Particle Tracking for Incompressible Flow in Electrical Field

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\textbf{Abstract}. In this paper, the motion of charged particles for incompressible flow in electrical field has been investigated. Two applications have been simulated and compared with experimental results. The first one is a simulation model for electric filter made of split type fiber. This simulation has been developed to study the filtration efficiency. The filter was assumed to be composed of rectangular fibers arranged in staggered array field. Single fiber efficiencies under various filtration conditions were calculated and compared with results obtained from semi-empirical expressions derived from experimental data. The second one is the numerical simulation of electrostatic powder painting. The purpose of this study was to understand the gas and particle flow fields inside a coating booth under given operating conditions and the effect of particle sizes on its trajectories. The continuous gas flow was calculated by solving Navier–Stokes equations including the standard $k$–$\epsilon$ turbulence. The discrete phase was modeled based on the Lagrangian approach. In both cases the flow field and the collection mechanisms were simulated using Fluent software. All results are in good agreement with experimental data.

Key words: Particle/gas flow, Numerical simulation, Electret filter, Powder coating
1 INTRODUCTION

An electret filter contains fibers that have a quasi-permanent electric charge which aid in capturing particles. Electret filters are widely used in those conditions that demand high-efficient cleaning. Electret fiber can be classified into spun type and split type. Typically a split fiber has tape-like cross-section and carries a high bipolar charge. Many investigators have carried out experiments to study the effects of different parameters on the collection efficiencies of the electret filters. In some studies, numerical simulated were also involved (Baumgartner and Lo€ffler, 1986; Baumgartner et al. 1993), while in the others, useful expressions were derived for evaluation of overall collection efficiency and for evaluation of single fiber efficiency due to individual capturing mechanisms such as the dielectrophoretic and electrophoretic capture mechanisms (Kanaoka et al. 1987; Romay et al. 1998). In addition, simulations for the flow field, particle trajectory and particle deposition have also been investigated by Brown (1981), Oh et al. (2002), and Kanaoka et al. (2001). As far as electret fibers are concerned, the numerical models were mainly for circular fibers (Oh et al. 2002, Kanaoka et al. 2001) or based on circular cross-section assumption.

Powder coating is considered a more economical and ecologically friendly process compared to wet painting due to the avoidance of solvents. Electrostatic powder spray painting is of significant industrial interest since it offers many advantages and great flexibility. Bottner and Sommerfeld (2002) used computational fluid dynamics (CFD) to simulate a complete electrostatic powder coating process under the Laplace condition using two types of corona spray guns, a slit nozzle and a round nozzle with a dispersion cone, and two types of coating parts, a flat plate and a tube. The results agree well with the experimental data for both the particle velocity field and the coating layer thickness. However, they ignored the effect of space charge on the electrostatic field and the effect of ion wind, which is generated by collisions between ions and molecules with neutral charge, on airflow field. Ye et al. (2002) simulated the electrostatic powder coating process using the commercial CFD code, FLUENT v5.2. The corona spray gun was used. They considered the influence of space charge due to charged particles on the overall electrostatic field, but ignored the effect of ion wind. The direct interaction between particles and the effect of the particle motion on the continuous phase were neglected. The numerical results were compared with the experimental data and good agreement was found for air velocities and coating layer thickness. Later, Ye and Domnick (2003) extended the above model to consider the space charge due to the free ions, but did not include the space charge due to charged particles and the effect of the particle motion on the continuous phase. In this paper, a complete powder coating process was modeled and simulated using a commercial CFD code, FLUENT v6.3.

2 Model setup

The present models can be divided into several sub-models in which the flow field, the electrostatic field.

2.1 Flow field setup

Electrostatic filter:
To solve the flow field inside the filter, a staggered arraymodel initially proposed by Fardi and Liu (1992a) is used in which infinitely long parallel rectangular fibers are placed perpendicular to the main flow direction, as schematically shown in Fig. 1. Space between the fibers is decided according to the packing density, $\alpha$, of the filter. Chen et al. (2002) solved the two-dimensional flow field through this staggered array model with improved
numerical techniques. The flow is assumed to be periodic within the domain along the flow direction (Patankar et al. 1977) and thus the flow field inside the module AEFD will provide a typical representation of the flow pattern through the filter. since one half of the periodic module, ABCD, is a symmetrical inversion of the other half BEFC, the problem can be simplified by considering either half of the periodic module. Flow inside the cell ABCD is solved by numerically integrating the Naiver-Stokes equations by applying appropriate boundary conditions. Details of flow field computation are in Chen et al. (2002). In this study, the model of Chen et al. (2002) is used to simulate the flow field of an array of staggered fibers with rectangular cross-section.

