Numerical Analysis of Ionic Wind Induced EHD Turbulence Flow Inside ESP

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Abstract—Electrostatic Participator (ESP) was used as an industrial dust removal equipment for over a century. Currently, most common efficiency estimate method is Deutsch’s equation, which consider particle removal efficiency is majorly related to specific collection area. However, a number of experimental results shown that the flow pattern inside ESP are also have a huge influence on collection efficiency. In order to visualize the flow pattern inside ESP, Numerical analysis method was applied. This also provided a better understanding about the Electro Hydrodynamic (EHD) turbulence flow and its impact on collecting efficiency. A simple wire-plate ESP model was being built and Finite Element Method (FEM) algorithm was applied to simulating flow pattern inside ESP, other physical elements and their coupling effects on particle trajectory were also considered, such as electric field, turbulence and gravity. The particle evaluation results shown that the major force applied on particles is electric force, followed by drag force. Under the stationary wall condition, the difference can reach 1-2 orders of magnitude. However, by extra 3-D flow tendency created by moving wall function, drag force gradually equaled to electric force.

Keywords—Numerical analysis, electro hydrodynamic flow, Multiphysics, particle evaluation

I. INTRODUCTION

Electrostatic precipitation (ESP) is a gas filter device which has large application on many industrial properties. High collection efficiency (99% for modern industrial types), relevantly low running cost make it became an important industrial technology since the early 1900s. However, further improving the collection efficiency is still necessary in order to meet higher emission standards. The principal of ESP is to drive charged particles to collection plate by electric forces. But other forces such as drag force created by primary flow and secondary electrohydrodynamic (EHD) flow—corona discharge creates moving ions, they collide with neutral gas molecules can induce gas motion—can also alter the trajectory of particles, making them not only harder to predict, but also influence the collecting efficiency significantly. In order to better understanding the trajectory of particles inside ESP, complex interaction of particle charging, electric field and turbulent flow has to be taken into consideration.

Laser-Doppler velocimetry (LDV), particle image velocimetry (PIV) systems and hot wire anemometers were major experimental methods on flow patterns visualize and EHD flows measurement [1], [2]. Mizeraczyk et al. [3] used 2-D PIV and 3-D PIV measurements respectively to investigate the EHD flow patterns in a multi-wire ESP with a laminar primary flow. Other aspect such as the particle collection efficiency of different particle diameters, wire geometry and different applied voltage were also presented [4], [5]. According to their results, the combination of primary flow and EHD flow make the mean flow pattern rather complicate. Resulting strongly 3D particle trajectories characteristics in the narrow ESP.

Due to experimental analysis has many limitation and restriction, such as interfere of the electrostatic field on measurements, limited view angle, relatively low efficiency on result output, etc. Numerical analysis has been widely preferred.

Finite Element (FEM)-Method of Characteristics (MoC) [6], [7], FEM-Boundary Element (BEM)-MoC [8], FEM-Charge Simulation (CSM) [9], FEM-Donor Cell (DCM) [10] and Finite Difference (FDM)-MoC [11] were applied major on obtaining electrical characteristic for 2-D ESP model. These methodologies were applied to obtain the electric field and charge density distributions, and V-I characteristics of corona discharge in a 2-D ESP model. Soldatii [12] and Skodras et al. [13] used DNS (Direct Numerical Simulation) to tracing particles in a multi-wire ESP. Using a Lagrangian approach, the effects of EHD flow and turbulence and collection efficiency were analyzed. It was also compared in the paper that collection efficiency for different particle sizes with and without EHD flow. According to their results, EHD flow has negligible influence on the overall particle collection and on particle deposition at the walls.

Although, various numerical techniques for modeling ESPs have been reported, each modeling methods has their limination. The actual situation inside ESP is rather hard to obtain. In most cases the results were compared with the related experimental data from other references.

In this paper, multiple effects were taken into calculation to simulate the 3-D particle trajectories in a simple two wire ESP configuration. This technique is based on FEM to calculate the electric field, the electric potential and the space charge density inside ESP cabinet. The airflow distribution, particle trajectories and deposition efficiency have been simulated by a commercial software package COMSOL. During calculation we assumed uniform negative corona distributed on the surface of wire electrodes, which will induce electrostatic fields, particle charging, EHD flow and electrical forces on particles. The algorithm was presented in the next chapter. Secondly, the
interactions between primary flow and secondary EHD flow indicates the combined influence on the particle trajectories inside ESP.

II. MODEL DESCRIPTION AND NUMERICAL ALGORITHM

The investigated model contains typical component of conventional ESP. as depicted in Fig. 1, the size of inner channel is 1 m \times 0.4 m \times 0.2 m. Two grounded collecting plates were vertically located on both inner side wall. The distance between two plates was 0.4 m. Two wire electrodes (20 mm diameter) located at the center of ESP, the projectile coordination of each wire on Y-axis was 0.25 m and 0.75 m, respectively. A negative 72 kV DC high voltage was applied on both wire electrodes. The gas temperature was set at 180 \degree C in order to simulate the environment in the real operation situation. The boundary condition for grounded electro plates were vertical and ion mobility k = 2.4 \times 10^{-4} m^2/Vs.

