SIMULATION OF THE SPRAY COATING PROCESS USING A PNEUMATIC ATOMIZER

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Abstract

The spray behaviour of a co-axial jet type pneumatic atomizer used in the painting industry has been experimentally investigated and numerically modelled. In contrast to previous work, the commercial FLUENT program was applied using the EULER-Lagrangian approach. The program was extended to calculate the film thickness from the local mass flux on the workpiece surface. The quality of the simulation was verified through comparisons of calculated and measured velocity profiles inside the spray cone and calculated and measured film thickness distributions on the work piece.

Two major results could be obtained: Firstly, it was found that the complete air flow field between the nozzle and the target can be calculated applying the known air inlet conditions directly at the atomizer. Hence, the effect of variations of the air flow rates on the flow field can be determined without additional experimental efforts. Secondly, the initial droplet conditions necessary for the simulations (size distribution, velocity and flux) can be taken very close to the nozzle. In this way, also the two-way coupling process between droplets and air flow altering the spray cone shape may be considered. The resulting film thickness distribution calculated with practically relevant air and paint flow parameters corresponds in its main features nicely to the experimental result.

Introduction

Pneumatic atomizers are widely used in the painting industry as they deliver the requested high optical quality, especially in the automotive industry. The basic geometry of the pneumatic atomizer used in this study is shown in Fig. 1. Atomisation is performed through a coaxial jet arrangement, in which the central paint jet with a typical diameter of 1.4 mm is surrounded by high-speed air, leaving the annular ring around the paint nozzle under sonic conditions. Around the annular ring, there are additional 8 small holes with a diameter of 0.6 mm to prevent the air cap from paint contamination. Four of them have an inclination of 45° relative to the spray axis. In addition, so-called shaping air nozzles with a diameter of 2 mm located on two sides of the centre jet are used to form an elliptical spray cone appropriate for painting of larger work piece.

Experimental and numerical investigations on the spray characteristics of such a kind of pneumatic atomizer have already been carried out [1], [2], [3]. Since the mechanism of the liquid atomization is quite complicated, there is no physical model that can be used to predict the primary atomization process. In general, the spray structure at downstream positions can be predicted by means of numerical simulations if certain boundary conditions and initial characteristics of the spray, e.g. drop velocity, drop size distribution and mass flux, are provided. These initial and boundary conditions for air and droplets can be experimentally obtained using, for instance, Phase Doppler Anemometry (PDA). However, it is difficult to perform these PDA measurement quite close the atomizer nozzle because of the high velocity and high number density of droplets.

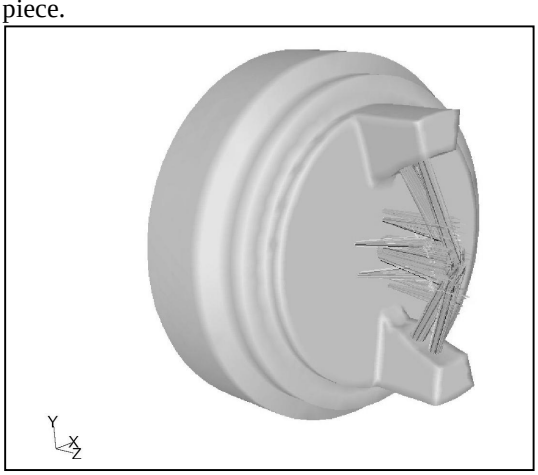


Figure 1: Inlet airflow in the nozzles of the pneumatic atomizer

Lindenthal [3] measured details of the spray structure at 100 mm distance below the spray nozzle. An elliptical spray region with 220 mm long axis and 80mm short axis was obtained. Altogether approximately 100 measuring points were taken in a quarter of the spray region. These spray measurements were used to perform first numerical simulations of the coating process with the final aim of estimating the film thickness distribution applied. However, practical relevance and applicability of the simulations are limited if new PDA measurements have to be performed each time important operation parameters, e.g. paint flow rate or air flow rates, are changed.

