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A mathematical model of particle transport in electrostatic spray coating

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Abstract

Although electrostatic spray coating (E-spray) is widely used, its complexity requires optimization based on an empirical understanding of the spray dynamics. The project goal is to develop a mathematical model of the electrostatic field, continuum flow-field, and particle trajectories in an E-spray process. By restricting the use of empirically based equations to the atomization phase of the spray process, this model should have the flexibility to tolerate "real-world" system complexities (i.e. multiple applicators, complicated geometries, etc.) and the ability to be used with any type of E-spray gun sharing the same atomization characteristics.

This model predicts coupling between three components: the fluid mechanics of the continuum flow field, the electrostatic field, and the particle trajectories. The system is a vertical bell-cup sprayer and a grounded disc centered on the gun axis. An axisymmetric electrostatic model is assumed, while the fluid mechanics and particle trajectories are solved in 3-D.

A dilute spray assumption (no particle-particle interactions) allows modeling single-particle trajectories resulting from a balance of electrostatic force, drag and inertia. Varying the particle size generates volume-averaged properties of individual paths to simulate the charge density and fluid drag of a sprayed particle distribution. A turbulence energy-dissipation rate (κ-ε) model provides the continuum velocity for the particle drag. These individual systems are solved sequentially and that sequence is iterated to convergence.

Results include the effect of charged particles on the electrostatic field and identification of the dominant factors affecting coating thickness distribution.

1 Introduction

Electrostatic spraying (E-spraying) refers to the use of an electric field to assist in the spraying of liquid droplets onto a grounded substrate. The droplets in the spray are charged as they exit the spray nozzle and are attracted to the grounded substrate. By providing this electric potential difference, the driving force of droplets is accentuated, thereby increasing the transfer efficiency of the spray. It has been shown that an optimized E-spray system has a transfer efficiency of up to 75-85%, whereas conventional spray applications can have efficiencies as low as 20-30% [1]. Most of this increased efficiency is the result of the finer spray droplets being electrostatically attracted to the target. Otherwise, smaller particles would not have the momentum to reach the target. In many instances, a stream of focused air is used to augment transfer efficiency. This stream of air is referred to as “shaping” air as it molds the spray profile.

In one of its earliest industrial uses, E-spraying was used to apply paint to metal parts in the automotive industry, where it is still widely used today [2]. Because of efficiency of material usage and completeness of coverage, this technique has been applied to many other areas. One such area is crop dusting. The ability of charged droplets to “turn a corner” and coat the underside of leaves makes electrostatic application of pesticides highly effective at reducing pest populations [3]. Another innovation in the use of electrostatics is in the pharmaceutical industry with charged inhalers [4]. However, the bulk of the E-spray industry is still the application of coatings. The system discussed in this paper is a non-aqueous paint, in the form of a xylene / polystyrene solution, applied to a conductive substrate using a rotary bell electrostatic spray gun.

2 Research objectives

The primary goal of this project is to establish a mathematical model of an E-spray system capable of predicting the coating thickness and uniformity by accurately describing the spray distribution. Such knowledge 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. We approached this goal by using numerical simulations to solve the equations that describe the flow of the entraining air stream, the electrostatic field, and the resultant particle trajectories. The numerical technique for this system is a combination of three models - an axisymmetric finite element method (AxFEM) solution of a k-ε turbulence model for the continuum velocity field, an AxFEM solution of the Poisson equation for the electrostatic field, and Newton’s equation of motion for the particle tracking of the sprayed droplets in 3D cylindrical coordinates. These equations are tied together by a projection mapping of the 3D solutions of the particle trajectories onto the axisymmetric coordinate system. The material properties and operating conditions of the E-spray gun are the inputs to the model. The model, by predicting the spatial distribution of the spray and charge accumulation on the substrate, is able to also gauge the effect of operating parameters on localized film thickness, transfer efficiency, and coating uniformity.

3 Background

Various aspects of the E-spray coating process have been the subjects of recent research. Hakberg, et al and Filippov, developed models of electrostatically charged droplets in flight through a quiescent domain (i.e. no shaping air involved) [5,6]. Elmoursi developed techniques for modeling the Laplacian field and electrical characterization of the bell-cup geometry; however, his models applied to transport of ions, not true droplets (i.e. drag forces, etc. are ignored) [7,8]. Meesters, et al, presented a fast computer simulation but it did not account for particle size or charge distribution. Also, Meester's model did not simulate a multitude of particles, neglecting particle-particle interactions [2].

Ellwood & Braslaw assembled a comprehensive model using an iterative particle source in cell (PSIC) approach [9]. They refer to a "torsional" axisymmetry that they used to solve the three fields of the system (electrostatic, particle trajectory and fluid velocity). Specifically, the velocity components for all three dimensions are independent of the azimuthal position. We have adopted this assumption in our solution method as well.