Electrostatic powder coating:
A typical powder coating process consists of a fluidized bed hopper, a powder transport line from the hopper to the spray gun, an electrostatic spray gun, a coating booth and the workpiece to be coated. The dimensions of the coating booth and the relative positions of the gun and coating part are shown schematically in Fig. 1. A 3 cm diameter suction hole at the top wall of the booth, as shown in Fig. 1, was used to maintain negative pressure inside the booth. So the powder particles will stay inside the booth. The back wall functions as a particle collector. Fig. 1 and Fig. 2 show the Configuration of filter and powder coating.

![Fig. 1 Scheme of staggered fibers’ array, vertical fiber arrangement](image1)

![Fig. 2. Coating booth dimensions and spray gun position](image2)

The 15 cm long corona spray gun as shown in Fig. 3 was used to spray the powder particles. The air fluidized powder flows through the annular space between the central trumpet shaped cylindrical deflector and the outer gun body. The adjustable gun sleeve, which is used to adjust the powder flow pattern, was kept through out the study with the same position as shown in Fig. 2. The thin wire electrode, which is mounted at the center of the deflector plate, was applied with _50 kV to generate the electrostatic field between the gun and the grounded
coating part. The radius of the tip of the electrode was 0.3 mm. The 7.6 cm *13.2 cm sized coating part was mounted 26 cm downstream of the gun-tip. The air fluidized powder spray flow inside the coating booth was simulated as a two-phase flow with air as the continuous and the particles as the dispersed phase. In the present study, the particle volume fraction is less than 0.1% and hence the process is a dilute gas–solid two-phase flow in the regime of two-way coupling. The two-way interactions between the gas and particulate phases are included in the drag source terms in the momentum equations for both phases. The effect of possible particle–particle interaction on the flow is neglected. The effect of the space charge due to free ions on the electrostatic field was included in the transport equation for the electrostatic field. The effect of ion wind, which could have strong influence near the gun electrode region, on the airflow field is ignored, which means the electrostatic field affects the airflow only through its influence on particle trajectories by adding electrostatic body force on particles.

2.2 Electrostatic field setup

To determine the electrostatic collection mechanisms, it is necessary to know the electrostatic field around each electret fiber. For loosely packed filter (packing density a < 0.1), the interaction between electrostatic fields generated by individual fibers can be neglected (Rao and Faghri, 1990). Surface charge on an electret fiber is considered as an arrangement of many parallel line charges of infinite extent along its axis (Emi et al. 1987). Accuracy is ensured when the line pair number is large enough. Figure 4 illustrates the model: electrostatic field at any point around the fiber can be determined by the sum of electrostatic fields generated by each of the line charge pair i.

Fig. 3. Cross-sectional view of Nordson corona spray gun.

Fig. 4 Simulation of electrostatic field at certain point around a split fiber
\[ \mathbf{E} = \sum_{i=1}^{n} \mathbf{E}_i^+ + \mathbf{E}_i^- = \frac{\lambda}{2\pi \varepsilon_0} \sum_{i=1}^{n} \frac{r_i^+}{(r_i^+)^2} - \frac{r_i^-}{(r_i^-)^2} \]

where \( n \) is the number of line charge pair and \( \varepsilon_0 \) is space permittivity, \( r_i^+ \) and \( r_i^- \) are displacement vectors and

\[ \lambda = \frac{b \sigma}{n \varepsilon_f} \]

\( \varepsilon_f \) is dielectric constant of fiber material and \( \varepsilon_f = 5 \). Thus the Coulombic force \( \mathbf{F}_C \) for singly charged particle and the polarization force \( \mathbf{F}_P \) for neutral particle can be expressed as:

\[ \mathbf{F}_C = e\mathbf{E} \]

\[ \mathbf{F}_P = \frac{\pi}{4} \left( \frac{\varepsilon_p - 1}{\varepsilon_p + 2} \right) \varepsilon_0 d_p^3 \text{grad} |\mathbf{E}|^2 \]

\[ \mathbf{F}_e = \mathbf{F}_P + \mathbf{F}_C \]

