration. As the inlet particle concentration increases, overall concentration inside the precipitator increased, while the particle-free area is almost not changed. This results in the unchanged collection performance for different inlet particle concentration as seen in Figure 15. Percentages of particle collection amount are unchanged for different particle concentrations so that the particle collection performance of an electrostatic precipitator is independent of inlet particle concentration for the range of variables considered in this study.

3.6 Effect of particle sizes

Particle size directly affects the particle charging and the particle motion in the air flow. To observe the effect of particle sizes on collection performance, simulations were performed for the range of particle sizes of 1.5~3.0 µm while keeping other variables the same as in the base model.

Figure 16 shows the distribution of particle concentrations in the precipitator for various particle sizes. Larger size particles experience higher charging and higher flow resistance at the same time. Since the Coulomb force increase due to charging is much stronger than the drag force increase when the particle size is larger, the larger particles diffract more and dust collection amount becomes higher. In the case of particle size 3.0 µm, all the particles are collected in early 2/5 of the collection area as shown in Figure 17. From the results of this study, it is recommended that the optimum design of the electrostatic precipitator is possible by adjusting the operating conditions based on the information on dust particles.
4 Concluding remarks

In this study, the EHD inside a wire-pipe type electrostatic precipitator was numerically studied by coupling the calculations of the electric field, the fluid flow and the particle motion. The presented numerical method was verified by performing the simulations and comparing the results of the electric field and dust collection performance of a wire-plate type electrostatic precipitator to available results from the literature. A 2D axi-symmetric computation by coupling the physics of the electric field, the fluid flow and the particle motion was performed to predict the collection phenomena inside the precipitator. Effects of various parameters such as the applied voltage, the inlet velocity, the particle concentration and the particle size on the dust collection performance are discussed. The presented numerical method may be used to design and operate the electrostatic precipitator in an optimal condition.

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