Simulation-based Study of the Impact of Mean Powder Particle Diameters on Key-Performance-Attributes of the Powder Coating of U-Profiles

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Abstract. A computational tool based on the open-source software OpenFOAM was designed to simulate the interaction between powder coating guns and metal surfaces during industrial coating. This tool accounts for various factors, such as airflow, movement of coating particles, interactions among particles, and interactions between particles and surfaces, including details like blow-off effects, electrical phenomena like corona formation around electrodes, and how particles get charged in the corona. Enhanced to work with cloud computing technology, this tool can simulate multiple coating scenarios at once, adjusting for different process parameters. Tests for accuracy and relevancy have been carried out, with positive results. This specific study showcases how the tool predicts coating patterns, *coating efficiency*, and *coating uniformity* on a U-shaped metal object based on varying *mean powder particle diameters*. It suggests optimum particle sizes for coating U-profiles both efficiently and uniformly, which is valuable information for commercial powder material suppliers.

1. INTRODUCTION

An OpenFOAM-based [1] powder coating simulation tool was crafted, incorporating factors like: i) air fluid dynamics in the process, ii) electro-statics, iii) dynamics of coating-powder particles, which includes their interaction with fluid, other particles, the electric-field, and specifically with substrates, iv) the generation and spread of corona, as well as v) kinetics of particle charging. This tool can numerically determine primary outcomes of the powder coating method, such as patterns, efficiency, and uniformity, according to set process and material factors [2-6]. Though other simulation methods like the fluid-particle feature in StarCCM+ as shown in [10], or the flux-enhanced Godunov techniques [9], can handle simulations of several solids and fluids and provide various fluid-solid boundary conditions, only a specialized Lagrangian particle simulation, featuring major aspects of an *Extended Discrete Element Method* (XDEM) method, could capture the detailed interactions between particles and substrate seen in powder coating.

Now fully compatible with *massive simultaneous cloud computing* technology [7], the software can model hundreds of coating parameter scenarios in an efficient timeframe. Specifically, the computation time for the showcased study of 100 simulations took only around 120% of a single simulation's duration.

This research showcases the ability of the solver to replicate the powder coating process for a stationary pistol applying coating powder to an electrically grounded U-profile metal substrate, located in a hexagonal chamber with inlet and outlet vents around the pistol-substrate alignment. Figure 1 illustrates the configuration of the pistol and U-profile, accompanied by a time-lapse of the particle cloud during coating.

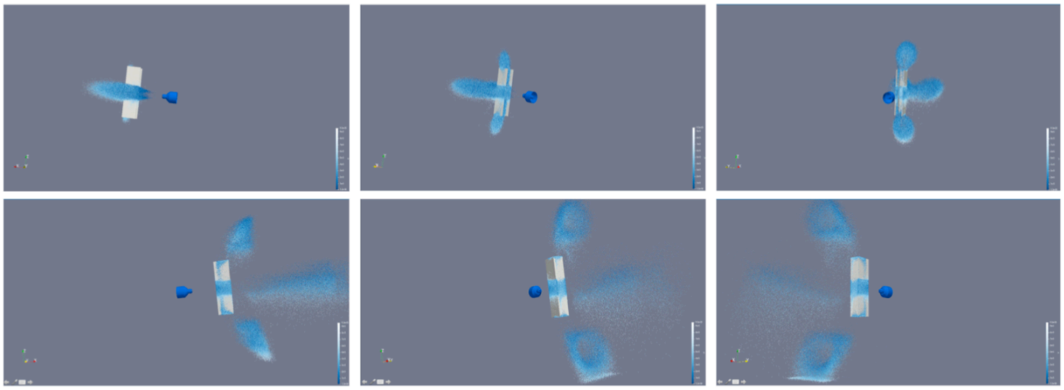

FIGURE 1. Progression of a modelled powder coating procedure on a metal U-profile. Initial stage: top-left; final stage: bottom-right. The depicted Lagrangian particle cloud (in light blue), consisting of around 250k particles, emerges from the coating pistol (in dark blue), envelops the substrate (in grey), and either adheres to or moves past the substrate.

