Numerical Simulation of Three-Dimensional Particle Migration and Electrohydrodynamics of Double Cylinder Electrostatic Precipitator

H. Kawakami, A. Zukeran, K. Yasumoto, T. Inui, Y. Enami, Y. Ehara, T. Yamamoto

1Fuji Electric Co., Ltd., Japan
2Department of Electronic and Electrical Engineering, Kanagawa Institute of Technology, Japan
3Department of Electrical and Electronic Engineering, Tokyo City University, Japan

Abstract—The double cylinder type electrostatic precipitator (DCESP) was developed to collect the entrained diesel particles. In this study, the three-dimensional particle motion in the DCESP was investigated which included the flow interaction between the primary flow and the secondary flow (or ionic wind), i.e., electrohydrodynamics. It was a coaxial double-cylindrical structure consisting of the outermost grounding case, the inner ground electrode punched with multiple holes, and the high voltage center electrode. The fundamental equations for solving the space-charge and electric field distributions are Poisson’s equation and the current-continuity equation, which are the driving-external-force for the electrohydrodynamics. The governing equations for solving the electrohydrodynamic flow fields are Navier-Stokes equation and the mass conservation equation. Three-dimensional flow interaction and particle trajectory are calculated using the commercially available STAR-CD. As a result, the maximum ionic wind velocity became 6.5 m/s. The flow interaction was induced towards the hole-punched inner grounded electrode from the high voltage center electrode and returned to the center electrode between star shaped electrodes. The particle trajectory was also calculated. The number of collected particles on the hole-punched grounded electrode was increased owing to the effect of the ionic wind.

Keywords—electrostatic precipitator, numerical simulation, electrohydrodynamics, particle migration, collection efficiency

I. INTRODUCTION

Electrostatic precipitators have been extensively used to decontaminate polluted exhaust gases emitted from industrial plants and to clean air from buildings, etc., because of their high collection efficiency. However, the collection of low resistivity particles, which is lower than $10^2 \ \Omega \cdot \text{cm}$, by the conventional ESPs is known to be difficult to precipitate. These particles are generated from various sources such as marine engines, diesel automobiles, and power generation engines. The low resistive particles cause particle detachment from the collection plate caused by an induction charge, i.e., dust reentrainment, which results in poor collection efficiency [1]:

Several ideas that have been proposed to suppress reentrainment are as follows;
1) Collection electrode coated with a dielectric sheet [2].
2) Mixing water mist with gases [3].
3) Using an ESP as an agglomerator [4-5]
4) Silent discharge type ESP [6]
5) Application of gradient force [7]
6) ESP by low frequency AC field [8]

However, these concepts achieved only limited success for minimizing the reentrainment under the high dust-loading and high gas temperature condition.

The electrostatic cyclone diesel particulate filter (DPF) [9] and the DPF by means of high frequency induction heating [10] for marine engines were suggested. The seawater scrubber system was also proposed [11]. However, these concepts also achieved only limited success for a compact system with low pressure drop. Recently, an electrohydrodynamically-assisted ESP was proposed for minimizing reentrainment [12]-[13].

The two-dimensional flow interaction between the primary flow and the ionic wind in the corona discharge was investigated theoretically and experimentally [14-15]. The three-dimensional flow interaction between the primary flow and the ionic wind was also investigated, since the two-dimensional analysis was limited for a discharge produced by discrete tufts for a wire-type electrostatic precipitator [16]. However, these analyses did not include investigation of the particle transport or migration processes.

The new double cylinder type ESP (DCESP) was developed to overcome the reentrainment [17-18]. In the previous report, the three-dimensional particle migration in the primary flow in the DCESP was investigated theoretically [18]. Its major focus was to study the numerical simulation for the aerodynamics behavior, the motion of suspended particles and reentrained particles. The DCESP utilized differential pressure to transport reentrained particles effectively into the low gas velocity space (the collection space) from the high gas velocity space (the charging space) through multiple small holes. The captured particles were trapped on the electrode in the low gas velocity space, where the hydrodynamic shear stress was low. However, the ionic wind was not need to be considered in this region. The numerical simulation of two-dimensional ionic wind was also investigated [19]. The results of the numerical simulation showed a good agreement with the experimental results.

