Investigations of Spray Painting Processes Using an Airless Spray Gun

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Abstract: This paper presents experimental and numerical studies on spray painting processes by using airless spray guns for ship painting. A computational fluid dynamics code was applied to calculate the flow field and the droplet trajectories. Droplet size distributions and droplet velocities as necessary inlet characteristics for the simulations were experimentally obtained using a Spraytec Fraunhofer type particle sizer and laser-Doppler anemometry. Effects of shoreline winds and painting distance on the transfer efficiency and on the paint film thickness distributions on the target were numerically studied.

Key words: Spray painting, airless gun, simulation.

1. Introduction

Airless spray guns are widely used in painting applications mainly focusing on corrosion protection, e.g., metal construction work, bridges or ships. With airless spray guns and appropriate coating materials, relatively thick films can be achieved. Due to the high impact momentum of the droplets, the coating material is penetrating into pits and scratches, improving the quality of corrosion protection. Compared to the well-known air spray painting, the droplets are large, but, nevertheless, the paint droplet deposition is affected by the air flow field. Also, uncontrolled gun-to-target distance due to different operator skill levels limits the transfer efficiency and influences the film thickness distribution. This is a specific problem in open air ship painting, as strong shoreline winds may occur. In order to get a well understanding of these painting processes and to get solutions for this problem, it is necessary to carry out detailed investigations on droplet deposition under the condition of strong side winds.

Experimental studies involving spray painting using airless guns have been performed, for example, by Settles [1] and Plesniak et al. [2]. They focused their studies mainly on the flow visualization [1] of airless spray painting and effects of application parameters on the spray TE (transfer efficiency) in painting booths [2], e.g., paint mass flow rate, gun-to-target distance, gun-to-target angle, etc.. Although there are many computational studies of air-assisted sprays in the research area of fuel injectors [3, 4], there are no detailed reports about numerical simulations of spray painting using airless as well as air-assisted guns. During the last 10 years, detailed experimental and numerical investigations of painting processes by using different atomizers, such as high-speed rotary bells with electrostatic support, pneumatic application using coaxial jet type atomizers, as well as powder coating, have been carried out at the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) [5-8]. The main task of these investigations was to
calculate the film thickness distribution and the transfer efficiency (amount of paint reaching the work piece) for a given set of application parameters and boundary conditions.

The present contribution presents experimental and numerical results of investigations on the spray painting using a typical flat jet airless gun. Red colour two-component paint was used. As PDA (phase-Doppler anemometry) can not be applied with real paint due to optical inhomogeneities of the paint material, Fraunhofer diffraction and LDA (laser-Doppler anemometry) have to be applied in combination. Both experiments delivered the necessary boundary conditions for the trajectory calculation of the droplets in the numerical simulations that were performed by means of the commercial CFD (computational fluid dynamics) solver ANSYS-FLUENT. The calculated film thickness distribution and the TE on the target were compared with experiments for model assessment. Parameter studies were carried out in the numerical simulations in order to obtain the effects of side winds and gun-to-target distances on film thickness distributions.

### 2. Experimental Investigations

In spray painting using airless guns, paint atomizing is produced without use of compressed air. Airless guns are simple pressure atomizers, usually with elliptically shaped outlet to achieve a flat spray cone. The atomization depends mainly on the used gun supply pressure (or paint mass flow rate), the tip geometry and paint properties, for instance, viscosity and surface tension. In the present research, relatively large tip sizes (effective orifice diameter) of 0.48 mm to 0.53 mm with a spray angle of ca. 45° (long axis of the spray cone), as they are usually applied in ship painting processes, were used. In Table 1, properties of the paint material, major characteristics of the airless gun, as well as the specific operating conditions investigated are summarized.

#### Table 1  Experimental parameters.

<table>
<thead>
<tr>
<th>Paint material</th>
<th>Solid fraction</th>
<th>Density (wet)</th>
<th>Density (dry)</th>
<th>Pressure supply</th>
<th>Effective orifice diameter</th>
<th>Spray angle</th>
<th>Gun-to-target distance</th>
<th>Booth air velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red color two-component paint</td>
<td>72.3%</td>
<td>1.317 g/mL</td>
<td>1.690 g/mL</td>
<td>200 bar, corresponding to a paint mass flow rate of 0.0273 kg/s</td>
<td>ca. 0.48-0.53 mm</td>
<td>ca. 45°</td>
<td>300 mm</td>
<td>0.1 m/s</td>
</tr>
</tbody>
</table>

### 2.1 LDA Measurements

Concerning the measuring techniques for the investigations of the atomization processes, locally resolved droplet velocity, size and mass flux measurements can be made with a PDA system. However, PDA, as mentioned in the introduction, can not be applied with real paint due to optical inhomogeneities of the paint material. Alternatively, LDA measurements were performed to obtain integral droplet velocities in the spray jet.

