Particle deposition in a full scale hybrid electrostatic-filtration collector

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Abstract. This paper presents a numerical model for a full scale hybrid particulate collector (HPC), which combines the ESP technology and the filtration technology together. The corona discharge is solved by using a finite volume method. The turbulent flow equations are solved by using the Fluent package. The effect of the electric field on the fluid field named electro-hydrodynamic is considered. The particle motion is calculated by using the Lagrangian method. The particle charging rate is calculated by using a field-diffusing combined model. The bag is modelled as a porous media but the pressure drop across the particle cake is neglected. Eight particle sizes are considered: 0.01, 0.1, 0.3, 0.5, 1, 2, 5 and 10 μm. The applied voltage is fixed at 60 kV. The results show that the collection efficiency of the electrostatic zone changes a little when the particle size is below 0.3 μm but increases clearly when the particle size exceeds 0.3 μm. Totally, the bag collection efficiency decreases from the first one to the last one in the same row.

1. Introduction
China has the biggest thermal power installed capacity, which reached up to 76.5 million kW by the end of 2011. It is a big challenge for the control of the particulate emissions from those power plants, especially for the PM₂.₅. Both the conventional electrostatic precipitator and the bag filter have some disadvantages for the PM₂.₅ control. A new type precipitator that combines the ESP and the baghouse together has been proposed for many years, named the advanced hybrid particulate collector (HPC) [1], as shown in figure 1. The HPC can provide ultrahigh collection efficiency and solve the problem of reentrainment. The flue gas first flows into the ESP zone to remove the most particles (about 90 % by mass), and then goes through the holes in the perforated plates into the fabric filtration zone to remove the left particles. Hence, the pressure drop across the collector increases far more slowly than the conventional bag filter.

Zhuang et al. have done lots of experimental research on the HPC including the voltage-current characteristics, collection efficiency of the electrostatic zone, different perforated-plate design, different types of bag and the pulse cleaning performances [1]. Long et al. have developed a finite volume method [2] to analyze the three dimensional electric field and the space charge density distributions in the HPC [3]. Though so many studies have been done, the particle deposition characters in the full scale HPC is still not clear. Experimental study can provide reliable data but

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usually lack of some details. Numerical method has been a powerful tool for the study of the ESP [4-7] and the filtration [8-9]. Numerical results could show the particle trajectories in the ESP and the structures of the particle layer in the filtration. It is hard to obtain that information from the experiments.

In this paper, a numerical model of the HPC is presented to study the particle deposition characters inside the full scale HPC, as shown in figure 1. The model is two dimensional and its geometrical parameters are close to an industrial one. The model HPC includes twenty-five discharge wires, eight perforated-plates with many staggered holes and thirty-two bags. Eight particle sizes are considered: 0.01, 0.1, 0.3, 0.5, 1, 2, 5 and 10 μm. For simplicity, the pressure drop across the particle cake is not considered in this paper.

![Figure 1. Demonstration of the hybrid particulate collector.](image)

2. Model description
In the HPC, the physical processes include the fluid flow, the corona discharge, the particle charging, the particle dynamics and the filtration. The coupled effects between the fields should be considered.

The governing equations describing the corona discharge include the Poisson’s equation and the current continuity equation [10]:

\[ \nabla^2 V' = -\frac{\rho_w}{\varepsilon_0 V_w} \rho_s' \]  \hspace{1cm} (1)

\[ \nabla \cdot J = 0 \]  \hspace{1cm} (2)

\[ J = \bar{b} E \rho_s' \]  \hspace{1cm} (3)

\[ E = -\nabla V' \]  \hspace{1cm} (4)

where \( V \) is the electric potential (V), \( V_w \) the electric potential at the corona wire, \( V' = V / V_w \), \( \rho_w \) is the space charge density at the corona wire (C/m³), \( \rho_s' = \rho_s / \rho_w \), \( \rho_s \) is the space charge density and \( \varepsilon_0 \) is the air permittivity (8.85 × 10⁻¹² C²/N·m²), \( \bar{b} \) is the ion mobility (m²/V·s), \( E \) is the electric field (V/m).

