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EFFECT OF ELECTROHYDRODYNAMIC SECONDARY FLOW ON THE PARTICLE COLLECTION IN A WIRE-PLATE ELECTROSTATIC PRECIPITATOR

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ABSTRACT

Electrostatic precipitator (ESP) has been widely used to remove small particles from dust-laden gas flows in many industries. The removal efficiency needs further enhancement for submicron particles which are believed to be more harmful to human respiratory system. In the current theoretical researches, the gas flow structure and electro-hydrodynamic secondary flow (EHD) induced by the electric corona are crucial to predicting the particle trajectories and the deposition process, but the underlying mechanism is still poorly understood. In this paper, a CFD model capable of simulating the coupling between electric field, wind flow and particle transport is developed using FLUENT solver combined with User Defined Functions (UDF). The corona model is verified with the published experimental data. Using the ESP model, the electrostatic precipitation process in a four-wire and plate ESP is simulated for the gas field with and without EHD secondary flow. The simulation results indicate that the EHD secondary flow has a negative effect on the particle collection. We therefore suggest that the intensity of EHD secondary flow should be minimized in the design of ESPs in order to further improve the dust removal efficiency.

NOMENCLATURE

A empirical constant
B empirical constant
b ion mobility
C_D drag coefficient
d_p particle diameter
D ion diffusion coefficient
$\mathbf{E}$ electric field intensity
E_{on} onset electric field
e electronic charge
$\mathbf{F_{EP}}$ electrostatic force
$\mathbf{F_0}$ other forces
g gravity acceleration
h wire-to-plate distance
$\mathbf{J}$ electric current
k Boltzmann's constant
K_p particle dielectric constant
m_p particle mass
P operating pressure
T operating temperature
q_p particle charge
r radius of discharge electrode
t time
t_q dimensionless charging time
$\mathbf{u}$ gas velocity
$\mathbf{u_p}$ particle velocity
V electric potential
v dimensionless particle charge
w dimensionless electric field
$\mathbf{x_p}$ particle position

ρ air density
ρ_p particle density
ρ_c space charge density
ε_0 air dielectric constant
δ T_0P/TP_0

INTRODUCTION

Electrostatic precipitators (ESP) have been widely used to remove fine particles (0.1 ~ 100 μm in diameter) from the flue gas emitted in many industries. It has been proved to have a high mass efficiency over 90% and the advantages of large handling capacity as well as low overall resistance. However, its removal efficiency for smaller particles (< 10 μm) is still poor. These micron or sub-micron size particles are detrimental to human respiratory system and further improvement to the collection efficiency of these particles is important.

In an ESP, the particle transport and deposition are controlled by the electric field and the turbulent gas flow. The complexity of the gas turbulence flow, as a joint result of the geometric structure, the EHD and their interaction, makes the research rather difficult. Consequently, the knowledge of the gas flow structure and its effect on particle collection is still limited to date. Experimental analysis is difficult because of the presence of the electrostatic field, which influences measurements of laser Doppler anemometers and hot-wire probes. Therefore, in the last twenty years, researchers tended to use numerical simulation to address this issue. Soldati (2000) utilized Direct Numerical Simulation (DNS) to study the influence of ionic flows on particle transport and collections. His simulation results indicated that the ionic flow has a negligible influence on the particle collection efficiency. Farnoosh et al. (2010) reported a simulation for a wire-plate ESP and stated that the electro-aerodynamic flow has a negligible effect on the ESP performance. However, other opinions were also presented in the previous literatures. The multi-wire and plate ESPs were simulated by Schmid (2003) to investigate the effect of inhomogeneity in the turbulence and ionic secondary flow on the precipitation process. The simulation results show that ionic flow slightly decreases the particle precipitation. Nikas et al. (2005) carried out a numerical modelling of an experimental laboratory scale ESP. Their results show that the ionic wind creates significant secondary flows that have a degrading effect on the collection efficiency, particularly for smaller particles. Talaie (2005)'s simulation demonstrated that the secondary flow has a negative effect on the dust removal efficiency. To sum up, no definite conclusion has been reached regarding the effect of the EHD flow on the particle collection efficiency.