Therefore, the aim of present investigations is to model the spray-painting process by means of a CFD code purposely using simplified inlet and boundary conditions for both the air and the liquid phase. This was performed in several stages:

- The 3-D compressible airflow field produced by the nozzles and the annular ring around the paint jet was directly simulated
- Instead of using PDA, a Spraytec particle sizer based on laser diffraction was used to obtain the droplet size distributions
- The inlet plane for the droplets was located as close to the nozzle as possible

The Euler-Lagrangian approach was used to calculate the two-phase flow field. The interaction between airflow and liquid phase was taken into account. The calculated results, e.g. velocity profiles and film thickness distributions on the painted work piece, were compared with the experiments.

Numerical method

In the current numerical simulations, the commercial CFD code Fluent based on the finite-volume approach was applied. The gas phase was modelled using the Eulerian conservation equations of mass, momentum, and energy. Turbulent transport was modelled using the RNG k-ε model. Figure 2 shows the computational domain with a size of 300x2000x2000mm, consisting of the pneumatic atomizer and a flat plate with a size of 200x1000mm at the distance of 250mm downstream of the atomizer. Unstructured meshes with 350 000 cells were used and mesh refinement was carried out. The major operating conditions of the atomizer are summarised in Table 1.

The liquid phase was simulated using the discrete phase model, i.e. the Lagrangian-tracking method. In this model the spray is represented by discrete droplets that can interact with the gas phase. Each droplet represents a parcel that has properties like a single effective droplet but with a given mass flow rate obtained from drop size distribution. With sufficient number of parcels the complete property range of a liquid spray can be represented in a computationally efficient way. The effect of turbulent dispersion on the particle motion was taken into account by using stochastic tracking model with an integral time scale constant of 0.3. In the current study the interaction between droplets was neglected due to the low mass flow rate of the liquid. Different droplet injection data were applied in order to study the influence of the initial spray characteristics on the spray structure downstream.

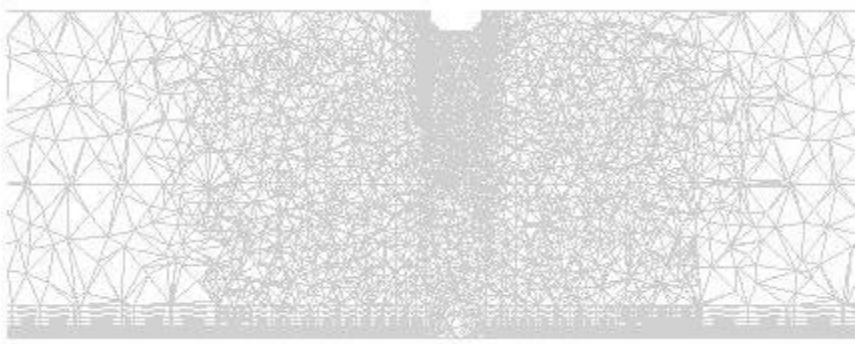


Figure 2 Computational domain with unstructured mesh

Atomizing air flow rate	300 l/min
Shaping air flow rate (elliptical spray only)	380 l/min
Liquid flow rate	300 ml/min
Liquid phase	Silver metallic paint

Table 1: Atomiser characteristics

Droplet size measurements

Since the CFD model is not able to simulate the primary atomization process and the resulting droplet size distribution, information concerning the initial spray angle, droplet size and injection velocity are required for appropriate droplet trajectory calculations. In the current study the atomization performance was measured at

locations 50 mm below the liquid nozzle applying a Spraytec Fraunhofer type particle sizer, yielding a 560 µm size range with a 300 mm receiving lens. The measuring volume of the system has a diameter of 9 mm.