This paper adopts the steady flow model. The steady, incompressible Navier-Stokes equations can be written as:
\[ \frac{\partial U_i}{\partial x_i} = 0 \]  

(5)

\[ \rho_f \frac{\partial U_i}{\partial t} + \rho_f \frac{\partial U_i U_j}{\partial x_j} = - (\mu + \mu_t) \frac{\partial (U_i U_j)}{\partial x_j} + \frac{\partial (\rho U_i)}{\partial x_i} = - \frac{\partial P}{\partial x_i} + F_{ci} + \rho_f g \]  

(6)

\[ F_{ei} = E_i \rho_v \]  

(7)

where \( U_i \) (i=1, 2, 3) is the fluid velocity (m/s), \( \rho_f \) is the fluid density (kg/m\(^3\)), \( t \) is the time (s), \( \mu \) is the laminar viscosity (kg/m\(s\)), \( \mu_t \) is the turbulent viscosity (kg/m\(s\)), \( P \) is the fluid pressure (Pa), \( F_{ci} \) is the electric body force (N/m\(^3\)), \( g \) is the acceleration of gravity (m/s\(^2\)).

For the turbulence, the RNG \( \kappa - \varepsilon \) model is employed.

The particle deposition adopts the Lagrangian method. The electric field force and the gravity force are the primary forces. According to the Newton’s second law, the equation that describes the particle motion is written as:

\[ \frac{dU_p}{dt} = C_D \frac{3 \rho_p [U - U_f] (U - U_p)}{4 \rho_p d_p^2} + g + \frac{3 E_0}{4 \rho_p d_p^2} \]  

(8)

where \( U_p \) is the local particle velocity, \( U \) is the local fluid velocity, \( \rho_p \) is the particle density, \( d_p \) is the particle diameter, \( q_p \) is the particle charge (C), \( C_D \) is the drag force coefficient, \( g \) is the gravity gradient.

To solve the Eq. (8), the particle charge \( q_p \) must be known. In this paper, the FMD model developed by Lawless [11] is employed to calculate the particle charge number along the trajectories in the HPC. The charging rate is expressed in the following dimensionless form.

\[ \frac{dv}{dt} = \begin{cases}  
  f(w) \frac{v - 3w}{\exp(v - 3w) - 1}, & v > w \\
  \frac{3w}{4} (1 - \frac{v}{3w})^2 + f(w), & -3w \leq v \leq 3w \\
  -v + f(w) \frac{-v - 3w}{\exp(-v - 3w) - 1}, & v < -3w 
\end{cases} \]  

(9)

where \( f(w) \) is the fraction of the surface covered by the diffusive band:

\[ f(w) = \begin{cases} 
  1, & w \geq 0.525 \\
  (w + 0.475)^{0.375}, & w < 0.525 
\end{cases} \]  

(10)

where \( v \) (\( = \frac{q_p e}{2 \pi \epsilon_0 d_p kT} \)) is the dimensionless particle charge, \( w \) (\( = \frac{K_p E d_p e}{K_p + 2 kT} \)) is the dimensionless electric field, and \( t_q = \frac{\rho_q b q \beta}{\epsilon_0} \) is the dimensionless particle charging time, \( k \) is Boltzmann’s constant (1.38×10\(^{-23}\) J/K), \( T \) is the temperature (K), \( e \) is the charge on an electron (1.6×10\(^{-19}\) C), \( K_p \) is the particle dielectric constant, \( E \) is the local electric field (V/m), \( \rho_s \) is the space charge density (C/m\(^3\)).

The discharge equations (1)-(4) are solved by a finite volume method [2]. The fluid equations (5)-(6) and the particle motion equation (8) are solved by using the CFD package Fluent. The particle
charge equations (9)-(10) are solved by using the user defined program. Figure 2 is the comparison between the numerical predictions and the experimental data in a laboratory electrostatic precipitator [12]. The model predictions agree well with the measurements of the hasten speed along a line near the collection plate.