Here in the current paper, a comprehensive numerical model is developed with FLUENT solver combined with user defined functions (UDF) to study the EHD flow and its effect on the particle collection in a wire-plate ESP. The particle transport and collection in a four-wire and plate ESP unit is simulated with and without EHD secondary flow. The particle collection efficiencies along the plate for the two cases are analysed statistically and comparisons are made.

MODEL DESCRIPTION

Electric corona

In corona generation process, the distribution of electric potential and electric field intensity are governed by Gauss law as:

$$\nabla^2 V = -\rho_c / \varepsilon_0 \qquad (1)$$

here, $-\nabla V = \mathbf{E}$

Continuity equation of electric current:

$$\nabla \cdot (\mathbf{J}) = 0 \qquad (2)$$

$$\mathbf{J} = \rho_c (b\mathbf{E} + \mathbf{u}) - D\nabla \rho_c$$

In this model, the ion diffusion is neglected as the velocity of ions diffusion is much smaller than that caused by the effect of electric field and wind flow. Hence the ion mobility *b* is assumed to be a constant.

Wind flow and turbulence model

As the wind velocity is low (< 5m/s) in the channels of a typical ESP, the wind flow can be assumed to be an incompressible viscous flow. Reynolds-averaged Navier-Stokes equations are used to describe the continuity and momentum conservation of the gas flow. A Coulomb force, $\rho_c \mathbf{E}$, is added as a source term of the momentum equations to model the effect of electric corona on the wind flow. The standard k-ε model is used to model the turbulence quantities and close the Navier-Stokes equations.

Particle tracking

Lagrange approach is used to model the particle transport. The trajectory of a particle is determined by its initial velocity and the forces acting on it. Apart from the aerodynamic forces, particles are charged by the ions along the way and an electrostatic force acts upon the charged particle. The position and speed of an individual particle are determined by Newton second law of motion which is given by:

$$\frac{d\,\mathbf{x_p}}{dt} = \mathbf{u_p} \qquad (3)$$

$$\frac{d\,\mathbf{u_p}}{dt} = \frac{3\rho\, C_D\, (\mathbf{u} - \mathbf{u_p})|\mathbf{u} - \mathbf{u}_p|}{4\,\rho_p\, d_p} + \mathbf{F_{EP}} + \mathbf{F_o} + m_P \mathbf{g} \qquad (4)$$

where, C_D is calculated using the equations from Morsi & Alexander (1972).

The electrostatic force is proportional to the electrostatic field and the particle charge:

$$\mathbf{F_{EP}} = q_p\, \mathbf{E}$$

here, q_p is the particle charge. The dimensionless charging rate is calculated using the following formula given by (Lawless, 1996):

$$\frac{dv}{dt_q} = \begin{cases} f(w)\frac{(v-3w)}{\exp(v-3w)-1}, & v > 3w \\ 0.75w(1-\frac{v}{3w})^2 + f(w), & -3w \le v \le 3w \\ -v - f(w)\frac{v+3w}{\exp(-v-3w)-1}, & v < -3w \end{cases} \qquad (5)$$

where $f(w)$ is the fraction of the surface covered by the diffusion band:

$$f(w) = \begin{cases} (w+0.475)^{-0.575}, & w \ge 0.525 \\ 1, & w < 0.525 \end{cases} \qquad (6)$$

where $v = e\, q_p / (2\,\pi\,\varepsilon_0\, d_p\, k\, T)$ and $w = (K_p/(K_p+2))(E d_p\, e/2kT)$ is dimensionless particle charge and dimensionless electric field, $t_q = \rho_c\;bt/\varepsilon_0$ is the dimensionless particle charging time.

The particle trajectory is also changed by the turbulent fluctuation of the wind flow. Here, discrete random walk model (DRW) is utilized to model the turbulent dispersion of the particles (Graham & James, 1996).

VALIDATION OF THE ELECTRIC CORONA MODEL

Boundary conditions

For the wire – plate ESP, the corona region around the wire is neglected and the corona boundary is assumed to be the same as the wire surface. The boundary conditions are defined as follows:

Wire surface: $V = V_0$, ρ_c is adjusted to meet Peek's law (Peek, 1929)

Collecting Plates: $V = 0$, $\partial\rho_c/\partial n = 0$

Peek's law indicated that the electric intensity on the corona boundary cannot exceed the following value:

$$E_{on} = A\delta + B\sqrt{\delta/r} \quad (7)$$

where E_{on} is the electric field at the start of corona, r is the radius of discharge electrode, A and B are empirical constants and usually have values 32.3×10^5 V/m, and 0.846×10^5 V/m$^{1/2}$. δ is T_0P/TP_0, T_0 is 293 K, P_0 is 1.01 ×10^5 Pa, and P and T are the operating pressure and temperature, respectively.