But for neutral particle \( \mathbf{F}_P \) is zero. Trajectories of particles that are released from the cell inflow surface AD (Figure 1) are traced and recorded as they flow through the cell domain ABCD. The ratio of number of particles captured to total number of particles released, after being normalized by height of the fiber, will yield the single fiber efficiency

\[ \eta = \frac{\text{capture particle number}}{\text{total particle number}} \cdot \frac{2h}{a} \]

in which \( a \) is the fiber height, i.e. the thickness of the fiber facing the incoming flow. The trajectory of a particle can be determined by solving the equation of motion of the particle as it travels with the fluid under the influence of various forces. For a spherical particle within the Stokes regime, the equation can be written as:

\[ \frac{du_i^p}{dt} = F_D(u_{ai} - u_i) + F_{\text{Saff}} + F_{\text{Virtual}} + F_{P,G} + F_{\text{Brownian}} + F_e \]

\( F_D \) is drag force, \( F_{\text{Saff}} \) is saffman force, \( F_{\text{Virtual}} \) is force due to virtual mass, \( F_{P,G} \) force due to pressure gradient, \( F_{\text{Brownian}} \) is Brownian force and \( F_e \) is electrical force.

A high negative voltage is applied to the emitting electrode at the gun-tip to generate the electrostatic field between the electrode and the grounded electrode, the coating part. The electrostatic field can be described by a Poisson equation

\[ \nabla^2 V = -\frac{\rho}{\varepsilon_0} \]

where \( \rho \) is the space charge density and \( \varepsilon_0 \) is the electrical permittivity of the gas phase. The \( V \) potential is related to the electrostatic field intensity, \( E \), according to
The space charge represents the contribution of free ions and charged particles to the overall electrostatic field. The space charge due to charged particles was not considered in this study because earlier work (Bailey, 1998; Ye and Domnick, 2003) suggested that its contribution to the total space charge is 1/10th of the ionic space charge. The ionic space charge density, \( \rho \), is related to the current density, \( J \). With the assumption of constant ion mobility, the correlation between \( J \) and \( \rho \) can be described as:

\[
\vec{J} = \mu_0 \vec{E} - D \nabla \rho
\]

where \( D \) is the diffusion coefficient. The value of ion mobility, \( \mu_0 \), can be taken from \( 1.82 \times 10^{-4} \text{ m/s} \) to \( 2.2 \times 10^{-4} \text{ m/s} \text{ } \text{ms}^{-1} \) (Ye and Domnick, 2003 and Anagnostopoulos and Bergeles, 2002). The value of \( 2.0 \times 10^{-8} \text{ m/s} \text{ ms}^{-1} \) was used in this study. The current density, \( J \), satisfies the following conservation equation:

\[
\nabla \cdot \vec{j} = 0
\]

Substituting Eq. (10) into Eq. (11) and combining with Eqs. (8) and (9), yields the following partial differential equation for the space charge density:

\[
D \nabla^2 \rho + \mu_0 \nabla V \cdot \nabla \rho = \rho^2 \mu_0 \frac{1}{\varepsilon_0}
\]

Eqs. (8) and (12) were solved iteratively to obtain the electrostatic field. These equations were incorporated into the numerical model using the user defined scalar transport equations and user defined functions.

The Discrete Phase Model (DPM) was selected to calculate the flow of the particulate phase since the gas–solid two-phase flow in the coating booth has been classified as a dilute flow. In DPM, the effect of particle–particle interactions on the solid flow was neglected since the volume fraction of the solid phase is very low in the powder coating system. Also, the powder particles were considered spherical and having smooth surfaces. The particle trajectories were predicted by integrating the equation of motion for the particles, which was based on the force balance on the particle and written in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle, and can be written (for \( i \)-direction in Cartesian coordinates) as

\[
\frac{du^p_i}{dt} = F_D (u_{ai} - u_{pi}) + F_{\text{Gravity}} + F_{\text{Virtual}} + F_{\text{P,G}} + F_{E_i} / m_p
\]

where \( F_{E_i} \) is the electrostatic force component in \( i \)-direction, and \( m_p \) is the particle mass. The first and second terms on the right-hand side of Eq. (13) are the drag force and gravitational force, respectively. The electrostatic force due to the electrostatic field \( F_{E_i} \), is given by

\[
F_{E_i} = q_p \vec{E} + \frac{q_p^2}{16 \pi \varepsilon_0 a^2} \vec{n}_p
\]

where \( q_p \) is the particle charge, \( a \) is the distance between the particle and the coating target, and \( \vec{n}_p \) is the unit vector from the location of the particle to the point on the coating target at which the distance between the particle and the coating part is the smallest. Due to the lack of
available models for the charge to mass ratio, the average value of \(-1 \mu C/\mu g\), obtained from experiments, was used for the charge to mass ratio in the current study.