**Figure 2.** Comparison of the model predictions with the experimental data [12].

### 3. Results and discussion

The inlet boundary condition is the velocity-inlet and the outlet one is the outflow. The boundary condition of the walls is the wall function. The mean inlet velocity is 1.5 m/s. The particle density is 2610 kg/m³. The particle size is monodisperse. The bag is modeled as a porous media, whose permeability is 3.6e-11 and thickness is 1.5 mm. The applied voltage and the corona current are 60 kV and 68.4 μA/m, respectively.

**Figure 3.** The voltage and the charge density distribution in the model HPC.

Figure 3 shows the voltage and the space charge density distribution of the model HPC. It clearly shows that the wire around area has the biggest voltage and space charge density. Besides, many ions go through the holes of the perforated plates. This indicates that the electric field intensity in the bags is not zero. Both the sides of the perforated plate can collect the particles. Figure 4 presents the streamlines in the model HPC. The electrohydrodynamic exists in the corona discharge field. But the electrohydrodynamic in the model HPC is not very obvious. This may be due to the low electric field intensity. There are some vortexes near the end of the model HPC due to the end wall [13].
Figure 4. The streamlines in the model HPC.

Figure 5. The relation of the electric zone collection efficiency with the particle size.

Figure 5 presents the collection efficiency of the electric zone of the model HPC. The electrostatic field zone includes the two collection plates and the eight perforated plates. The results show that the electrostatic zone collection efficiency changes a little when the particle size is below the 0.3 μm but increases clearly when the particle size exceeds 0.3 μm. The particle dynamics in the model HPC is decided by the drag force and the electric force. For the particles lower than 0.3 μm, the differences between two forces are small. Thus, the collection efficiency is similar. But the drag force and the electric force differ a lot for the larger particles. Thus, the collection efficiency increases obviously. Therefore, it is still a big challenge to increase the collection efficiency of the electric zone of the model HPC for the fine particles. Almost half fine particles are deposited onto the bag surfaces. The porosity of the cake on the bag surface will be smaller.

Figure 6. The comparison of the bag collection efficiency for different particle sizes.

Figure 6 shows the collection efficiency of each bag in rows 1 and 2. The bag is numbered 1-8 from left to right. The rows 3 and 4 are symmetrical with the rows 1 and 2. In row 1, the bag collection efficiency decreases from the bag 2 to the bag 8 for all the particle sizes. The collection efficiencies of the bags 1 and 2 are nearly the same for particle size 0.3, 0.5, 1.0 and 5.0 μm. Besides, the collection
efficiencies of the bag 1 for the eight particle size are at the range of 0.021 to 0.024, which is very narrow. The other seven bags also have the similar characters but for different particle size range. The eight bags have similar collection efficiencies for the particle size 0.01, 0.1 and 0.3 μm but significant difference for the other particle sizes. In row 2, the collection character is different with the row 1. The collection efficiencies decrease from the bag 2 to the bag 7 for the eight particle sizes. But the collection efficiencies increase slightly from the bag 1 to bag 2 for the particle size 0.1 and 10 μm. And the collection efficiencies increase obviously from the bag 7 to bag 8 for the particle size 0.01, 0.1 and 0.3 μm. Each bag has also similar collection efficiency for different particle size range. For example, the collection efficiencies of the bag 1 have a range of 0.02 to 0.021 for the particle size 0.01, 0.1, 0.3, 0.5, 1 and 2 μm.

4. Conclusion
This paper presents a numerical model for a full scale hybrid particulate collector. The corona discharge field is solved by using a finite volume method. The turbulent fluid flow equations are solved by using the Fluent package. The effect of the electric field on the fluid field named electro-hydrodynamic is considered. The particle motion is modelled using the Lagrangian method. The particle charging rate is calculated by using a filed-diffusing combined model. The bag is modelled as a porous media but the pressure drop across the particle cake is neglected. The results show that the collection efficiency of the electrostatic zone changes a little when the particle size is below the 0.3 μm but increases clearly when the particle size exceeds 0.3 μm. Totally, the bag collection efficiency decreases from the left one to the right one in the same row except the first bag and the last bag. But each bag has similar collection efficiency for a special particle size range.

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