This paper primarily delves into the effect of varying *mean powder particle diameters* in a Gaussian distribution on the main outcomes of the coating process of a standard U-profile. The outcomes under scrutiny are: visible coating pattern, *coating efficiency*, and *coating uniformity*. These projected findings can guide informed decisions for powder quality adjustments suited for U-profile tasks.

2. METHODS

2.1 Solver Capabilities

The foundational abilities of the numerical simulation model were elaborated upon in references [2], [5], and [6]. Key elements include: Reynolds Average Stress (RAS) representation for turbulence in the pistol, the coating chamber and surrounding the substrate; empirical estimation of specific turbulence impacts on particle movement, even with localized RAS turbulence averaging [6]; the electro-static field's depiction between any high-voltage electrode and grounded substrate by resolving the consistent Maxwell equations; detailed mapping of the internal mechanism of the powder-coating-pistol for particle-loaded flow; Lagrangian representation of several hundred thousand released coating particles to signify the particular powder cloud for each use-case; an in-depth analysis of fluid-particle dynamics, both mechanical and electrical interactions among particles, and between particles and substrate; combined electro- and aerodynamic species-transport representation for ionized oxygen distribution near the high-voltage electrode, indicating corona formation [4]; semi-empirical methods for particle charging and deposition on the substrate.

2.2 Solver Validation

Qualitative and Quantitative Validation - Flat Plates

The powder-coating solver underwent a qualitative and quantitative evaluation based on varying process parameters as detailed in [2]. This assessment centred on the powder-coating of multiple metallic flat-plate substrates, juxtaposing actual and simulated coating patterns, coating efficiencies, and comparative coating volumes against changing parameters, specifically: input voltage, rate of process air flow, distance between pistol and substrate, as well as the angle and position of the pistol relative to the substrate.

Application & Qualitative Validation - U-Profiles

This research applied the powder-coating solver particularly to the coating of metallic U-profile substrates. Figure 1 portrays the progressive stages of a Eulerian-Lagrangian modelled process. With this study's emphasis, qualitative evaluations of the solver delved deeper into U-profile modelling. An actual metallic U-profile was coated under set lab conditions, mirroring these conditions in a numerical simulation. The post-coating thickness on the real U-profile was gauged using Coatmaster-3D [8] technology. This allowed for a qualitative matchup with the simulation, where the anticipated coating design was depicted. A side-by-side look at the real and simulated outcomes is exhibited in Figure 2.

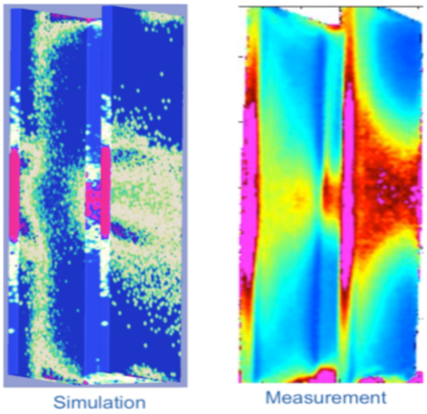

FIGURE 2. Predicted coating pattern from simulation (left) compared to the experimentally obtained pattern (right) for a powder-coated U-profile. Parameters are voltage: 50kV, pistol-substrate gap: 15cm, main process airflow: 2m^3/h, secondary process airflow: 0.5m^3/h, coating time for both experiment and simulation: single-burst/0.5 sec, mean particle diameter: 34µm, particle size variation in Gaussian distribution: +/- 16µm, particle mass: 1400 kg/m^3.

3. RESULTS

The powder-coating solver was configured to determine the effects of changing *mean powder particle diameters* on the U-profile powder coating outcome. Within this framework, the solver post-processes the anticipated coating outcomes focusing on visualization of coating patterns indicating local coating thickness (equivalent to the *Volume Fraction Field*); the proportion of the coated volume to the total volume of injected particles (equivalent to coating *efficiency*), and an indicator of coating uniformity (described as *standard batch-based coating deviation*).

