Effect of the EHD flow on the collection efficiency of fine particles in wire-plate electrostatic precipitators

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Abstract. This paper focuses on the low collection efficiency of fine particles in air pollutant. Based on analyzing the collection rate of fine particles in electrostatic precipitator (ESP), a two-dimensional model of wire-plate discharge was established. The CFD code FLUENT was used to simulate the ionic winds at typical voltages 25, 40, and 45 kV, respectively. In the process of simulating, the ionic wind was replaced by the dynamic wind. According to the state graphs of ionic winds, the abnormal manifestation of the fine particles collection appeared in 40 kV voltage was explained. This work will provide a theoretical support for optimizing electrodes matching.

1. Introduction
The fine particles removal is an emphasis for the study of high voltage electrostatic precipitators in modern dust removal. In the dust source, the smaller particles which occupy a small weight proportion relative to the larger particles have an absolute advantage in the numbers. Especially the fine particles (PM$_{2.5}$) have smaller diameter, bigger specific surface area and they can stay a long time in the atmosphere. They are more likely to be the carriers of other harmful substances leaving harmful substances enter the body. So they have great impact on people’s health and the quality of atmospheric environment [1-3]. At present, the ESP has low collection efficiency on PM$_{2.5}$. Therefore, it is an important issue to study the efficient collection methods of fine particles.

The electrohydrodynamic (EHD) field makes the collection process of particulate matter extremely complicate in the discharge space [4-6]. According to the related researches [7-10], the influence that the ionic wind force has on the particulate matter can’t be ignored. In this paper, at first we analyzed the collection rate of fine coal particles under different voltages by experiments. Then the distributions of the ion wind were obtained under different voltages by numerical simulation. We explained the abnormal phenomenon of fine particles collection when the voltage was 40 kV. These results finally provide the basis for seeking efficient electrode matching of ESP.

2. Experiment of coal particles collection
The ESP uses wire-plate negative corona discharge device of multi-electric field. The wire-to-plate space was 150 mm. The fine coal particles of different electric fields were collected under different voltages. The distributions of particle diameters were analyzed using BT-9300 laser particle size analyzer.

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In this experiment, 25 kV was the discharge inception voltage. The collected particles in the first electric field were analyzed. The collection rates (the volume percentage that certain particle diameter takes in all collected particles expresses the collection effect) of different particle diameters were obtained. It is shown in figure 1.

At 25 kV, the fine particles collection was nearly the same as it was in the natural state. This is because the discharge energy, the number of ions, the ion wind strength and electric field strength were weak at 25 kV. Particles were charged incompletely. The coulomb force on the fine particles was weak. The fine particles were deposited due to natural coagulation and electric coagulation with large particles.

As the voltage increased, the electric field strength reinforced and the number of space ions increased. The collection rate of PM$_{2.5}$ increased as well. However, the collection rate was abnormal at 40 kV. The collection rate of PM$_{2.5}$ at 40 kV was only higher than that of 25 kV.

3. Numerical simulation of ionic wind

As discussed above, the collection process of particles is very complex. The particles move under various forces in the electric field. Especially the ionic wind has great influence on the fine particles. Thus the ionic wind in the discharge space is simulated. The simulation also give a reasonable explain for the abnormal phenomenon of collection rate appeared at 40 kV.

3.1. Model building

Several hypotheses:

(1) In the practical application, the upper limit of the inlet concentration should be controlled in the ESP. The concentration of the coal dust was generally set to 20 g m$^{-3}$ [11]. That is 0.01 % if it is converted to volume fraction. As the duty cycle of the particles was very low, the dust stream could be idealized as a single-phase flow (i.e. air). The fluid of the discharge space was regarded as incompressible viscous fluid without regard to the change of the flow density.

(2) In this experiment, the influence among the corona wires was so small that each corona wire could become an independent discharge unit. The wire-plate discharge model was established for one independent unit.

(3) The differences of the flow in different directions of the corona wire were ignored. The flow perpendicular to the plane of the corona wire in the discharge process was considered as isotropic. The three-dimensional discharge model was simplified as two-dimensional. The wire-to-plate space was set to 150 mm. The final model is showed in figure 2.
3.2. The governing equations
According to the established two-dimensional model and the characteristic of the fluid [12, 13], the governing equations of the fluid flow in the discharge space could be described as follows:

The continuity equation: \[ \text{div}(\mathbf{u}) = 0 \] (1)

The momentum equations:
\[ \frac{\partial (\rho \mathbf{u})}{\partial t} + \text{div}(\rho \mathbf{u} \mathbf{u}) = \text{div}(\mu \text{grad} \mathbf{u}) - \frac{\partial p}{\partial x} + F_x \] (2)
\[ \frac{\partial (\rho v)}{\partial t} + \text{div}(\rho v \mathbf{u}) = \text{div}(\mu \text{grad} \mathbf{v}) - \frac{\partial p}{\partial y} + F_y \]

