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A Discrete Particle Transport Model for Predicting Coating Patterns in Electrostatic Spray

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In electrostatic spray coating, atomized liquid droplets are propelled toward a substrate by the combined affects of an electrostatic field and a directed jet of "shaping air". The primary goal of this work is to establish a mathematical model of an E-spray process capable of predicting coating uniformity and transfer efficiency. This goal is approached by using numerical simulations to solve the equations that describe the flow of the entraining air stream, the electrostatic (E/S) field, and the resultant droplet trajectories. The model is applied to the electrostatic spraying of a non-aqueous paint, in the form of a xylene / polystyrene solution, applied to a conductive substrate using a rotary bell electrostatic spray gun.

A mathematical model of E-spray has been developed and will be used to answer the following research questions the answers to which would enable users of E-spray equipment to attain high levels of cost savings in the form of reduced material usage and lower lead times to production.

1) *What parameters dominate coating thickness distribution and transfer efficiency?*
2) *Are coating uniformity and transfer efficiency inter-related?*
3) *What parameter set will provide the best coating uniformity at the best transfer efficiency?*
4) *How are the optimal conditions affected by the spray material properties (and other "uncontrollable" properties)?*

The numerical technique for this project is a combination of three models - an axisymmetric solution of a k-ε turbulence model for the continuum velocity field, an axisymmetric solution of the Poisson equation for the E/S field, and droplet tracking of sprayed droplets in 3D cylindrical coordinates. The material properties and operating conditions of the E-spray gun are the inputs to the model. A dilute spray assumption (no particle-particle interactions) allows modeling single-droplet trajectories resulting from a balance of electrostatic force, drag and momentum [Crowe, 1998]. These equations are coupled through time-averaged space charge solutions made from the droplet trajectories. The model, by predicting the spatial distribution of the spray and the charge accumulation on the substrate, is able to also gauge the effect of operating parameters on localized film thickness, transfer efficiency, and coating uniformity.

1. Physics of Electrostatic Spray. A Ransburg Aerobell 33 model electrostatic rotary atomizer was used as the basis for this model and subsequent laboratory work. This E-spray gun uses a rotating bell-cup and an annular shaping air to facilitate the atomization of the liquid (see Figure 1). The bell-cup rotates at high speeds (10-45 kRPM) and is maintained at a high electrostatic potential (30 – 90 kV). The charged cup also charges the droplets by induction.

The performance of E-spray applicators is highly sensitive to droplet size. This becomes evident when considering the forces acting on the droplet during flight. Figure 1 pictorially shows the three primary forces experienced by the droplet: fluid drag (F_{DRAG}), electromotive force ($F_{E/S}$), and gravity (F_G). While the droplet mass and body force scale with the volume of the droplet, the electromotive force and the drag both scale with the surface area of the droplet.

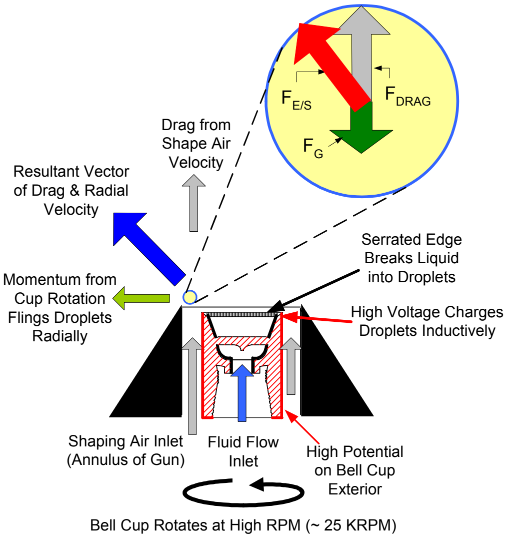

Figure 1: Cross-section of a rotary bell electrostatic atomizer along with dominant forces acting on an individual particle

The effect of these forces varies as the droplet passes through the system. Upon atomization, the dominant forces acting on the droplet are drag and inertia. However, these forces are acting in perpendicular directions as shown in Figure 1. Because the droplets are small (~ 5-100 µm) inertia quickly succumbs to drag as the droplet leaves the atomization region. If the initial inertia is high enough to force the droplet outside the focused air stream where drag dominates, the electromotive force becomes the primary force in guiding the droplet to the target.