The Finite Element Method (FEM) algorithm has been implemented to solving each governing equations. three physical fields (electric field, flow field and gravity field) were taken into calculation to find their coupling influence on particle trajectory inside ESP. the basic governing equations for each field are shown as follow:

A. Electric field

The static electric potential V is defined by the relationship:

\[ E = -\nabla V \]  

Also, given the constitutive relationship between the electric displacement D and the electric field E as: \[ D = \varepsilon_0\varepsilon_r E, \] Gauss’ law can be represented as the following form:

\[ \nabla \cdot D = \rho_v \]  

\[ \nabla \cdot (\varepsilon_0\varepsilon_r) = \rho_v \]  

And the boundary condition for grounded electro plates are defined as follow:

\[ n \cdot D = 0 \]  

E is electric field intensity, D is electric displacement or electric flux density, \( P \) is the electric polarization vector, \( \rho \) is electric charge density, \( \varepsilon_0 \) is the permittivity of vacuum, and \( \varepsilon_r \) is the relative permittivity.

B. Particle charge

In this modeling, only field charging was considered in order to simplifying the calculation. The expression for particles charging at electrostatic field are [14]:

\[ q(t) = q_\infty \frac{t}{1 + t/c} \]  

\[ q_\infty = \frac{3\varepsilon_s}{\varepsilon_r + 2d_r^2} \]  

where \( q_\infty \) is the saturation charge, \( t \) is the charging time, \( \tau \) is the time constant of the field charging, \( \varepsilon_0 \) is the permittivity of vacuum, \( \varepsilon_r \) is the specific permittivity, \( d_r \) is the particle diameter, and \( J \) is the current density.

C. Turbulence flow model

The Reynolds-averaged Navier-stokes (RANS) equations are applied for calculating turbulence flow. We assume the fluid inside ESP channel as Newtonian fluid (compressible). For such situation, CFD computing containing four components, which are [15]: Momentum conservation:

\[ \rho(u \cdot \nabla)u = \nabla \cdot \left( -pI + \left( \mu + \mu_T \right)(\nabla \cdot u)I - \frac{2}{3} \rho \varepsilon I \right) + F \]  

Mass conservation

\[ \nabla \cdot (\rho u) = 0 \]  

Energy conservation

\[ \rho(u \cdot \nabla)\kappa = \nabla \cdot \left[ \left( \mu + \frac{\mu_T}{\sigma_k} \right) \nabla \kappa \right] + P_\kappa - \rho \varepsilon \]  

Dissipation

\[ \rho(u \cdot \nabla)\varepsilon = \nabla \cdot \left[ \mu + \frac{\mu_T}{\sigma_k} \nabla \varepsilon \right] + C_{e1} \varepsilon \kappa - C_{e2} \varepsilon^2 \frac{k}{\varepsilon} \]  

\[ \varepsilon = \varepsilon_p \]  

\[ \mu_T = \rho \alpha \frac{k^2}{\varepsilon} \]  

\[ P_b = \mu_T \left[ \nabla u \cdot \left( \nabla u + (\nabla u)^T \right) - \frac{2}{3} (\nabla \cdot u)^2 \right] - \frac{2}{3} \rho k \varepsilon \nabla \cdot u \]  

where u is velocity field (SI: m/s), p is pressure (SI: Pa), \( \rho \) is mass density, I is unit matrix, F is mean-flow flux vectors, k is turbulent kinetic energy, \( P_b \) is net production per unit dissipation of k, \( \varepsilon_p \) is turbulent dissipation rate, \( C, \mu, \sigma \) are closure coefficients.
space. But the flow near the collecting plate was showing high proportion of the primary flow by occupying large area of inner ESP channel. Obstructed most of the collecting plate, creating a complex, symmetric flow structure. In this case, wire electrodes generated ionic wind towards both collecting plates. Corona discharge altered the primary flow significantly. The original trajectory of particle near the collecting plate experience a very limited electric force to alter its motion. Thus the particle near the collecting plate and sphere shape near the wire. The strongest discharge occurs at the very close radius area along the corona wire. Particle inside this area will be charged most effectively, Coulomb force near this area will create turbulence to the primary flow, making it hard to distinguish the source of generated vortices (from EHD flow or turbulence of primary flow).

**A. Electric field**

As depicted in Fig. 2, the electric field are shown as multislice (each slices were set at the middle of each axis), and electric potential was shown as contour graph. It can be seen from the picture that constant electric potential was formed along with discharge wires. Generating more ellipsoidal shape near the plate and sphere shape near the wire.

The strongest discharge occurs at the very close radius area along the corona wire. Particle inside this area will be charged most effectively, Coulomb force near this area were also strongest. At the further area, electric field density decrease significantly. Thus the particle near the collecting plate experience a very limited electric force to alter its original trajectory.