A DANTEC two-component backscatter fibre LDA system, equipped with a 5 W Ar-ion laser, was applied in the present studies. Fig. 1 shows the setup of the LDA measurement. The axial velocity and the velocity component in the direction of the jet spread were measured along the centre lines within two spray cross sections, i.e., 50 mm and 100 mm below the liquid nozzle. Figs. 2 and 3 show the measured velocity profiles. It can be seen that the droplet axial velocity in the spray centre is quite high, i.e., 110 m/s and 80 m/s at the jet location of 50 mm and 100 mm, respectively.

### 2.2 Droplet Size Measurement

Droplet size measurements were carried out applying a Malvern Spraytec Fraunhofer type particle sizer at various distances from the spray nozzle. It was found that the liquid break-up is finished at approximately 100 mm distance below the nozzle. Since the measuring volume of the laser beam has a diameter of 9 mm, the measured results are actually average values within the tube-shaped measuring volume.
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Fig. 1  Setup of LDA measurement.

Fig. 2  Measured axial mean velocity 50 mm and 100 mm below the liquid nozzle.

Fig. 3  Measured velocity component in the jet spread direction 50 mm and 100 mm below the liquid nozzle.

of the Malvern. Fig. 4 shows the setup of the droplet size measurement. By traversing the spray gun that was mounted on a robot along the major axis of the elliptical spray region, droplet size distributions along the major axis of the elliptical spray cone were obtained.

Fig. 5 shows the droplet Sauter mean diameter (D3,2) distribution in the measured spray cone region. It can be clearly seen that there is an accumulation of large droplets at both edges of the major axis of the spray pattern. This tendency has been validated by the visualization of the disintegration process obtained by using a Nanolight flash. Evidently, as shown in Fig. 6, there are two clear chains of large droplets at the edges of the spray cone, resulting from the disintegration of the sheet rim. Similar image of paint atomization near an airless nozzle can also be seen in Ref. [1]. Fig. 5 indicates a certain asymmetry between lower and upper edge, however, it should be noted that the droplet concentration near the edge is quite low, resulting in a significant uncertainty of the measurement in these regions. A representative droplet size distribution for the measured spray cone, the so-called integral droplet size distribution as shown in Fig. 7, was calculated based on the individual size distributions and the measured droplet concentration distributions [5]. Obviously, the atomization with the used airless gun is characterized by the occurrence of large droplets. The corresponding mean sizes are 68.5 µm for D3,2 and 81 µm for Dv, 50. The integral droplet size distribution is required in the numerical simulations presented below.
2.3 Paint Film Thickness Measurement

Dynamic spray painting with a relative speed between gun and target of 0.9 m/s and a gun-to-target distance of 300 mm was performed. The target, a flat panel with a size of 200 × 800 mm², was positioned vertically. The gun axis was perpendicular to the target surface so that the major axis of the spray pattern was formed along the 800 mm direction. After painting, the panel was put horizontally into an oven for baking. The dry film thickness on the panel was then measured by means of magneto-inductive method. Fig. 8 shows the mean values of the measured film thickness distribution including uncertainty bars. It can be seen that high film thickness exists not only in the spray centre but also close to both edges of the spray pattern, which is quite a typical spray structure produced by airless guns.

3. Numerical Simulation

3.1 Computational Method

The commercial CFD code ANSYS-FLUENT 13.0, based on the finite-volume approach, was applied in the present numerical simulations. The gas phase was modeled using the Eulerian conservation equations for mass and momentum. The three-dimensional incompressible airflow was calculated with the segregated solver. The turbulent transport was modeled using the realizable $k-\varepsilon$ model with the scalable standard wall function. An unstructured mesh with 1.5 million cells for the computational domain with a size of $1.5 \times 1.2 \times 0.8$ m³ was used and mesh refinement was carried out.

As primary inlet boundary condition for the continuous phase, a booth air velocity of 0.1 m/s, similar to the experimental condition, was applied. Later, the booth air velocity was purposely increased to 5 m/s and 10 m/s, in order to simulate the case with strong shoreline winds. Except for the booth air velocity, other boundaries on the computational domain were defined as ambient pressure.

The Lagrangian tracking method was applied for the droplet phase. A significant problem arises in numerical simulations using airless guns concerning the determination of the inlet conditions for the droplet phase, since there is no compressed air from the atomizer and the high droplet number density close to the gun anticipates the application of any optic measuring techniques. In previous simulation using a
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pneumatic atomizer [5], it was found that the initial droplet conditions necessary for the simulation of the liquid phase can be set close to the nozzle. A similar method is applied in the present study. Basically, the droplet injection data were applied to a small rectangular region of $8 \times 2$ mm$^2$, the projection area of the effective orifice surface, which is considered quite close to the nozzle. As droplet size distribution, the integral distribution shown in Fig. 7 was used. Based on the experimental results of the LDA measurements, the axial and the radial velocities of the droplets as well as the droplet flux distribution in the injection region were fitted to match the film thickness distribution on the target panel.

The effect of turbulent dispersion on the particle motion was taken into account by using a stochastic tracking model. The two-way coupling for the momentum exchange between the two phases was applied, which is quite important in the present numerical simulation. The simulation results are discussed in the following section.