Validation

Before simulating the turbulent wind flow and particle collection, we need a reliable electric corona model that can accurately predict the electric field in ESP. In this regard, the electric field without considering the effect of wind flow was simulated first and compared with the published experimental data for wire-plate ESP. Figure 1 is an example of the comparisons which clearly indicate that the simulated results including the distributions of potential, electric field intensity, space charge density and current density are in good agreement with the measured data. Therefore, the corona model and the boundary conditions used here are reasonably reliable.

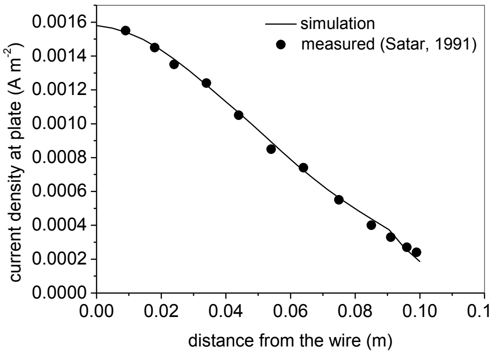

Figure 1: Comparison between simulated results and experimental data

SIMULATION METHODOLOGY

The simulation domain is defined as a 2D space as shown in Figure 2. A geometric configuration with four-wires in series and two parallel plates is used to examine the particle transport and deposition along the ESP channel. The voltage applied on each wire is 40 kV. The inlet velocities are set to be uniformly distributed and the values are 0.3~1.8 m/s. 400 mono-dispersed particles with the diameters of 1.5 μm are introduced into the domain from the inlet at uniformly distributed positions. The initial particle speed is the same as the inlet gas velocity. The particle trajectories are recorded for the two cases, with and without EHD secondary flow under various simulation conditions. All the particles colliding with the plates are considered to be collected.

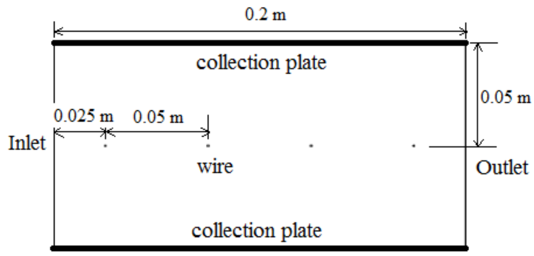

Figure 2: Simulation domain and its dimensions

SIMULATION RESULTS

The wind flow

The EHD secondary flow has a significant effect on the primary flow. Figure 3 shows the comparison between the flow fields with and without the influence of the EHD secondary flow. A so-called EHD number, $N_{EHD}=Jh/(\rho b u_0^2)$, was introduced to describe the intensity of the electricity induced secondary flow. The figure shows that for small N_{EHD}, the streamlines of the primary flow is slightly pushed towards the plates after the wires, but with the increase of N_{EHD}, a pair of vortices are formed in the downstream region of the wires. Another pair of vortices is also formed in the upstream regions for

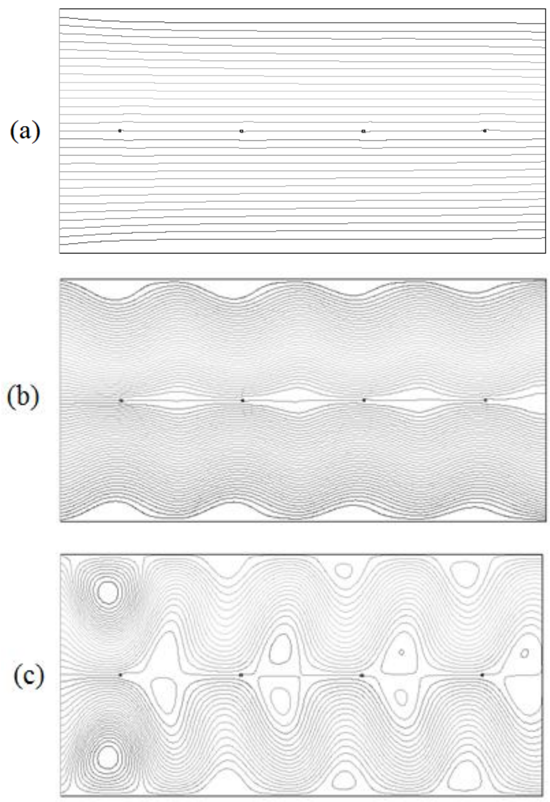

Figure 3: Flow streamlines for various N_{EHD}: (a) 0; (b) 10.3; (c) 15.6:

