Computational Fluid Dynamics Approach to Evaluate Electrostatic Precipitator Performance

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Abstract

A computational model was developed for the simulation of Electrostatic precipitator (ESP) operation and the parameters of interest were evaluated by COMSOL Multiphysics 5.3. The model used takes into account the coupling between the air flow field, electric field, and particle trajectories. This paper also demonstrated the importance of applied voltage in the design of the ESPs in order to increase its particle trapping capability and the collection efficiency. The numerical results allow for estimation of ESP performance and can be considered as a valuable tool in the development of this type of technology in air filtration systems.

Keywords: CFD, Electrostatic precipitator, ESP, Particle efficiency

Introduction

In recent years, Air pollution-related illness receives remarkable attention and epidemiological studies show a consistent increase in cardiac and respiratory morbidity and mortality from exposure to particulate matter (PM) [1]. Several researchers have analyzed the particle behavior by means of computational fluid dynamics (CFD) software to characterize its harmful effects [2], [3]. Therefore, an efficient particle removing device is necessary to treat particulate matters in exhaust gases.

For this purpose, Electrostatic precipitator (ESP) is commonly used to collect particles from the air stream. An ESP consists of a charger in the upstream and a collector in the downstream. Once particles enter the system, they are charged in the charger, and then move toward the collector. The collector has a strong electric field between the high voltage electrodes and grounded collecting electrodes, so that charged particles are subjected to electric forces and travel to the collecting electrodes, where they settle. This paper employs a numerical model to show the effect of high voltage on the ESP and its impact on particle trap mechanism. The beginning of this paper discusses the theory behind the numerical model and the boundary condition. This is followed by discussions on the characteristics of the flow field, electric field and collection efficiencies.

Theory and Boundary Condition

During the simulation, it is assumed that the particle concentration is low enough and does not change the space charge density. The electric field is solved by using Poisson's equation

$$\nabla^2\varphi = -\frac{\rho_{el}}{\varepsilon_0} \qquad (1)$$

Where ρ_{el} is space charge density, ε_0 is vacuum permittivity and φ is electric potential.

The standard linear k-ε RANS model is used to predict the velocity field, because only the mean velocity field is needed in deriving the particle trajectory. Previous researches have revealed that the total particle charges are adequately reliable by adding up the field charging rate and the diffusion charging [4], [5]. Particles with diameter larger than 0.5 μm are charged by obtaining additional ions from the collisions with other charged particles (ions) which is usually referred to field charging. For particles smaller than 0.2 μm (fine), diffusion charging is the dominant effect.it is resulted from ionic collisions with the particles due to the random thermal motion of the ions [6]. Both field and diffusion charging can be seen in equation (2) and (3).

$$\frac{d_q\ f}{dt} = \pi b N_0\, d_p^2\, E_0 G\left(1 - \frac{q_e}{d_p^2\ E_0 G}\ \right)^2 \qquad (2)$$

$$\frac{dq_d}{dt} = \pi V_{rms}\, N_0 d_p^2\, exp\left(\frac{-qe^2}{d_p KT}\right) \qquad (3)$$

$$G = 1 + 2\,\frac{\epsilon_{p-1}}{\varepsilon_{p+2}} \qquad (4)$$

where q_f is field charging as a function of time t, q_d is diffusion charging as a function of time, b is ion mobility, N_0 is ion concentration, d_p is particle diameter, E_0 is electric field strength in the charger, e

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is elementary charge, V_{rms} stands for the root- mean-square thermal velocity of the ions, K is the Boltzmann constant, T is temperature, and ε_p is the relative permittivity of the particles. To make calculation easier, particles are assumed to be fully charged.

Particle trajectories are simulated according to the Newton's law, which is the inertial force resulting from vector sum of the electrostatic force and drag force for a single particle in an ESP. The gravity force is neglected because its magnitude is relatively small when compared to others

$$m_p \frac{dU_p}{dt} = \frac{3\pi\mu d_p}{C_c}\left(U - U_p\right) + q_p E \qquad (5)$$

where m_p is particle mass ($\pi d^3_p\, \rho_p /6$), ρ_p is particle density, U is the velocity field of the fluid, U_p is the velocity field of the particle, C_c is the Cunningham slip correction factor which is considered as 1.57 for particle diameter 0.3 µm and q_p is the total charge for particle .In equation (5), the first term on the right-hand side represents drag force, whereas the second term represents electrostatic force.

Figure 1 shows the simulation model for this study. Figure 1.a gives the 2D simulation domain for better understanding. The diameter for particles is 0.3 µm. Three different voltages (6 KV, 12 KV and 18 KV) applied to the discharge electrode. The re-entrainment and rebound factors are excluded in the simulation.

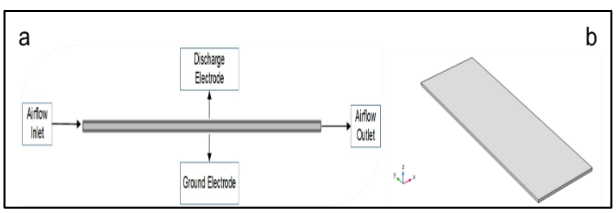

Figure 1. Numerical model.

The simulation is structured within three studies as follows:

•The "Turbulent Flow, K-ε" approach is used to simulate the velocity field.
•The "Electrostatics" module is used to simulate the electric field which is solved by equation (1).
•In addition, the particles are subjected to drag and electric forces, coming from the results of "Turbulent" and "Electrostatic" modules respectively. "Particle Tracing for Fluid Flow" is used to trace the particle trajectories.