The details of atomization are not resolved, instead a lognormal distribution [Hatch & Choate, 1929] about a mean droplet size [Bell & Hochberg, 1981], starting location and speed are assumed as initial conditions on droplet trajectories [Elwood & Braslaw, 1998]. The bell-cup voltage, rotational speed and shaping air velocity are key parameters that affect the size, charge and trajectory of the spray droplets. Bell & Hochberg (1981) demonstrated a power law relationship for the mean droplet size versus the bell voltage (Φ), rotation speed (ω), fluid feed rate ($\dot{V}_L$), and feed viscosity (μ_L). The constant, C, is dependent upon the geometry of the bell-cup used. For example, in the Bell paper, C equals 12500 for a bell-cup diameter of 72.5 mm.

$$\overline{D}_p = f\left(\Phi, \omega, \dot{V}_L, \mu_L\right) = C\ \Phi^{-0.2}\ \omega^{-0.7}\ \dot{V}_L^{0.4}\ \mu_L^{-0.2} \tag{1}$$

2. **Coupled Model of the Electrostatic Spray System.** The fluid velocity field, the E/S field, and the droplet trajectories are all coupled, but the coupling is assumed weak enough that the fields can be calculated separately in an iterative procedure as shown in Figure 2. Because the turbulent fluid mechanics are assumed to be unaffected by the drag of the droplets, the turbulent flow field is predicted first. A turbulence energy-dissipation rate (k-ε) model provides the mean gas velocity field and the turbulence intensity, which are used to calculate drag forces on the droplets. The turbulent flow field is predicted using FEMLAB (a commercial finite element package), and the E/S field and the droplet trajectories are predicted with a custom-built computer program. The finite element meshes required for accurate representation of the fluid mechanics and the electrostatics are different. Interpolation of the turbulent velocity field solution to the E/S mesh is done using the postinterp function in Matlab (FEMLAB is implemented within Matlab). The average radial and axial velocities as well as the values for the turbulence intensity are interpolated in this manner and used in the droplet trajectory

calculations. In each iteration, the E/S field and droplet trajectories are updated to account for changes in the E/S field to achieve global convergence.

The requirements for the E/S field solution (See Figure 2) are the boundary conditions and spatial distribution of charge in the spray. The electrostatic force vectors obtained from these calculations, as well as the instantaneous velocities of the air stream produced in the prior step, are both used as inputs to the droplet trajectory calculations.

Apart from the operating parameters of the gun (spray material feed rate, shaping air speed, etc.), other inputs to the trajectory field calculations are the size distribution and initial trajectory of the droplets – a log-normal distribution of droplets randomly released from an arbitrary location near the bell-cup lip at random initial velocities.

Each droplet path is modeled independently, which corresponds to the droplet loop in Figure 3. The time of flight of the droplet is defined by the summation of all elemental residence times from droplet release to landing. Once a droplet makes contact with a physical barrier, a contribution to the local charge and coating thickness accumulation is made. The next droplet path is modeled until all droplets have landed on some impenetrable boundary, which represents the spray accumulation time-step.