Owing to the shaping air from the atomizer, an elliptical spray cone is formed downstream the atomizer. Size distributions along the long axis of the spray were obtained by moving the atomizer along the x-direction as shown in Fig. 3. In the same way, distributions along y were determined turning the atomizer by 90°. As an example, the individual droplet size distribution in the centre of the spray and the integral distribution for the whole spray region are compared in Fig. 4. The latter can be used to study the effect of the droplet injection positions on the film thickness. Fig. 5 shows the corresponding profile of the Sauter mean diameter D_{32} along

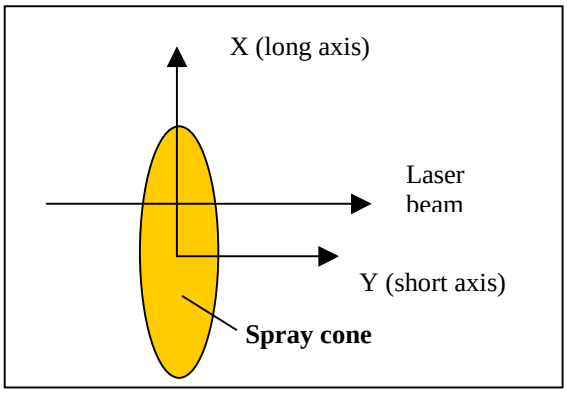


Figure 3: Definition of coordinate system

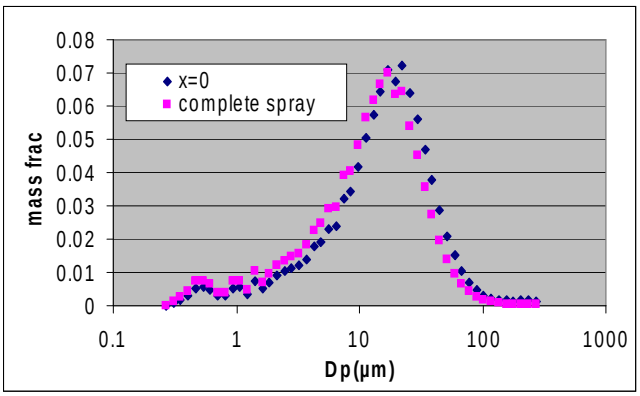


Figure 4: Measured droplet size distribution

the long axis.

Generally, the spray is characterised by relatively fine droplets. The value of the Sauter mean diameter D_{32} is increasing both towards the centre and the edge of the spray. The increasing mean diameters towards the edge of the spray, which is in contrast to standard coaxial jet atomisers, are mainly the result of the interaction of the spray with the additional shaping air flow. The liquid mass fraction distribution in the direction along the long axis was calculated according to the measured droplets concentration and is shown in Fig. 6. In the centre of the spray the maximum mass fraction can be obtained, corresponding to a high film thickness in the centre of the spray on the painting object. Since the spray is quite narrow in X-axis direction, only up to 3 measurements were performed in this direction. For the simulation of the droplet phase, a normal distribution for the mass fraction in this direction was applied.