3 Results and discussion

Kanaoka et al. (1987) conducted efficiency tests of split type electret filters and accordingly generated two semiempirical expressions on the assumption of rectangular fibers in the vertical array arrangement (with long side of fiber's cross section perpendicular to the flow, as shown in Figure 1. In this paper the result are compared with semiempirical expressions. Figure 5 and 6 show the simulated single fiber efficiencies of uncharged particles and singly charged particles deposited on fibers in two charge states: 460 \(\mu\) As/m2 and half of this charge, 230 \(\mu\) As/m2. Single fiber efficiency of uncharged particles is plotted in Fig. 5 as function of particle size, in which filtration velocity is 0.1 m/s and particle size is in the range of 0.01–2.0 \(\mu\)m. Calculated results from semi-empirical expressions are also presented in the figure as solid lines. Likewise, single fiber efficiency of singly charged particles is plotted in Fig. 6. In both cases, the simulated results and those calculated from the semi-empirical expressions predicted same trends and the two groups of results agree with each other reasonably well.

![Fig. 5 Single fiber efficiency of uncharged particle under various fiber charges, U=0.1m/s](image)

![Fig. 6 Single fiber efficiency of singly charged particle under various fiber charges, U=0.1m/s](image)
For uncharged particle, collection efficiency in Fig. 5 first decreases almost linearly as particle size decreases until a minimum value is reached and then increases non-linearly with further decrease in particle size. The linear portion reflects that the dielectrophoretic effect is dominating while the non-linear part reflects the diffusional effect. There is a region of minimum single fiber efficiency on each curve where both effects are weak. These results can be easily explained because larger particle can be polarized to higher level and therefore is subjected to stronger polarization force, which will enhance the capture due to dielectrophoretic effect. On the other hand, low filtration velocity and small particle size will result in low Pe number, which corresponds to intensified Brownian diffusion effect. For singly charged particle, Figure 6 also shows the same trend. The efficiency decreases over the particle size range 2.0–0.3 μm is caused by the weakening of dielectrophoretic effect. The efficiency increases as particle size further decreases because the Coulombic force begins to dominate. Figure 7 and 8 show similar simulation results except that the calculation is based on 0.5 m/s filtration velocity. Higher filtration velocity will result in shorter resident time of a particle around the fiber, which results in generally lower electrostatic collection efficiencies. Figs. 5 to 8 also show that the fiber charge greatly influences the magnitude of the efficiency but change very little the trend by which collection efficiency varies with particle size.

Fig. 7 Single fiber efficiency of uncharged particle under various fiber charges, U=0.5m/s

Fig. 8 Single fiber efficiency of singly charged particle under various fiber charges, U=0.5m/s

During the coating process the grounded coating part is present in the spray zone. To check how the numerical model behaves under the conditions with and without a coating part, the comparisons were made for velocities under both of these conditions. This exercise also showed how the particle spray profile gets affected with the presence of the coating part. Figs. 9 and 10 show the predicted gas flow velocity vectors inside the coating booth and in the vicinity of the spray gun, respectively, with the electrostatic field and with a coating part in the coating booth. To allow a better visualization of the wake region near the spray gun deflector and the coating part, only the velocity vectors with magnitude from 0 to 5 m/s have
been presented in the figures. The results clearly show the wake regions near the spray gun deflector front and the coating part.

Fig. 9. Gas velocity vectors inside the coating booth on the y–z vertical plane at the gun center

Fig. 8. Gas velocity vectors in the vicinity of the gun deflector plate.

Particle velocity profiles: with a coating part. The numerical model is also examined for its ability to predict the particle velocity profiles when a coating part is placed in the coating booth and there is no electrostatic field by comparing the predicted results with the measured values. The coating part, 7.6 cm · 13.2 cm, was placed at 26 cm downstream of the gun tip.