\( k \) equation:
\[ \frac{\partial (\rho k)}{\partial t} + \text{div}(\rho k \mathbf{u}) = \text{div} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \text{grad} k - \rho \varepsilon + \mu_i P_g \right] \] (3)

\( \varepsilon \) equation:
\[ \frac{\partial (\rho \varepsilon)}{\partial t} + \text{div}(\rho \varepsilon \mathbf{u}) = \text{div} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \text{grad} \varepsilon \right] - \rho C_2 \frac{\varepsilon^2}{k} + \mu_i C_1 \frac{\varepsilon}{k} P_g \] (4)

Where \( \mathbf{u} \) is the velocity vector, \( u \) and \( v \) the component of the velocity vector in the direction of \( x \) and \( y \), \( \rho \) the fluid density, \( \mu \) the kinetic viscosity, \( p \) the pressure on the fluid element, \( F_x \) and \( F_y \) the physical force on the element, \( k \) the turbulent kinetic energy, \( \varepsilon \) the turbulent dissipation rate, \( \mu_t \) the turbulent viscosity, respectively. \( \mu_i = \rho C_\mu \frac{k^2}{\varepsilon} \). In this two-dimensional model, \( P_g \) could be written as follows:
\[ P_g = 2 \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 \right] + \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 \] (5)

\( \sigma_k \) and \( \sigma_\varepsilon \) are the Prandtl number that the \( k \) and \( \varepsilon \) correspond with. \( \sigma_k=1.0, \sigma_\varepsilon=1.3, C_\mu=0.09, C_1=1.44, C_2=1.92 \).

3.3. The parameter settings
The boundary conditions were set as follows: the corona wire was set as velocity inlet. AB and CD were set as outflow boundary conditions. The plate electrodes were no-slip side wall boundary conditions.

The governing equations were discrete by the finite volume method (FVM). The discrete scheme for the diffusion term and the convection term were the central difference scheme and the first-order upwind scheme, respectively. The numerical calculation was the SIMPLE algorithm.

3.4. The simulation graphs of the ionic wind
According to our previous research results [14-15] and the analysis above, we simulated the ionic winds of typical voltages (25, 40 and 45 kV) in the discharge space. The results are showed in figure 3, figure 4 and figure 5.

The three figures showed that as the voltage increased, the vortexes of double helix shape near to the plate electrodes gradually. The scale of helix also increased. The degree of turbulence was intensified in the discharge space. A fully double-helix structure developed until the voltage was 45 kV.

When the voltage was 25 kV, the electric strength was weak and the ionic number was very few. Only near the corona wire formed ionic wind with small spiral scales. The ionic wind made particles rotated around the corona wire, which increased the coagulation probability of fine particulate particles to a certain degree. Because the corona zone was only a few millimetres, and out of the corona zone, the ionic wind velocity reduced quickly. The ionic wind had little influence on the...
migration velocity of fine particles. All of these evidences supported that the collected fine particles presented a state of natural distribution under the voltage of 25 kV.

![Figure 2](image2.png) **Figure 2.** The model of discharge space.

![Figure 3](image3.png) **Figure 3.** The simulated graph at 25 kV.

![Figure 4](image4.png) **Figure 4.** The simulated graph at 40 kV.

![Figure 5](image5.png) **Figure 5.** The simulated graph at 45 kV.

When the voltage was 40 kV, large horizontal airflows along the plate electrodes were formed. On the one hand, these airflows just had scouring effect to the collected particles attached to the plate electrodes. Thus the fine particles were easily dropped from the plate electrodes with this airflow force. On the other hand, due to the small scale of vortexes, the dropped fine particles couldn’t go into the vortexes to be collected again in good time. Part of the dropped particles only moved along the electrode plates under the ionic wind flow. As we know, the concentration of the ions and the electric strength near the plate were the weakest in the discharge channel. Therefore, these particles didn’t have enough electric force. With the ESP operating for a long time, the concentration of gathered particles in the eddy would be more highly. The comprehensive effect led to a low collection rate of fine particles at 40 kV, then an abnormal phenomenon of fine particles collection appeared.

At 45 kV, the scale of vortex was large and the electric field strength was large as well. When the fine particles moved into the vortex, they could be fully charged. Finally, they got rid of the vortex in the strong electric force. They were collected again without washed away by the ionic wind.
4. Numerical simulation of ionic wind

(1) The ionic wind exiting in the discharge space has a great impact on the collection of fine particles. Not only should the influence of electric force be considered, but the role of ionic wind should be considered.

(2) The abnormal phenomenon of fine particles collection at 40 kV reminds us that improving the voltage unilaterally is not the best way to collect the fine particles efficiently.

(3) According to the analysis of the particles collection rate, it showed that the multi-electric field has a great advantage. A single electric field couldn’t guarantee the efficient collection of fine particulate matters. Optimizing the electrode matching is the guaranty.

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