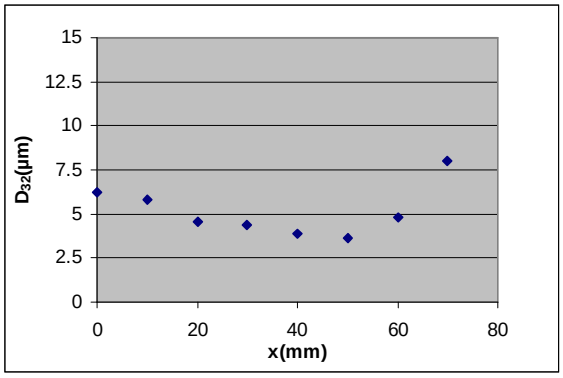


Figure 5: Distribution of D_{32} along the long axis

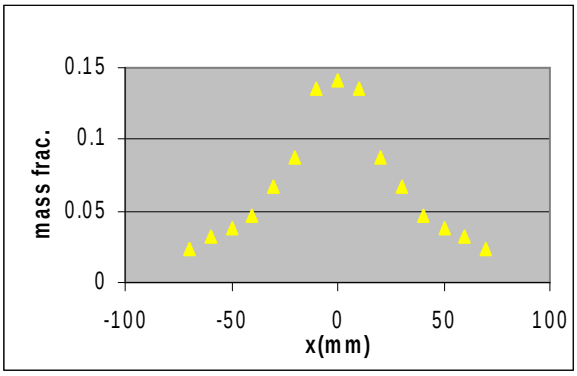
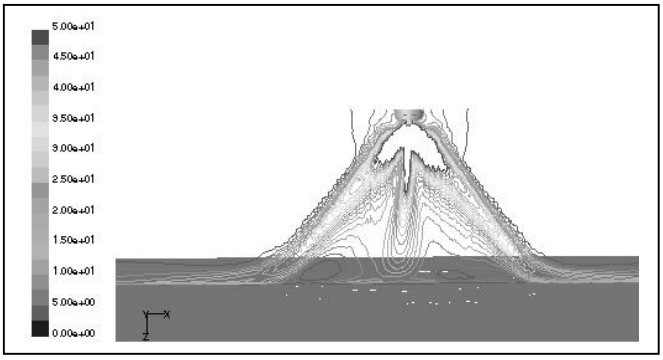


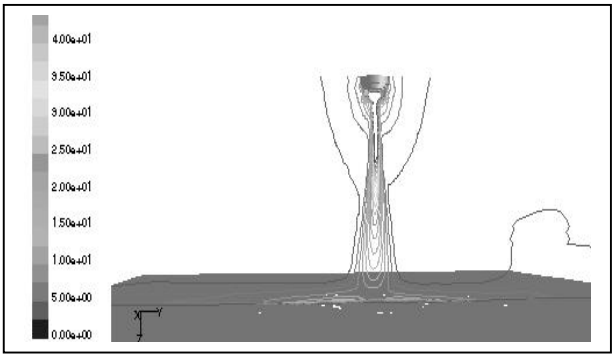
Figure 6: Distribution of liquid mass fraction along the long axis

It should be pointed out again that the measured results presented here are actually average values owing to the tube shaped measuring volume of the Malvern. Locally resolved droplet velocity, size and mass flux measurements can be obtained with a PDA system. However, these measurements are difficult to perform due to the high spray number density of small droplets especially in the spray region close to the nozzle where the initial droplet conditions should be determined. In addition, PDA measurements are in general quite time consuming for complicated spray structures, i.e. non-symmetric spray cones.

Computed air flow field

In contrast to former investigations on pneumatic atomisers used for painting purposes, the complete fully three dimensional air flow field between the nozzles in the air cap and the flat plate was simulated. Hence, well known, controllable inlet conditions such as air mass flow rates in the individual nozzles and stagnation temperature could be applied. Of course, compressibility effects have to be taken into account due to the sonic conditions at the nozzles. In the current situation, the coupled solver that was found to be more stable than the segregated solver. The calculated velocity contours of the air flow field in the plane y = 0 and x = 0 under standard conditions (elliptical spray cone) are shown in Fig. 7 and Fig.8, respectively. For clarity, velocities above 50 m/s are suppressed. Due to the shaping air the gas flow field is deformed, deviating from the standard symmetric free jet of coaxial jet atomizers. Here, an elliptic flow region is formed with an only narrow extension





along y. In spite of the shaping air flow the figures indicate the highest velocities in the spray centre. This is because of the coaxial jet flow and additional 4 cleaning air nozzles located around the centre jet with an inclination of 45° (see Fig.1), which work against the effect of the shaping air. The velocities of the air flow in the vicinity of the flat plate are still around 10 m/s, which is one of the reasons for the excellent quality of metallic paint, as the flakes in the droplets tend to be orientated parallel to the substrate's surface due to droplet spreading at impact.