We investigated the three-dimensional particle migration in the flow interaction field between the primary flow and the secondary flow in the DCESP,
using the commercially available STAR-CD (Ver. 4.1). The flow interaction between the primary flow and the ionic wind, the particle migration and the collection efficiency were calculated.

II. THEORETICAL INVESTIGATION

A. Geometry

The three-dimensional flow in the DCESP having the electrode structure as shown in Fig. 1 is calculated. The DCESP is a coaxial double-cylindrical structure consisting of the grounding case, perforated inner ground electrode and the high voltage center electrode. The high voltage center electrode has needles which produce corona discharge at their tips. The hole-punched inner ground electrode is made from stainless steel; the thickness is 1 mm, the hole diameter 2.5 mm and the aperture rate 35.0%. The upstream and downstream portions of the space between the hole-punched inner ground electrode and the grounding case are closed. The flue gas is connected to the upstream portion between the high voltage center electrode and the multiply hole-punched inner ground electrode. The grounding case is a rectangular-parallel piped casing made of stainless steel. The multiply hole-punched inner ground electrode is 500 mm. The space between the multiply hole-punched inner ground electrode and the grounding case is called "charging space", and the space between the multiply hole-punched inner ground electrode and the high voltage center electrode is called "charging space", and the space between the multiply hole-punched inner ground electrode and the grounding case is called "collecting space". The charged particles are collected on the multiply hole-punched inner ground electrode. The collected particles become positively charged by induction charge, growing into larger particles by agglomeration [1]. The large particles are reentrained by hydrodynamic repulsion force and introduced into the collecting space by differential pressure [18], which is approximately 1 Pa in this condition. The calculation value of average gas velocity in the collecting space is 1/3 or less of the value in the charging space, so that the reentrained particles are re-collected on the surface of the multiple hole-punched inner ground electrode and the grounding case in the collecting space.

B. Governing equations

The fundamental equations of the ionic wind are Poisson's (Eq. 1) and current-continuity equations (Eq. 2) [16]:

$$\nabla \cdot \nabla V = -\frac{\rho}{\varepsilon} \quad \text{(Eq. 1)}$$

$$\nabla (\rho \omega \nabla V) = 0 \quad \text{(Eq. 2)}$$

where $V$ is the voltage [V], $\rho$ is the ionic space-charge density [C/m³], $\varepsilon$ is the dielectric constant of air [F/m], and $\omega$ is the ion mobility [m²/Vs]. These are used to determine the electric field and current-density distributions.

The ionic wind force $F_e$ [N/m³] can be written as [16]:

$$F_e = \rho E = -\rho \nabla V \quad \text{(Eq. 3)}$$

where $E$ is the electric field [V/m].

The fundamental equations of flow field are Navier-Stokes equation (Eq. 4) and the equation of continuity
The ionic wind is calculated by substituting Eq. 3 for $s_i$ in Eq. 4.

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_j - \tau_{ij}) = -\frac{\partial p}{\partial x_j} + s_i$$  \hspace{1cm} (Eq. 4)

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i) = s_n$$  \hspace{1cm} (Eq. 5)

where $u$ is the gas velocity [m/s], $x$ is the spatial coordinate in rectangular coordinate system [m], $\rho$ is the air density [kg/m$^3$], $t$ is time [s], $\tau_{ij}$ is the stress tensor, and $p$ is the pressure [Pa].

The numerical algorithm is the simple method. The flow is calculated on the assumption that the fluid is incompressible. The three-dimensional flow interaction between the primary flow and the secondary flow within a DCESP was calculated using the commercially available STAR-CD (Ver. 4.1).