An extensive simulation parameter-study was undertaken, comprising 100 separate simulation runs. In these runs, the *mean powder particle diameter* ranged in 100 increments from 5µm to 205µm. It is noteworthy that with the utilization of *massive simultaneous cloud computing*, the cumulative computation time was roughly equivalent to 120% of the duration of a singular simulation. Figure 3 and Figure 4 comprise the findings of this study.

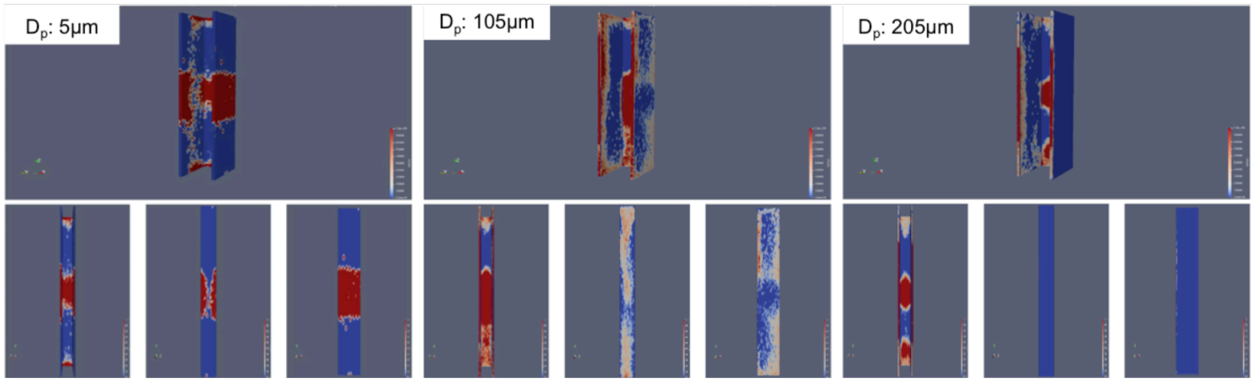

FIGURE 3. Modelled coating patterns (representation of *volume fraction fields*) at differing *mean particle diameters*: 5µm (left), 105µm (middle), and 205µm (right). The top row displays the front view of the U-profile substrate, while the bottom row illustrates the front (left), rear (middle), and side (right) perspectives of the U-profile for each *mean particle diameter*.