Figure 7: Calculated velocity contours in the plane y = 0

Figure 8: Calculated velocity contours in the plane x = 0

The calculated velocity profiles of the air flow field were compared with LDA measurements using small droplets for flow seeding. This was achieved by applying significantly reduced water or paint flow rates of less than 50 ml/min through the nozzle. At these flow rates, the measured number mean diameters D_{10} were below 5 µm in the whole spray cone. In Figs. 9-10, a good agreement between measurements and simulation close the spray centre can be seen, however in regions closer to the spray edge calculated velocities are lower than the measured results. Unfortunately , no appropriate seeding could be found so far to verify the reason for this effect. Two-way coupling calculation was considered, but there was no large influence on the flow structure.

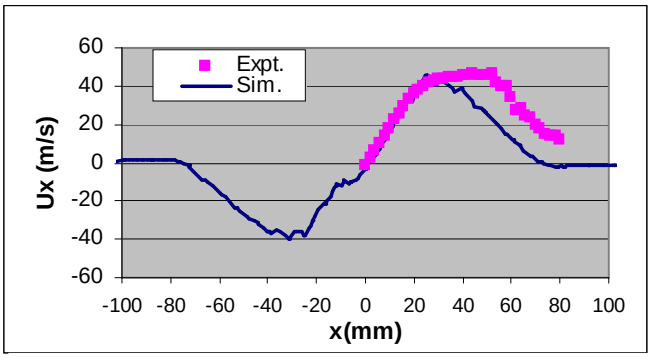


Figure 9: Comparison of calculated and measured radial mean velocities along the x-axis.

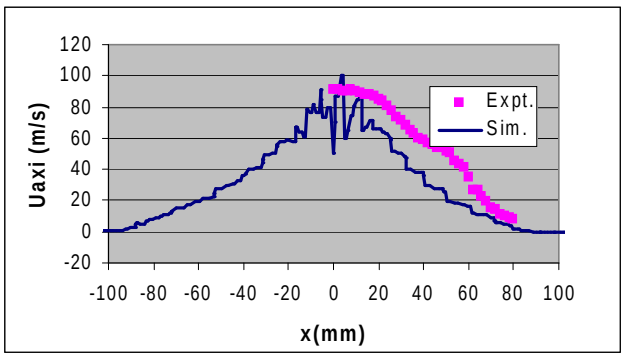


Figure 10: Comparison of calculated and measured axial mean velocities along the x-axis

Effect of droplet initial conditions

In a first approach with respect to the initial conditions of the liquid phase, the droplets were introduced at a distance 50 mm below the liquid nozzle applying the measured spray structure, namely the size distribution and mass flux profile. The initial droplet velocities were taken from the velocity field of the air flow at this location, assuming a dilute spray system. The simulated static film thickness on the work piece was then used to derive the so-called dynamic film thickness distribution with moving atomizer, applying an integration of the film

thickness in y direction. The resulting dynamic film thickness profile for a velocity of 0,15 m/s is shown in Fig. 11, together with experimental results. The calculated transfer efficiency (mass fraction of deposited paint) was 70%, whereas 63% was obtained in the experiment. In the centre region, the difference between predicted and measured film thickness is within the experimental accuracy, however, closer to the edge of the spray cone the film thickness is over predicted which is consistent with the overestimated transfer efficiency.