In general, most of the prior models have focused on the electrostatic aspects of the E-spray system, with little or no attention paid to the multiphase transport phenomena involved. Others have had simplifying assumptions that have significantly limited the applicability of these models to typical industrial use. One primary reason for the necessity of these assumptions in prior work would be limited computational capability. With the proliferation of powerful microcomputers and parallel computing platforms, the model we propose should be able to shed some of the assumptions deemed necessary by our predecessors. One important difference between this work and those mentioned above is the incorporation of charge accumulation on the target substrate and how that affects the coating thickness distribution.

4 System description

A Ransburg Aerobell 33 model electrostatic rotary atomizer was used as the basis for this model. This electrostatic spray gun incorporates a rotating bell-cup and an annular shaping air to facilitate the atomization of the liquid. The bell-cup has a serrated lip and rotates at very high speeds (10-50 KRPM). A conductive coating along the outer surface of the bell cup supplies the charge to the spray material via induction. While some E-spray guns have additional high voltage sources near the nozzle to modify the electric field and repel the particles forward, the Aerobell system used here does not. The high voltages

(30 – 90 kV) applied on the bell-cup provide a substantial electrostatic driving force.

The bell-cup voltage, rotational speed and shaping air velocity are the key parameters contributing to some of the most important characteristics of the particles in this system; specifically, their size, charge and trajectory. The voltage not only imparts a charge onto the droplets, but because the potential is maintained throughout the process, it provides an additional electrostatic driving force onto the particles. Furthermore, the charge on the droplets aids in atomization by virtue of the Rayleigh limit for electrostatics; i.e. droplets with a high surface charge spontaneously break into smaller droplets [10, 11], This phenomenon provides a narrower particle size distribution than that of conventional atomization [12]. The size of the particles formed from atomization is critical in determining the trajectory of the particles in the spray. The amount of charge that each particle is capable of holding is also a strong function of the particle size. The charge-to-mass ratio of the spray can be calculated from the number of particles (or loading), particle size and current draw of the induction process. Particle size is a significant factor in determining the drag and electrostatic effects of this system [13]. In most cases, the distribution leans toward either a Gaussian or Log Normal distribution [14]. Gaussian particle size distributions available from the literature have been used in this work [15,16].

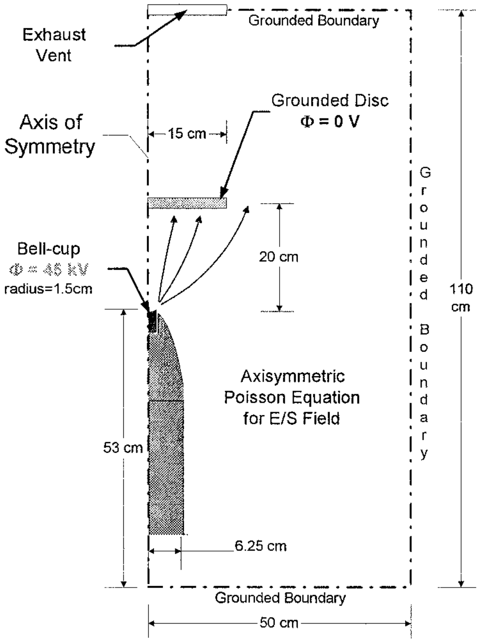

Figure 1: Schematic of E-spray system modeled in this paper.

5 Coupled model of the electrostatic spray system

An axisymmetric slice of the system used in this project, including some of the proposed boundary and initial conditions, is shown in Figure 1. The initial model will involve the gun pointing directly upward and spraying at a circular target that is a fixed distance away. The entire system is surrounded by a grounded physical boundary with the exception of an exhaust vent located at the top of the domain. All other system boundaries are considered outflow planes or the axis of symmetry.

The rotational speed and voltage of the bell-cup, the flow rates of the liquid and shaping air streams into the system, along with several material properties and the system geometry, define the variables necessary to calculate the particle transport in an E-spray system from nozzle to target. Despite the complexities of this system, the motion of the particles results from only three coupled forces: drag force from the surrounding air, electromotive force, and gravity.

The fluid velocity field, the electrostatic field, and the particle trajectories are all coupled, but we assume the coupling is weak enough that the fields can be calculated separately in an iterative procedure as shown in Figure 2. In the iteration, the electrostatic field and particle trajectories are updated to account for changes in the electrostatic field so as to bring the entire system to global convergence.

The first step is the production of the axisymmetric mesh used to solve the turbulent fluid velocity and electrostatic systems individually. Calculations indicate the shaping air flowing out of the annulus of the gun is in the fully turbulent regime. Also, a dilute particle loading is assumed for this system, which means the drag force exerted by the particles on the gas can be neglected. While true for a majority of the system, this assumption could be questioned near the nozzle of the bell-cup.