**B. Velocity field and streamline**

It can be clearly seen from Fig. 3 that, when the primary flow at very low velocity, the EHD flow generated by the corona discharge altered the primary flow significantly. The wire electrodes generated ionic wind towards both collecting plate, creating a complex, symmetric flow structure. In this result, six obvious vortices in the mean flow. Obstructed most of the primary flow by occupying large area of inner ESP space. But the flow near the collecting plate was showing high speed. Which is not ideal for collection efficiency due to it can decrease the residence time significantly.

However, along with growing primary flow speed, two vortices in the upper stream was vanished, and the strength of each vortex were decrease rapidly. When the primary velocity at 1.5 m/s, only small vortices behind wire electrodes remains.

Furthermore, it was also shown in the Fig. 3 that under this configuration, the tendency of the flow pattern was still basically 2-D, no obvious 3-D structure can be witness.

**C. Particle evaluation**

Shen et al. [16] has thoroughly investigated the relationship between applied voltages and collection efficiency of different particle sizes (0.03–8 μm), result suggested that the collection efficiency was not always increase with applied voltage, at around 10 (kV/cm)² collection efficiency hit the peak and gradually decreased. Which indicate that the EHD flow shown negative impact on collection efficiency when high voltage applied.

In this simulation, four different diameter particles (0.3, 1, 2.5, 10 μm) were released in the ESP in order to reveal the particle trajectory. The movement of particles inside ESP is major defined by the applied Coulomb force, drag force and gravity force.

As can be seen in Fig. 4, the trajectory of particle generally obeys the flow pattern. In the vortices area, particles been trapped inside and moving relatively slow. Those particles showing insignificant tendency on moving towards collecting plates, which means they are much harder to be collected. Furthermore, particles have greater speed near the collecting plates, and electric field are weak at this region. The former has shortened the residence time of particles. As for fastest particles, the residence time can be as little as 1 second (1/10 of mean residence time). The latter means Coulomb force applied on this region were much weaker than center. Those particles have more tendency to be carried out by the flow rather than be collected on the plates. Those were main affects which can influence collection efficiency significantly.

However, when the primary flow velocity increase, fine particle also shown greater tendency to be directly carried to the outlet by the flow rather than been collected. Particle trajectory were only altered at the region very near to the discharge electrodes. This phenomenon partially due to the limited charges on the fine particles, also because particles with small aerodynamic diameter tend to follow mean flow more.

In order to evaluate the main effect on particle movement, 100 particles were sampled and each applied force were calculated. The averaged result can be seen as Fig. 5. The result suggests that major effect on particle movement was drag force created by the mean flow. Another was the electric force created by electrostatic field. But the difference between them was insignificant, meaning they have equal contribution on particle trajectory. And the applied forces were also rising with growing particle diameter. On the other hand, gravity has very limit impact on movement for submicron particles. For 0.3 μm, gravity only equal to 1/1000 of electric/flow
Fig. 3. Velocity field (multislice) and streamline of mean flow pattern after introducing EHD flow at different primary flow velocity. a) 0.1 m/s, b) 0.5 m/s, c) 1 m/s, d) 1.5 m/s.

force. However, the effect of gravity rises faster than the drag force and electric force within rising particle diameter. For 10 µm particles, gravity is in the same magnitude with electric force. Plus, for most ESP, the direction of gravity is usually perpendicular with other two force. Which can explain the reason for different collection efficiency for various particle diameter.

Particles in the center region can be driven by maximum Coulomb force, but this region occupied by vortices. Particles near the plate cannot be collected due to high speed. This

Fig. 4. Particle trajectory inside ESP at different primary flow velocity. a) 0.1 m/s, b) 0.5 m/s, c) 1 m/s, d) 1.5 m/s.
result indicated several directions for further optimization on ESP to increase the collection efficiency, one is to decrease the strength of vortices (i.e. by changing wire geometry or using collecting plate with different shape) to make the mean flow more evenly distributed. Another is to decrease the speed of particles near the collecting plate (i.e. applying higher voltage to increasing the electric field density).

**IV. CONCLUSION**

In this paper, a FEM-Multiphysics coupling method were applied to simulating the particle trajectory in ESP, the aim of this paper is to visualizing and evaluating the charged particle movement under several physical condition. It was found that the flow pattern in the ESP was rather complex due to EHD induced secondary flow. Complex flow structure may have un-negligible impact on collection efficiency. 6 vertices were generated in given model and parameters, which obstructed and created unevenly flow distribution in ESP channel.

In order to have a better understanding about the cause of particle movement in ESP, each applied force on particles were evaluated to compare and identify the major contribution effect.

Visualizing flow pattern and trajectory can not only reveal the particle movement tendency, but also reveal the main obstructing effect on collection efficiency. Which have significant importance on ESP optimization.

**REFERENCES**