further increased N_{EHD}. The patterns of the streamlines before the first wire and in the region between the neighbouring wires agree well with the measured results from Yamamoto & Velkoff (1981).

Particle transport and collection

Figure 4 is an example of the particle trajectories simulated. The cumulative collection efficiencies along the plate in the stream-wise direction are analysed and the some data points are shown in Figure 5. From the figure, it can be seen that for the non-EHD and EHD cases, the collection efficiency increases in a similar law with the distance from the inlet. However, the cumulative collection efficiencies for the wind flow without EHD secondary flow are higher than those for the wind flow with EHD secondary flow. These results indicate that the electric field and primary flow play a major role in determining the particle trajectory and collection, whereas the structure of EHD local flow has a secondary effect. The existence of the EHD secondary flow promotes the generation of the vortices and eddies so that the effect of turbulence fluctuation on the particles increases, and most particles need a longer journey to reach the collection plates due to the increasingly random variation of the trajectories. This may explain why the particle collection efficiency is lower when the EHD secondary flow occurs. Accordingly, it is proposed that improvements should bemade in geometry and operation conditions in ESPs to eliminate the effect of the EHD secondary flow.

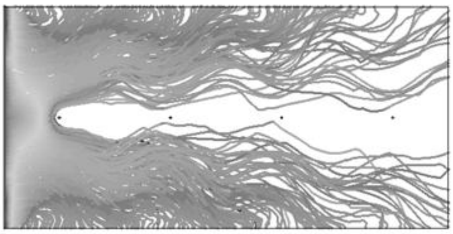

Figure 4: Particle trajectories

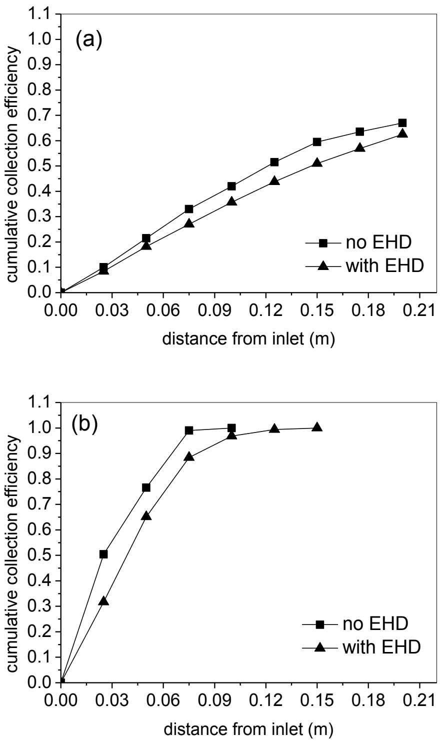

Figure 5: Cumulative collection efficiency for V=40kV and d_p=1.5 μm: (a) u_0=1.8 m/s; (b) u_0=0.3 m/s

CONCLUSIONS

In order to clarify the effect of the EHD secondary flow on the particle transport and collection in an ESP, the wind flow and particle trajectories in a four-wire and plate ESP are simulated using the FLUENT solver combined with the subroutines developed by user defined functions. The turbulent flow is modelled with Navier-stokes equations closed by k - ε model and the particle dispersion is simulated with the random walk model. The EHD secondary flow and particle collection efficiencies for the gas field with and without EHD secondary flow are simulated and compared. The results indicate that the particle trajectory and collection are controlled not only by the electric field and inlet wind velocity, but also by the EHD secondary flow. The EHD secondary flow has a negative effect on the particle collection efficiency due to the increased turbulence dispersion of particles resulting from the EHD induced vortices.

ACKNOWLEDGMENT

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