3.2 Simulation Results

It is important to validate the used models in the numerical simulation, especially the injection model in the case of the present study. Spray painting simulation was at first carried out under the experimental conditions shown in Table 1. Air velocity contours in a cross-section at $z = 0$ are depicted in Fig. 9. Although the booth air velocity is quite low, a higher air velocity can be observed in the spray jet centre due to the momentum exchange between the droplet phase and the air phase, especially in the region quite close to the nozzle. The static wet film growth rate on the target is shown in Fig. 10. By artificially moving the spray pattern (Fig. 10) along the z-direction taking into consideration the robot velocity, the wet as well as the dry density of the paint material, the dry film thickness distribution on the target was calculated and compared with the experimental results, as shown in Fig. 11. A quite good agreement between experiment and simulation can be observed. The validated injection data can further be applied for the investigation of more complicated painting applications, such as studying the effect of shoreline winds, spray painting on complicated work piece geometries or arbitrary positioning of the atomizer, etc..

In the numerical simulations, further parameter studies concerning the effects of wind velocities and painting distances on TE (transfer efficiency) and film thickness distribution were performed. Two constant velocities, 5 m/s and 10 m/s, were applied in the simulations with two painting distances, 300 mm and 600 mm, respectively.

Figs. 12 and 13 show the simulation results for the painting distance of 300 mm. Although a significant effect of wind velocity on the air velocity contours in the spray cone can be observed, the TE on the target is 99% for the wind velocity 5 m/s, and 97% for 10 m/s, since
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Fig. 11  Comparison of calculated and measured dynamic film thickness distributions.

Fig. 12  Velocity contours (m/s) in cross-section $z = 0$ for painting distance 300 mm: (a) wind velocity = 5 m/s; (b) wind velocity = 10 m/s.

Fig. 13  Static film growth rate on the target (µm/s) for painting distance 300 mm: (a) wind velocity = 5 m/s; (b) wind velocity = 10 m/s.

Fig. 14  Velocity contours (m/s) in cross-section $z = 0$ for painting distance 600 mm: (a) wind velocity = 5 m/s; (b) wind velocity = 10 m/s.

Fig. 15  Static film growth rate on the target (µm/s) for painting distance 600 mm: (a) wind velocity = 5 m/s; (b) wind velocity = 10 m/s.
the strong axial momentum of the droplets significantly reduces the influence of wind velocity. Detailed analysis of droplet trajectories will be presented below.

By increasing the painting distance, e.g., to 600 mm, the axial momentum of the droplets decreases tremendously near the target. As shown in Figs. 14 and 15, the effects of wind velocity on the air flow field in the spray cone and on the static film distribution on the target are enormous. The corresponding TE decreases to 82% for wind velocity 5 m/s and 55% for 10 m/s, respectively.

Fig. 16 shows the droplet trajectories. For the painting distance of 300 mm, droplets, and especially the larger droplets, are still deposited on the target even by the wind velocity 10 m/s, which results in little change in TE. Small droplets that have lower momentum can not penetrate easily the air flow boundary layer formed on the target, and disperse with air flow as overspray. However, in the present study, small droplets are not dominant for the total mass flow rate (Fig. 7), resulting in a rather little effect on the TE. Of course, in the cases with side wind the film thickness distributions on the target are different from those without wind velocity, which can be seen in Figs. 13 and 17. For the painting distance of 600 mm, much more droplets disperse with the air flow, resulting in a lower TE, which is identical with the simulation results in Figs. 14 and 15.

Important simulation results concerning the dynamic film thickness distributions and the transfer efficiency on the target are summarized in Fig. 17 and Table 2.

4. Conclusion and Outlook

In this paper, experimental and numerical investigations of the spray coating process using an airless gun have been presented.

The atomization process with an airless gun has been experimentally studied by measuring the droplet integral velocity using LDA and by determining the droplet size using a Spraytec Fraunhofer type particle sizer. A representative droplet size distribution was obtained. The spray was characterized by relatively large droplets and a high axial momentum. Based on the experimental results, the injection model for calculating initial conditions for the droplet trajectory simulation was created. The droplet phase calculations were then carried out by using the obtained injection data that were set very close to the nozzle. Model assessment was performed by comparing measured and simulated film thickness distributions.

Parameter studies were carried out within the numerical simulations. It was found that wind velocity has significant effects on the film thickness distribution on the target but little effects on the transfer efficiency if the painting distance is kept to 300 mm. In case of blowing side wind, with increasing painting distance, a strong decrease of the transfer efficiency and inhomogeneous film thickness distribution on the target can be observed. To solve this problem for the outdoor ship painting process, a method to reduce the effect of side winds is to paint in the wake region of an obstacle. Numerical simulation will be an effective tool for the optimization of the obstacle geometry, which is used in an ongoing project at IPA (the Fraunhofer Institute for Manufacturing Engineering and Automation).
Fig. 17  Effects of wind velocity and painting distance on dynamic film thickness distribution.

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