A characteristic time for the spray is developed based on the total volume of the particles released versus the volumetric flow rate of the spray material used in the simulation. Because this value is proportional to the number of particles released, the system requires a large enough number of particles to be simulated ($N=10^4$). This value represents the accumulation time-step and is used in the calculation of coating thickness and surface charge.

A commercially available software package (FEMLAB) was used to solve the turbulent air velocities via an axisymmetric k-ε model. The locations of each of the nodes in the axisymmetric mesh are imported into FEMLAB, where the average radial and axial velocities as well as the values for the turbulence intensity, k, are obtained. Because k is equal to the turbulent velocity squared, the magnitude of the turbulent velocity is known. Using a random vector to give k directionality, the instantaneous air velocity can be calculated. Because the turbulent velocity is time dependent, a newly chosen random vector is chosen as each time-step in the spray simulation progresses.

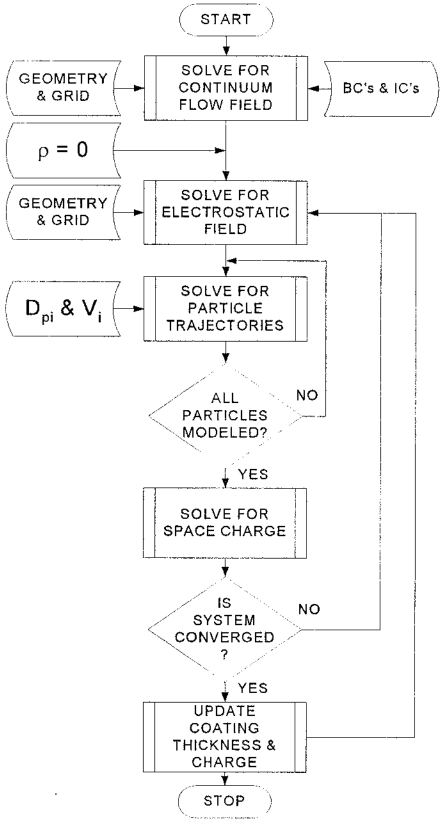

Figure 2: Iterative Solution Algorithm for E-Spray Calculation

The electrostatic system solution shares the same grid as the one that was imported into FEMLAB. The requirements for the FEM solution of the electrostatic system are the boundary conditions and spatial distribution of the charge in the spray. As mentioned earlier, a particle-free assumption is made for the initial calculations, which translates to a zero charge density. After the initial spray plume is defined, the charge cloud is then established and the ensemble average of the charge density can be characterized. To model the charge density, the residence time of a particle as it passes through each element is multiplied by the particle's charge and then normalized to the volume the axisymmetric element represents and to the accumulation time-step. The electrostatic force vectors obtained from these calculations, as well as the continuum velocities produced in the prior step, are both used as inputs to the particle trajectory field calculations.

Apart from the operating parameters of the gun (spray material feed rate, shaping air pressure, etc.), other inputs to the trajectory field calculations are the size distribution and initial trajectory of the particles, which are a distribution of particles being released from a random location at random initial velocities in the vicinity of the bell cup lip. It is assumed that the

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charge from current draw on the gun (and input parameter) is evenly distributed over the surface area of each of the droplets formed.

The time step for modeling the particle trajectory is controlled by dividing the distance necessary for a particle to reach the border of an element's quadrant by its velocity at t=0. These calculations are repeated per particle until the position of the particle coincides with a physical barrier in the system. Once a particle makes contact with a physical barrier, a contribution to the local charge and coating thickness accumulation is made. The next particle path is modeled until all particles have landed on some impenetrable boundary, which represents the spray accumulation time-step.

The complete equation of motion may be simplified as many of the terms become insignificant when dealing with a gas-liquid multiphase system where the density ratio is typically of the order of 10^{-3} (e.g. buoyancy, virtual mass, and Basset force). For the majority of the domain, with the exception of near the nozzle, flow local to the particles can be described by creeping flow based on the relative velocity and particle diameter. Furthermore, dimensional analysis of the system indicates that gravity is also an insignificant contributor to this acceleration equation; therefore, the final equation becomes:

$$m\frac{d\mathbf{v}}{dt} = 3\pi\mu D\left(\mathbf{u} - \mathbf{v}\right) + q\mathbf{E} \tag{1}$$

As the droplets strike the substrate, the spray material forms a dielectric coating on which a charge accumulates, which contributes to the superior thickness uniformity of E-spray vs. that of conventional spray by causing incoming particles to become diverted to areas of lesser charge – and lesser thickness.

The coating thickness and charge are assigned to the two nodes in the immediate area of the landing site in a manner similar to that of the charge cloud calculation. As the particles land, the charge and volume of each droplet is assumed to spread to cover this entire area resulting in a specific contribution per drop. The decay of the charge is then modeled as a parallel-plate capacitor, using the accumulation time-step.

