A 3D numerical model of the electrostatic coating process for moving targets

N Toljic¹, G S P Castle¹, K Adamiak¹, H H Kuo² and H T Fan²

¹Department of Electrical and Computer Engineering, University of Western Ontario, London, ON, Canada
²GM Global Research & Development, Warren, MI, USA

ntoljic@uwo.ca

Abstract. A 3D realistic numerical model of the electrostatic coating process has been developed including all relevant mechanical and electrical phenomena. The commercial computational fluid dynamics (CFD) software FLUENT was used to simulate the mechanical portion of the process. The electrical phenomena including space charge fields due to ions and poly-disperse particle charge distributions were added to FLUENT through the User Defined Function (UDF) capabilities. Selected example results are shown to demonstrate the effect of particle charge to mass ratio distributions, electrohydrodynamic flow effects and corona currents on particle trajectories and deposition efficiency. These numerical results correlate well with the theoretical expectations for static targets. In addition, an efficient method for handling 3D cases with moving flat parts is presented using the superposition principle. A procedure for extending the model for the general case of 3D moving targets is suggested.

1. Introduction

Advancements in the capability of computational tools introduced numerical modeling as a preferred way for enhancing numerous industrial applications. Electrostatic coating is one of the applications which benefits significantly from numerical optimization as it involves many interdependent variables. However, due to the complexity of the problem, certain challenging tasks still remain unsolved. Namely, the electrostatic coating process can be regarded as a composition of intricate mechanical and electrical phenomena, which are not entirely understood. This is especially true for the electrical portion of the process. Different particle charge and charge to mass ratio distributions, corona current effects and electrohydrodynamic flow are still a subject of ongoing theoretical, numerical and experimental studies.

The complex nature of the charging process limits our ability to assess the value of charge to mass ratio (q/m) of individual particles in a cloud of particles when they are electrically charged by induction or conduction. All the measurement techniques for particle charge can be classified in two major groups: static and dynamic [1-2]. In the static methods particle charge is measured directly, whereas in the dynamic methods it is calculated indirectly from the measurement of the particle mobility. Static methods are crude and simple, but they can be easily implemented. Dynamic methods are more reliable, but they require added complexity in the measurement system. It has been shown in [2] that considerable conflicting data exists for the dependence of q/m on particle size and it has been suggested that this area needs further research.
Also, as a result of the application of high voltage and the specific configuration of conductors, corona discharge is usually an inevitable part of the electrostatic coating process. A full mathematical model of the corona discharge is practically impossible to implement [3]. One of the least known effects of the corona discharge is the secondary electrohydrodynamic (EHD) flow, which is produced by transferring of momentum from high-speed drifting ions to surrounding air molecules. Incorporation of EHD makes numerical modeling much more computationally demanding.

In this paper, an efficient 3D model of the electrostatic coating process is presented. The mechanical part of the coating process is directly modeled with the computational fluid dynamics software FLUENT. Its User-Defined Functions (UDF) are used to solve the Poisson equation by incorporating it into the general scalar transport equations. Obtained numerical results are presented. In addition, an efficient method for handling 3D cases with moving flat parts is presented using the superposition principle and a procedure for extending the model for the general case of 3D moving targets is suggested.

### 2. Description of the computational domain and numerical procedure

The computational three-dimensional domain encompasses a simplified representation of the rotary bell type atomizer and a flat target of the radius 0.5m situated 0.25m away from the atomizer. The geometry of the computational domain was created by the GAMBIT software package [4] and meshed with hexagonal cells. The mesh between the atomizer and the target was refined compared to the rest of the computational domain. The numerical algorithm includes solving the gas phase of the shaping air, the discrete phase of the charged particles, the electrostatic field and coupling between them to get a self-consistent solution [5].

The shaping air flow in FLUENT was considered as incompressible, steady and viscous turbulent. The RNG (renormalization group) k-ε turbulent model was used in the modeling. The method used for simulation of the particle discrete phase in FLUENT is solved by the Lagrangian approach, in which the particles are tracked by the stochastic tracking (random walk) model in turbulent gas flow [6]. Coupling between the air flow and the particle discrete phase is included via source terms of mass and momentum. The particles are ejected with the predefined size and charge distribution and directed to the target by the shaping air and electric forces.

The electric field generated by the voltage applied to the bell cup and the space charge formed by the charged particles and ions is governed by Poisson’s equation. In order to take into account the space charge density due to corona discharge into the numerical analysis, a new scalar \( \Psi \) is defined:

\[
\Psi = -\nabla \cdot J
\]

where \( J \) is the ionic current density. The equation can be solved by the FLUENT solver as user-defined scalar transport equation. It is assumed that the total corona current at the electrodes is known and is zero at the other boundaries of the computational model domain.