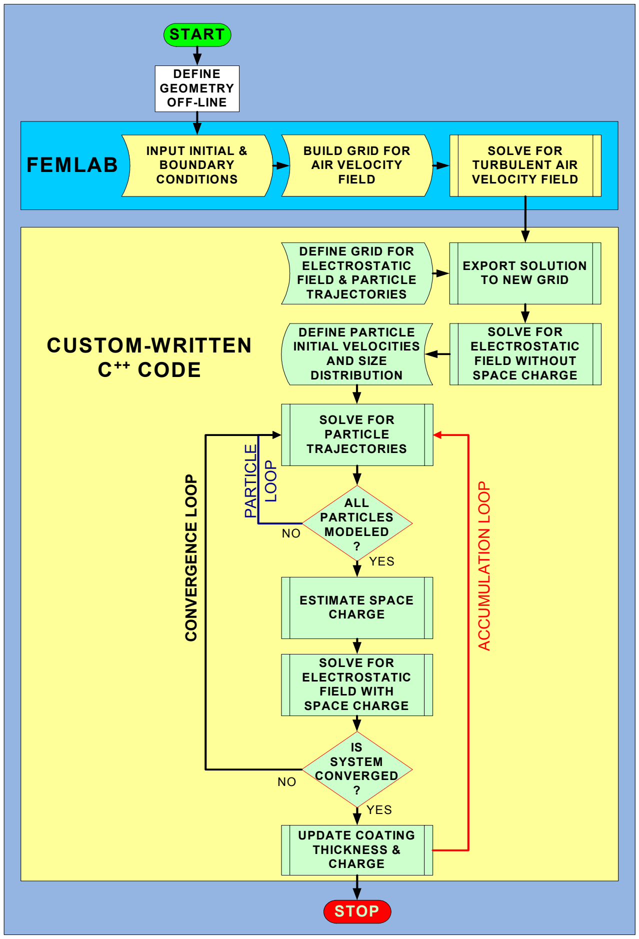

Figure 2: Iterative Solution Algorithm for E-Spray Calculation

To account for the charge accumulation and spatial charge density, the electrostatic solution and droplet trajectories are iterated until global convergence is achieved. In this sense, global convergence is defined as a tolerable change in the root-mean squared difference in coating thickness distribution between iterations. The characteristics of the spray plume and deposited coating are only carried over to the next accumulation time-step after the global convergence is realized. A convergence criterion of 10^{-3} was used for simulations in this paper. Because of the significant affect that the space charge has on the electrostatic field, particularly near the spray nozzle, updates in the electrostatic potential at each iteration, Φ_i, are relaxed based on the potential from the previous iteration, Φ_{i-1} and the potential calculated using the current space charge field, Φ_{calc}. A relaxation parameter, α, between 0 and 1 is chosen to represent the weight of the new solution versus the old solution. In the simulations presented here, α is set to 0.05.

$$\Phi_i = (1-\alpha)\Phi_{i-1} + \alpha\,\Phi_{calc} \tag{2}$$

3. **Comparison of Simulated to Experimental Results.** A set of 25 E-spray experiments was preformed at the Thomson facility. The parameters of these experiments were arranged in a 5x5 Greco-Latin square design of experiments the values of which are outlined below. Shaded cells in Table 1 indicate values of base case. A light absorption method and a CCD camera were used to provide detailed thickness maps. Overall, the trends tended toward three basic shapes – a donut, a footprint and a dot as shown in Figure 3A, B, & C; respectively.

Table 1: Experimental parameters used in 5x5 Greco-Latin Square design

	Shaping Air (psi)	Bell Voltage (kV)	Fluid Flow (cm^3/s)	Bell Speed (kRPM)	Spray Time (s)
Level 1	20	0	1	9.7	2
Level 2	25	22.5	1.5	19.4	3
Level 3	30	45	2	29.3	4
Level 4	35	67.5	2.5	38.9	5
Level 5	40	90	3	43.7	6

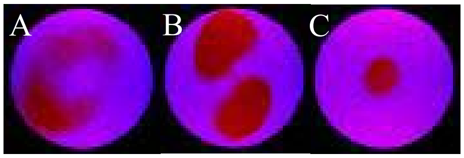

Figure 3: Typical spray patterns from physical experiments as measured on thickness gauge: A) Donut shape, B) Footprint outline, and C) Dot.

Setting	A	B	C
psi	20	40	30
kV	45	45	45
cm^3/s	2.0	3.0	1.0
kRPM	38.9	29.3	9.7
s	5	3	3

The model was to simulate these same spray conditions using an assumed atomization constant. Because of the axisymmetric nature of the simulation, all simulated patterns result in circular patterns, which would prevent simulation of the "footprint" patterns encountered in experiments. Two examples of the spray patterns simulated are shown in Figure 4. However, the operating conditions that lead to specific spray patterns in the simulations and experiments do not currently agree. In future work, we will explore how some of the assumed input parameters affect the ability of the model to qualitatively match the experimental trends. In particular, the value of the atomization constant (i.e., mean droplet diameter) has a large impact on the simulated coating profiles.

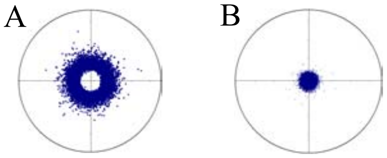

Figure 4: Spray Patterns Obtained Using Simulation

A	Setting	B
40	psi	30
90	kV	22.5
1.0	cm^3/s	3.0
43.7	kRPM	19.4
4	s	2

ACKNOWLEDGEMENTS

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