Fig. 9 and 10 show the comparison between the numerical and experimental results for the velocity profiles along the vertical (y) axis at 25 cm and 20 cm downstream of the gun tip. The numerical model predicted the similar pattern as it was seen in the measurements. In the numerical simulation, the assumption was made that all the particles hit to the coating target stay on the target while in the experiment some particles reflect back. In the comparison between the numerical and experimental results shown in Fig. 13, all negative particle z velocities are removed from the experimental data. The discrepancy shown in Fig. 13 between the numerical results and experimental data at 25 cm from the gun tip, which is 1 cm from the coating part, could be due to the choice of standard k–ε turbulence model that is often not suitable for resolving flows near stagnant boundaries.
Fig. 9. Particle velocity profiles along the vertical (y) axis at 25 cm downstream of the gun tip (without electrostatic field and with a coating part).

Fig. 10 Particle velocity profiles along the vertical (y) axis at 20 cm downstream of the gun tip (without electrostatic field and with a coating part).

Fig. 11 and 12 show the comparison for particle size distribution along the vertical (y) axis at 20 and 25 cm downstream of the gun tip. The diameter distributions along the vertical axis show that the bigger particles tend to land on the bottom of the coating booth and smaller particles are at higher position inside the coating booth. This is because bigger particles are under higher gravitational force and tend to drift downwards while smaller particles follow the gas flow path and remain suspended for a longer time. The profile is more flat at 25 cm than it is at 20 cm because many big particles have fallen down. Both figures show good agreement between the predicted results and the experimental data.
Fig. 11. Particle size profiles along the vertical axis (y) at (a) 25 down-stream of the gun tip.

Fig. 12. Particle size profiles along the vertical axis (y) at (b) 20 cm down-stream of the gun tip.

Fig. 13 and 14 show the comparison for particle velocities along the horizontal (x) axis at 20 cm and 10 cm downstream of the gun tip for the case with a coating part in the coating booth and with electrostatic field. These figures show a reasonable agreement between the numerical results and experimental data for both the z- and y-velocities except for the z-velocity at x = 20 mm and 10 cm from the gun tip, where the experimental value is much lower than the simulation value as shown in Fig. 15(b). The comparison at 25 cm downstream of the gun tip, which is very close to the part, was not made since the back ionization affects the experimental data for particle velocities very close to the coating part and the numerical model used here does not account for the effect of back ionization.
Fig. 13. Particle velocity profiles along the horizontal (x) axis at 20 cm downstream of the gun tip (with electrostatic field and with coating part).

Fig. 14. Particle velocity profiles along the horizontal (x) axis 10 cm downstream of the gun tip (with electrostatic field and with coating part).

The particle velocity profiles with the electrostatic field were compared with those without the electrostatic field to understand the effect of the applied electrostatic field on the particle motion and the trajectories of the particle. Fig. 16 shows the comparison along the horizontal (x) axis at 20 cm downstream of the gun tip. It shows that the electrostatic field causes an increase in the particle velocity towards the coating part, i.e. an increase in z-velocity.
4 CONCLUSIONS

Firstly charged and neutral particle collections in an electret filter composed of rectangular split-type fibers are simulated. Both the flow field and the electric field around the fiber are numerically determined. All the major collection mechanisms, mechanical and electrostatic, have been coupled in the differential equation of particle motion. The single fiber collection efficiency is obtained from tracing and recording the particle trajectories. Simulations have been conducted under wide range of filtration conditions and results are compared with those obtained from Kanaoka, et al.

The numerical model for the simulations of the gas and solid particle flows in a powder coating system was presented and its results were compared with the experimental data. It was found that the numerical model predicts quite accurately the particle velocities and average particle diameter at different locations inside the coating booth when there was no electrostatic field. The numerical results showed similar effect of the electrostatic field on the flow field as that from experimental results. The differences between numerical results and experimental data, for the case of with the coating part and with electrostatic field, are most probably due to the assumption of constant charge to mass ratio and spherical shape of particles for this study. Thus, it should be important to numerically resolve particle charging using unsteady particle tracking or consider variable particle charge based on its diameter. In general, the presented simplified model appears useful for carrying out parametric studies considering different monosize powders. The gas and particle flow fields could be understood by measuring the particle velocities and diameters at various locations inside the booth. Near the spray gun region the aerodynamic force is dominant and so the particles travel under its effect. Moving away from the spray gun, the electrostatic and the gravity force become dominant. The bigger particles tend to accumulate near the bottom of the coating booth and fine particles remain suspended with the gas flow for the longer time and finally being carried away through the suction hole. The electrostatic force is in the axial direction of spray and acts as an additional source to the particles’ momentum. Thus, the electrostatic force plays an important role to increase the particle transfer efficiency. In addition, it affects the particle trajectories and expands it in the radial direction and finally concentrating on the target edges along the field lines.
REFERENCES