In the numerical model, the shaping air flow rate was set to be 0.02 kg/s. The downdraft air acts in the negative \( y \) direction and its magnitude is 0.5m/s. The atomizer voltage was set to be -90kV, whereas the target was grounded. Diameter of particles is between 10µm and 80µm and the value of the charge to mass ratio is set to be inversely proportional to the particle radius and equal to -1mC/kg for the particle with 35µm diameter. The corona current was obtained experimentally and equal to 10µA.

### 3. Numerical results

Numerical results show that the air flow forms a conical shape as it moves towards the target. When the air hits the target, it spreads evenly in the tangential direction. The maximum air velocity is at the tip of the atomizer and it gradually reduces as the axial position is increased. The cone is tilted in the direction of downdraft air. In the region between the atomizer and the target, the particles follow almost linear patterns. The majority of particles end at the target directly below the atomizer. The particles that escape this initial impact with the target follow the air pattern that directs them towards the edge of the target. A certain number of these particles deposit at the distal parts of the target and the rest of them travel beyond the target to the edge of the computational domain. It can be noticed...
that the turbulence treatment of particle movement in FLUENT results in characteristic piecewise linear trajectories of the particles.

The numerical results for the deposition profiles along the radius of the target are depicted in Figure 1. The value of the accumulation rate is very low in the centre of the target; it increases very quickly as the radius is increased. After the local maximum is reached, the accumulation rate decreases as the radial position is further increased. The particle accumulation along the target radius in the $x$ direction exhibits local symmetry. For the particle accumulation rate along the target radius in the $y$ direction, the influence of downdraft can be observed. The local maximum that is closer to the source of the downdraft air is lower than the local maximum that is further away from the source of the downdraft air. Transfer efficiency is calculated as a ratio of the input flow rate and the deposition mass flow rate and its value is 90%. This is a relatively high value, but can be explained by the large size of the target and its flat surface, perpendicular to the droplet trajectories.

The electrical potential contours are dense in the area between the atomizer and the target, and sparse elsewhere. In the immediate vicinity of the atomizer tip the electric potential values are very high. The electric potential contours in the vicinity of the atomizer body are perpendicular to the atomizer surface. This is a result of the assumed boundary conditions for the atomizer body. Areas close to target have value of the electric potential close to zero as the target is grounded.

It should be noted that EHD flow had no significant impact on the continuous phase results and the trajectories of the charged particles. This is because the EHD flow is very weak compared to the shaping air. Its influence can, therefore, be neglected for this particular studied case.

![Figure 1 Particle accumulation rate along the target diameter in the $x$ direction](image)

4. Simulating a moving target
To simulate a moving target, we considered a simplified case where the target is flat and very wide. It was further assumed that the gun moves relatively slowly. If these conditions are fulfilled, stationary deposition patterns for different gun positions will be practically identical and all calculations can be based only on the deposition pattern for one stationary target. The deposition pattern for a moving target can be derived by superposition of the incrementally shifted deposition patterns for the stationary target. FLUENT software is required only in the initial step to obtain the stationary
deposition pattern. The post processing of the data was done in a mathematical software package MATLAB.

The overlapped deposition profiles during coating period are shown in Figure 2. Higher values of deposition profile correspond to the larger increment in time. The greater value of reversal position and higher moving velocity result in more uniform coverage. In this manner the mass build up on portions of the target is avoided.

![Overlapped Graphs of Specific Mass Profiles for 1s Time Increments, Reversal Position of 0.5m and Target Velocity of 0.2m/s.](image)

Figure 2 Overlapped graphs of specific mass profiles for 1s time increments, reversal position of 0.5m and target velocity of 0.2m/s.

5. Conclusion

In this paper, a numerical model of the electrostatic coating process has been developed including all relevant mechanical and electrical phenomena. The numerical simulation was performed for the full three-dimensional model of the problem and the results of the simulations were presented. In addition, the deposition patterns for the moving target were estimated by superposition of the incrementally shifted deposition patterns for the stationary target.

References

[1] Brown C 1997 Tutorial review: Simultaneous measurement of particle size and particle charge *J. Aerosol Sci.* 98 pp 1373–1391
[2] Toljic N, Adamiak K and Castle G S P 2009 Charge to radius dependency for conductive particles charged by induction *Journal of Electrostatics* 68 pp 57-63
[3] Zhang J, Adamiak K and Castle G S P 2007 Numerical modeling of negative-corona discharge in oxygen under different pressures *Journal of Electrostatics* 65 pp 174-181
[4] *FLUENT 6.2 User’s guide*. 2005 FLUENT Inc
[5] Zhao S Adamiak K and Castle G S P 2007 The implementation of poisson field analysis within FLUENT to model electrostatic liquid spraying *Proc. IEEE Canadian Conference on Electrical and Computer Engineering* Vancouver
[6] *FLUENT 6.2 UDF manual*. 2005 FLUENT Inc.