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A computer simulation for predicting electrostatic spray coating patterns

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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 (i.e. no direct 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 (k–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.

Keywords: Electrostatic spray; E-spray; Axisymmetric jet; Rotary atomizer; Particle tracking

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 airless E-spray system has a transfer efficiency of up to 50–60%, 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

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discussed in this paper is a non-aqueous paint in the form of a xylene/polystyrene solution and an indicator dye applied to a conductive substrate using a rotary bell electrostatic spray gun.

1.1. 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.

1.2. 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. In addition, Meesters' model did not simulate a multitude of particles, neglecting particle–particle interaction [2].

Ellwood and Braslaw assembled a comprehensive model using an iterative particle source in cell (PSIC) approach [9]. They assume that the three fields (electrostatic, particle trajectory and fluid velocity) are axisymmetric and include a torsional velocity component.

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.

1.3. 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 modeled 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].

An axisymmetric slice of the system used in this project, including some of the proposed boundary and initial conditions, is shown in Fig. 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 exterior of the system is surrounded by a grounded physical boundary with the exception of an exhaust vent located at the top of the domain.

1.4. Model description

The details of atomization are not resolved in the model presented in this paper, instead a log-normal distribution [13] about a mean droplet size [14], a uniform distribution of starting locations and an initial droplet velocity are assumed as initial conditions on droplet trajectories [9]. The