To account for the charge accumulation and spatial charge density, the particles are re-released 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 the iterations of particle release. 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.

Because the continuum velocity field varies with time, the drag effects on the particles change as each accumulation time-step progresses. Additionally, the charge density of the spray changes with each accumulation time-step in tune with modifications in the particle paths resulting from the continuum velocity field variations. The accumulation time-steps continue to progress until an arbitrary total time has elapsed, for example, 10 seconds of spray.

6 Results

Figure 3 shows the resultant equipotential lines and the air speed profiles of a converged solution of the accumulation time-step.

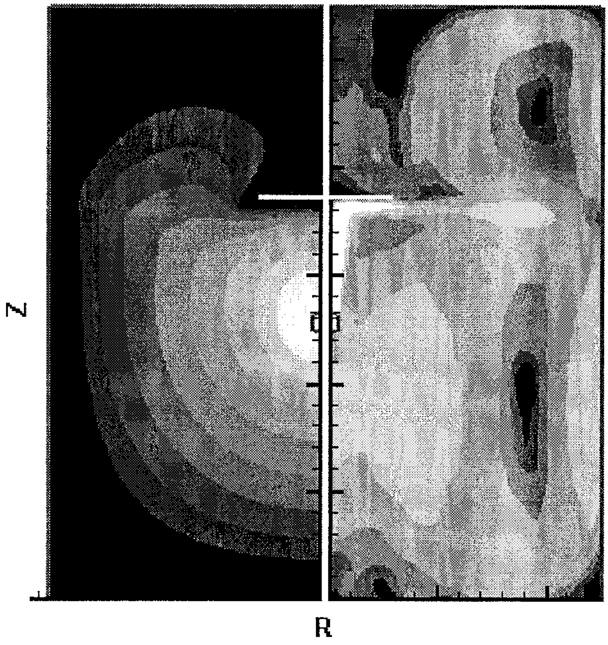

Figure 3: Logarithmic Contour Plots of Electrostatic Potential (Left) and Air Speed (Right). Gun voltage = 45kV; Gun RPM = 20,000; Mean Particle Diameter = 131μm; Fluid Feed Rate = 0.5 mL/s. White contours signify maximum values of 1.0 for both plots.

From these plots, one can see that both the electrostatic and drag forces are greatest in proximity to the spray nozzle, as expected. The contribution of the space charge on the electrostatic field distorts the overall shape of the equipotential lines such that there is an "instability point", which manifests itself as the sharp corner in the contours. The velocity profile shows two vortices, one above and one below the grounded disc (in white). The jet entrains the surrounding air to give rise to the wind velocity outside of the primary path of the jet

In Figure 4, the thickness of two deposited coatings is shown. This figure indicates that the majority of the spray lands on the edge of the grounded disc, and that the spray distribution is a hollow cone. While not all of the spray landed on the target, the overall transfer efficiency improved by roughly 10% by doubling the voltage setting on the gun.

7 Conclusions

A computer algorithm capable of simulating the path of an electrostatic spray-gun distribution has been demonstrated. By solving each portion of the model individually, a converged solution was achieved. This program should allow for parametric studies of how the individual variables involved in electrostatic spray affect the overall spray pattern, which should help operators of such equipment define their optimum spray setup without the need of costly trial-and-error empirical development. Although the results compare well qualitatively to operator experience, laboratory experiments to validate the model are still required.

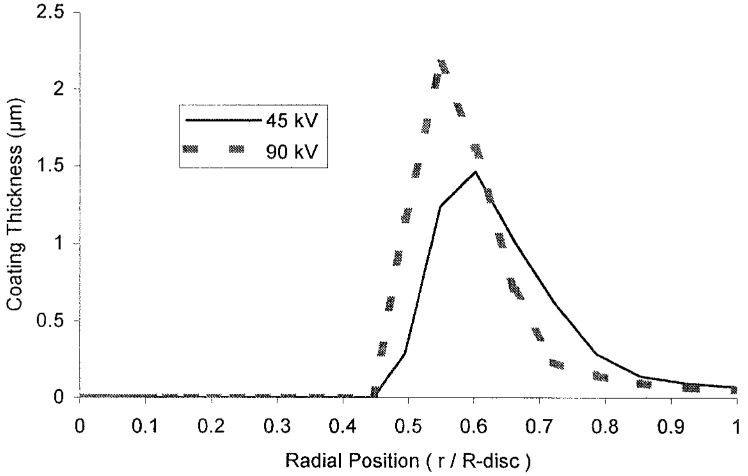

Figure 4: Coating thickness as a function of radial position (10 time-steps w/ 10^4 particles per step) for 45 kV and 90 kV gun voltages.

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