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Validation of a numerical model for the simulation of an electrostatic powder coating process

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Abstract

Numerical modeling of a complete powder coating process is carried out to understand the gas-particle two-phase flow field inside a powder coating booth and results of the numerical simulations are compared with experimental data to validate the numerical results. The flow inside the coating booth is modeled as a three-dimensional turbulent continuous gas flow with solid powder particles as a discrete phase. The continuous gas flow is predicted by solving Navier–Stokes equations using a standard k–ε turbulence model with non-equilibrium wall functions. The discrete phase is modeled based on a Lagrangian approach. In the calculation of particle propagation, a particle size distribution obtained through experiments is applied. The electrostatic field, including the effect of space charge due to free ions, is calculated with the use of the user defined scalar transport equations and user defined scalar functions in the software package, FLUENT, for the electrostatic potential and charge density.

Keywords: Powder coating; Numerical simulation; Lagrangian method; Space charge density; κ–ε Turbulence model; Electrostatics

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1. Introduction

Powder coating is considered a more economical and ecologically friendly process compared to wet painting due to the avoidance of solvents (Bailey, 1998). Electrostatic powder spray painting is of significant industrial interest since it offers many advantages and great flexibility. The powder coating process involves fluidization and transport of powder particles, which are charged and sprayed over an electrically earthed workpiece using a spray gun, and deposition of charged powder particles over the workpiece. When the required coating thickness is obtained, the workpiece is placed in an oven where the powder layer is fused to form a continuous film. Usually the coating process is carried out inside an enclosed space, a coating booth, to be able to reclaim the oversprayed powder and to keep work environment clean.

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The performance of a powder coating process is mainly measured by two parameters, the first pass transfer efficiency (FPTE) and the coating quality. The FPTE is generally defined as the ratio of the amount of powder deposited on the workpiece to the amount of powder sprayed from the spray gun. Powder properties such as particle size, particle size distribution, chemical composition, tribo and corona charging characteristics, electrical resistivity, hygroscopicity, fluidity and shape distribution all play significant roles on the performance of a powder coating process, such as FPTE, the uniformity of the coating film, adhesion and appearance (Mazumder et al., 1997). The uniformity of the coating film and appearance are the major issues for potential use of powder coating for high-end surface coatings, such as the large market of automobile top clear coats. Presently, the powder coating industry uses 30 μm or larger size particles. These coarse powders cannot provide very smooth surfaces finishes. As a result, the use powder coating in the automotive industry has been restricted to some underhood components and parts, such as hubcaps, door handles and radiators, and is generally not used for the more lucrative automotive top clear coat applications. Yanagida et al. (1996) reported that high-quality clear coating for the automotive industry is attainable using mean paint particle diameters around 10 μm. Industrial experiments carried out in our Powder Technology Research Centre have also shown that the use of 15 μm paint powder, if not agglomerated, results in excellent surface finish. Therefore, it is possible that powder coating can provide the required surface finishing and the cosmetic look required to penetrate the large potential market of automotive top clear coat using finer particles.

A major issue relating to the use of the fine powder is its fluidity. Fine powders tend to agglomerate and form clumps. Zhu and Zhang (2002) developed a technology to fluidize these fine particles and it is now possible to use fine powder in coating industries and replace liquid painting for high-end surface finishing. To this end, however, it is very important to study the flow field of the sprayed powder and air inside the coating booth to understand its influence on the performance of the coating process and to design appropriate operating conditions and geometric parameters of the coating booth for a given spray gun. Numerical simulations can be a very useful to investigate such flows and understand various underlying phenomena. Elmoursi (1989) studied the electrostatic field, under Laplacian condition, in the space between bell and the paint target as well as at their surface for the bell type electrostatic liquid spray-painting system. Later, this model was expanded to study the space charge effect of charged paint droplets (Elmoursi, 1992). It was found that the space charge tends to enhance particle deposition and also causes the spray pattern to expand. Woolard and Ramani (1995) developed a three-dimensional finite element model for predicting the electrostatic field. The model was used as a tool for predicting the effect of various parameters on the electrostatic field. Ali et al. (2000) developed a mathematical model for the electrostatic field of the corona powder coating system to simulate single particle trajectories for a given charge to mass ratio, particle diameter and initial position. It was found that as the charge to mass ratio increases the particle trajectory spread further out in the radial direction. So far, most efforts were to study the electrostatic field but not to completely model a coating process.

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. A standard κ–ε turbulence model was used for the gas-phase flow. 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. They also included the influence of turbulence dispersion on the sprays, which was previously ignored. It was observed that the effect of the space charge is significant and it tends to increase the strength of the electrostatic field in the region between the two electrodes especially near the target, which enhances the particle deposition. They validated their model by