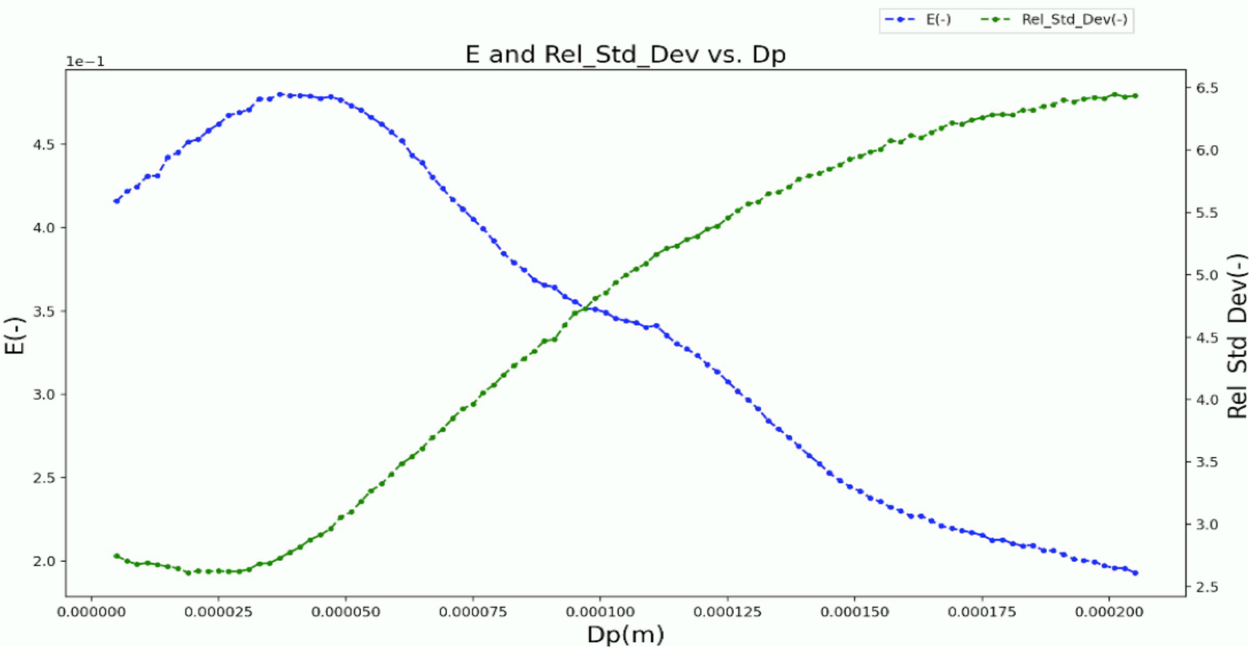

FIGURE 4. Aggregated findings from 100 simulation runs with *mean particle diameters* ranging incrementally from 5µm to 205µm. Consistent process parameters include: applied voltage at 50kV, gap between pistol and substrate at 15cm, airflow rate at $2m^3/h$, particle diameter fluctuation: +/- 16µm, and particle mass at 1400 kg/m^3. The graph juxtaposes *coating efficiency* (E, highlighted in blue) and the *relative standard batch-based coating deviation* (Rel_Std_Dev, marked in green) against the *mean particle diameters* (D_p).

The aggregated outcomes from the 100 powder coating simulations, as illustrated in Figure 4, reveal that optimal *coating efficiency* is attainable with *mean particle diameters* around 35µm, with a variation of +/-2µm. The least *relative standard batch-based coating deviation*, or the highest *coating uniformity*, is found at *mean particle diameters* of approximately 25µm, again with a variation of +/-2µm. It is important to note that the mentioned uncertainty of +/-2µm stems from the interval of the parameter investigation and does not signify comprehensive numerical uncertainty assessment.

CONCLUSION AND OUTLOOK

A new, validated, Euler-Lagrangian solver rooted in OpenFOAM was utilized to study the effects of changes in *mean particle diameters* on powder coating outcomes. The research primarily examined the coating of a standard metallic U-profile substrate and aimed to predict primary attributes of the powder coating process, namely coating patterns, *coating efficiencies*, and *coating uniformity*. Enhanced compatibility with the *massive simultaneous cloud computing* technology facilitated an extensive simulation parameter study, including 100 individual runs. Though simulations were confined to a fixed pistol-substrate arrangement and singular particle burst application, the findings hold significant implications for general U-profile coating. This is due to the comparative process performance, even within a fixed, singular burst context, offering insights into potential intricate process scenarios.

The current research highlights that distinct optimal values for *mean powder particle diameters* exist for both *coating efficiency* and *coating uniformity*. Considering otherwise typical process conditions, specifically 50kV voltage, 15cm pistol-substrate distance, and 0° pistol-substrate rotation, these optimal values were catalogued in Table 1.

	Mean Particle Diameter
Optimum Coating Efficiency	35.0µm +/-2µm
Optimum Homogeneity	25.0µm +/-2µm

Table 1: Optimal *mean powder particle diameters* in regards to maximum *coating efficiency* and highest *coating uniformity*, as retrieved by simulations.

The data in Table 1 provides a comprehensive framework for informed powder material selection for U-profile applications. Compared to existing methodologies, the authors believe these results possess the potential to both decrease resource usage and enhance the quality of U-profile powder coating applications.

Nonetheless, future endeavors will seek to delve deeper in this domain. Despite the completion of about 100 simulation runs in this study, it only captures a fraction of the entire U-profile powder-coating parameter space. Parameters like *particle size deviation*, powder *particle mass*, U-profile shape, *pistol-substrate gap* and alignment, *applied voltage*, primary and secondary *process air flow rates* as well as environmental factors such as *moisture levels*, have been set to commonly accepted standards. A more thorough exploration will offer a comprehensive understanding of the entire system, shedding light on inter-parameter relationships.

Upon accomplishing this next phase, an associated mechanism will be developed to streamline the entire simulation process. Consequently, the current findings will be transformed into a software tool, suitable for both academic and commercial usage.

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