Details of the boundary conditions are listed in Table 1:

Table 1. Boundary conditions.

	Flow field	Electric field	Particle transport
Inlet	U_x = 0 m/s U_y = 2 m/s U_z = 0 m/s		2000 Particles
Outlet	0 Pa		Freeze
Wall	No Slip		Freeze
Discharge electrode	No Slip	6/12/18 KV	
Collecting electrode	No Slip	Ground	

Results and Discussions

Flow Field

The velocity profile of fluid flow between two electrodes is illustrated in Figure 2 .The velocity is assumed to be 2m/s. The air flow is assumed to be steady and the result of this section is required to evaluate the particle trajectory. The "Turbulent Flow, SST" RANS model, is used to simulate the flow velocity fields. The SST combines the advantages of both the k−ε and k−ω methods. The k−ε turbulence model has a near-wall treatment allowing accumulation of nodes towards the wall without any special non-linear damping function, whereas the k−ω turbulence model is more accurate for flows involving strong streamlines curvature. The constant parameters for turbulence model in this study are: a_1 is 0.31, β_1 is 0.075, β_2 is 0.0828, $\sigma_{\omega 1}$ is 0.5, $\sigma_{\omega 2}$ is 0.856, σ_{k1} is 0.85, σ_{k2} is 1, K_v is 0.41, and B is 5.2.

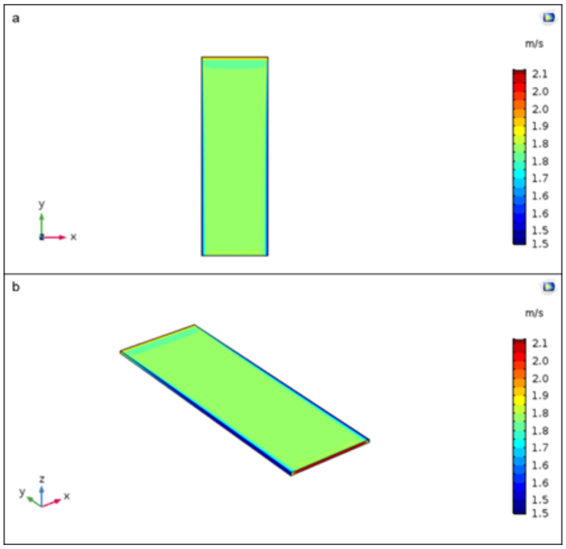

Figure 2. Velocity field and corresponding contour.

Electric Field

In Figure 3 , the electric field is demonstrated by directional arrows. As it can be seen, the discharge electrode voltage obviously changes the electric field strength. As expected, the highest electric field strength is for Figure 3.c where the applying voltage is 18 KV.

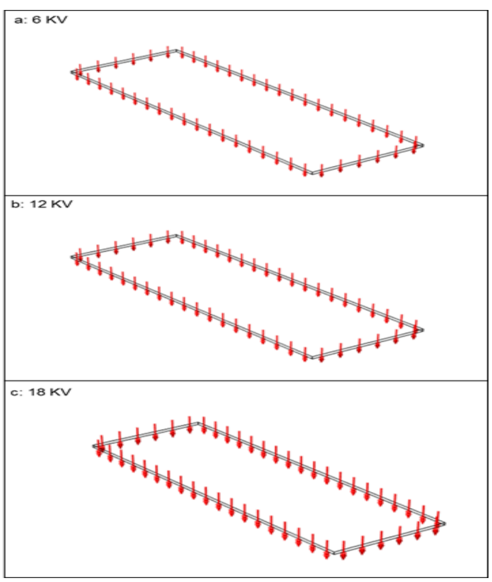

Figure 3. Electric field.

Particle Trajectory

Figure 4, gives the particle trajectories with different applying voltages where the color represents the resultant velocity of particles. Airflow direction and electrostatic force cause the particles settle down on the collecting electrode. Additionally, when the discharge electrode voltage increases, particles subjected to stronger electrostatic forces and collected farther before the outlet.

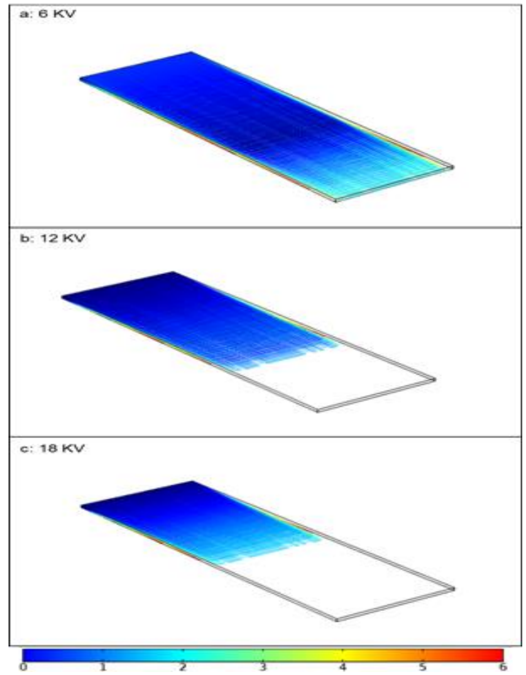

Figure 4. Particle trajectories.

Conclusion

Numerical simulation is carried out by modelling the particle transport, flow field, and electric field. This paper presents the flow and electrical characteristics of the ESP. Particle trajectories and collection efficiencies are also demonstrated. As it can be seen in the results, the particle deposition increases with increase of applied voltage for discharge electrode. Furthermore, the results confirmed the effectiveness of the ESPs for dust collection and the power of COMSOL Multiphysics software for particle behavior studies.

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