The effect of the ionic wind on the particle collection due to calculating the particle migration in the DCESP is investigated. The equation of motion for particles can be written as:

$$m_p \frac{du_j}{dt} = F_{dr} + F_p + F_{am} + F_b + F_e$$  \hspace{1cm} (Eq. 6)

$$F_{dr} = \frac{1}{2} C_d \rho_d A_d |u - u_j| (u - u_j)$$  \hspace{1cm} (Eq. 7)

$$F_p = -V_d \nabla p$$  \hspace{1cm} (Eq. 8)

$$F_{am} = -C_{am} \rho V_d \frac{d(u_j - u)}{dt}$$  \hspace{1cm} (Eq. 9)

$$F_b = m_p [g - \omega \times (\omega \times r) - 2(\omega \times u_j)]$$  \hspace{1cm} (Eq. 10)

where $m_p$ is the particle mass [kg], $u_j$ is the particle velocity [m/s], $F_{dr}$ is the drag force [N], $F_p$ is the pressure force [N], $F_{am}$ is the virtual mass force [N], $F_b$ is the general body force [N], $F_e$ is the Coulomb's force [N], $C_d$ is the drag coefficient, $A_d$ is the particle cross-section area [m$^2$], $V_d$ is the particle volume [m$^3$], $V_p$ is the pressure gradient in the fluid, $C_{am}$ is the virtual mass coefficient (0.5), $g$ is the gravitational acceleration vector [m/s$^2$], $\omega$ is the angular velocity vector [rad/s], and $r$ is the distance vector to the axis of rotation [m].

C. Calculation domain and boundary conditions

The analysis domain is shown in Fig. 1. A quarter of the DCESP is the computational domain. The analysis domain is discretized into 2,500,000 tetra mesh. The boundary conditions are shown in Fig. 2.

The specific boundary conditions are as follows:
1) Lines a-b and d-a: symmetry boundary
2) Lines b-c and c-d: wall boundary
3) Inlet velocity: 12 m/s
4) Turbulent intensity: 0.03
5) Characteristics length: 0.06 m
6) Inlet Temperature: 170 °C
7) Voltage of multiple hole-punched inner ground electrode surface: 0 V
8) Voltage of grounding case: 0 V
9) Voltage of high voltage center electrode: -7.8 kV
10) Outlet boundary layer
   Flow rate: 1.0

The mobility of negative ions of the air (as measured at 0 °C) is $1.51 \times 10^{-7}$ m$^2$/Vs [20]. The particle diameter is 0.4 μm, which is the peak value of particle weight diameter distribution in diesel exhausted particles. The amount of particle charges is $-1.1 \times 10^{-7}$ C/particle, which is the authors' empirical value. The number of particles is 1,000 particles.

It has been confirmed that the following quantities become converged to respective steady-state values;
1) Gas flow velocity, pressure, turbulent energy, potential
2) Total value of the currents at the grounded electrode and the high voltage center electrode.
3) Ion density, maximum value of ion density

III. RESULTS

A. Ionic wind

The three-dimensional ionic wind in the DCESP is shown in Fig. 3. The multiply hole-punched inner ground electrode is connected to the ground. DC -7.8 kV is applied to the high voltage center electrode. The primary flow is not considered in this calculation. This result shows that the ionic winds are generated from all needle electrodes. The flow interaction is induced toward the hole-punched inner grounded electrode from the high voltage center electrode and returns to the center electrode between the needle electrodes. The maximum ionic wind velocity is 6.5 m/s, the minimum velocity is 0.25 m/s.

The three-dimensional flow interaction between the primary flow and the ionic wind is shown in Fig. 4. The flow is faster in red region than in blue. Fig. 4-a shows the primary flow without the ionic wind. The primary flow passes horizontally from inlet to outlet as shown by the arrow. However, the flow interaction between primary flow and the ionic wind is induced toward the multiply hole-punched inner ground electrode due to the effect of the ionic wind as shown by the arrow on Fig. 4-b. This result shows that the ionic wind has influenced on the gas flow in the case of high gas velocity, which is 12 m/s in this study. This is because there are multiple needles horizontally arranged from inlet to outlet. The differential pressure in Fig. 4-a was approximately 0.82 Pa, that in Fig. 4-b was 0.56 Pa.

![Fig. 3. Three-dimensional ionic wind distribution](image)

![Fig. 4 Three-dimensional flow in DCESP](image)
B. Particle migration

The particle migration in the case of the primary flow is shown in Fig. 5. The grounding case and the hole-punched electrode are connected to the ground. DC -7.8 kV is applied to the high voltage center electrode. However, the ionic wind is not considered for this calculation. The migration of charged particles influenced the primary flow and Coulomb force is calculated. The particles are introduced into the charging space, and then migrate towards the multiply hole-punched inner ground electrode and the collecting space. The number of particles is 1,000 particles. The particles in the charging space are indicated in blue and light blue. Those on the multiply hole-punched inner ground electrode are indicated in green and yellow, and those in the collecting space are indicated in pink and red. This figure shows that the particles are collected on the multiply hole-punched inner ground electrode due to Coulomb force while flowing into downstream area.

The particle trajectory in the electrohydrodynamic field is shown in Fig. 6. The grounding case and the hole-punched electrode are connected to the ground. A DC -7.8 kV is applied to the high voltage center electrode. The particle migration of charged particles under the influence of the flow interaction and Coulomb force is calculated. The amount of particles collected on the electrode is greater than in the case of the primary flow as shown in Fig. 5. Especially, the number of collected particles on the downstream area of the electrode, which is indicated by black box in Fig. 6, is increased to 1.7
times more as shown in Fig. 5 due to the effect of the ionic wind as shown in Fig. 4-b.

C. Collection efficiency

The effect of the ionic wind on the collection efficiency is shown in Table 1. The collection efficiency is calculated by equation (Eq. 11).

$$\eta = \left(1 - \frac{N_O}{N_I}\right) \times 100 \quad (\text{Eq. 11})$$

where $N_I$ is the number of inlet particles (1,000 particles), and $N_O$ is the calculated number of outlet particles.

The collection efficiency without considering the ionic wind is 36.9 %. On the other hand, in the case of the flow interaction between the primary flow and the ionic wind, the efficiency is 45.7 %. The collection efficiency is increased by 8.8% due to the effect of the ionic wind in comparison with the neglect of ionic wind. This is because the number of particles which is migrated towards the multiply hole-punched inner ground electrode is increased due to the ionic wind. The collection efficiency is not high in this result but can be easily improved, for example, by controlling the voltage or the number of needle electrodes.

V. CONCLUSION

The three-dimensional particle migration in the flow interaction between the primary flow and the ionic wind was investigated. Results are as follows;

1) The particle transport in the electrohydrodynamic flow interaction was calculated and visualized.

2) The ionic wind was induced toward the hole-punched inner ground electrode from the high voltage electrode and returned to the center electrode between discharge electrodes. The maximum ionic wind velocity was 6.5 m/s.

3) The flow interaction between the primary flow and the ionic wind was induced towards the multiple hole-punched inner ground electrode due to the effect of the ionic wind. This result demonstrates that the ionic wind has influenced the collection efficiency greatly even the primary gas flow velocity of 12 m/s.

4) The number of collected particles on the grounded hole-punched electrode was increased by 8.8 % owing to the effect of the ionic wind.

The effect of the ionic wind on collecting reentrained particles and the comparison of calculated result and the experimental result will be investigated in the future.

### Table I

<table>
<thead>
<tr>
<th>Case</th>
<th>Collection Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary flow</td>
<td>36.9</td>
</tr>
<tr>
<td>Flow interaction</td>
<td>45.7</td>
</tr>
</tbody>
</table>

ACKNOWLEDGMENT

This work was supported by a Grant-in-Aid for Scientific Research (B) of the Japanese Society for the Promotion of Science.

REFERENCES