For obvious reasons, injection of the droplets very close to the liquid nozzle should be preferred. In this way, the uncertainty of the mass flux measurements, which is inherent to most of the particle size measuring techniques, can be prevented. In addition, the droplet-airflow and droplet-droplet two-way coupling processes may be well considered, if necessary. Therefore, a second case was considered in which the droplet injection data was applied in a round region with a radius of 3 mm at an axial distance of 3 mm below the liquid nozzle. According to flow visualisation results, the disintegration process should be completed at this location. As droplet size distribution, the integral distribution shown in Fig. 4 is used. The droplets are uniformly distributed in the injection region. The axial velocity of the droplets was again taken from the gas flow simulation, for example, Uax = 300 m/s in the centre and Uax = 50 m/s at the edge of the droplet input region. In addition, the radial distribution for the radial velocity, as shown in Fig. 12, has to be estimated to match the film thickness distribution on the work piece. Fig. 13 shows the film distribution on the work piece in the case of a round spray, i.e. the spray without shaping air, for both simulation and experiment. Here, a very narrow film thickness profile can be seen. Clearly, there are some differences between measured and calculated film thicknesses, however, some of these discrepancies may be attributed to the experimental results. In the case of the round spray, the air flow is impacting on the target surface with high velocity, causing some flow effects during the film build equalising the film thickness distribution. As measured (85 %) and estimated (88 %) transfer efficiencies are in good agreement, the areas under the dynamic film thickness distributions, which are equivalent to the paint flow rate deposited should also consistent.

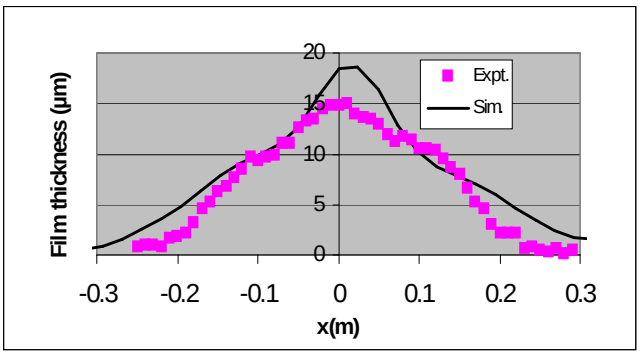


Figure 11: Dynamic film thickness distribution using inlet conditions at 50 mm below the liquid nozzle. Moving speed of the atomizer 0.15 m/s.

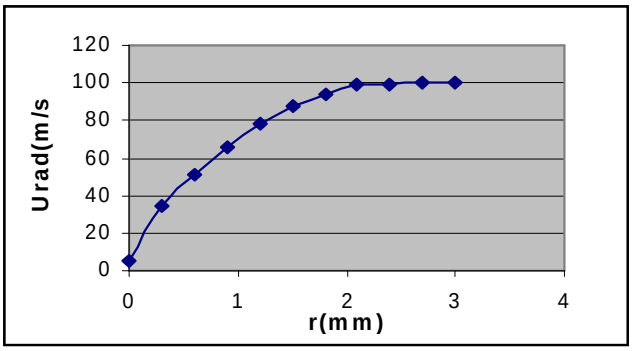


Figure 12: Assumed radial velocity distribution near the nozzle

Including shaping air the typical flat spray structure was obtained (Fig. 14). Comparing the results with the results in Fig. 11, a better agreement between measured and predicted film thickness was obtained. Likewise the round jet calculations, the calculated transfer efficiency of approximately 65% is very close to the measured value of 63 %. In general, the agreement achieved is appropriate for further calculations of the coating process of larger and more complex geometries, where multiple overlapping of the dynamic film thickness distribution is performed.

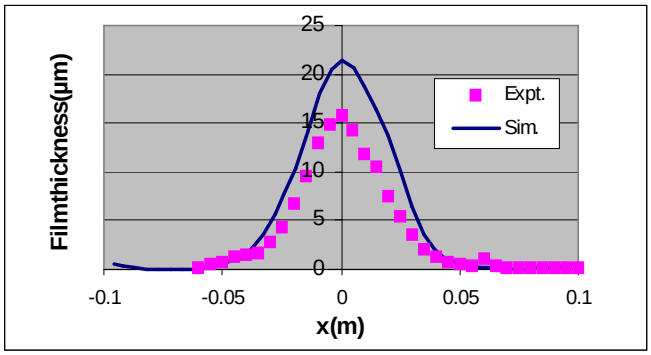


Figure 13: Dynamic film thickness for round spray with 1 m/s traversing speed of the atomizer - droplet injections very close to the nozzle

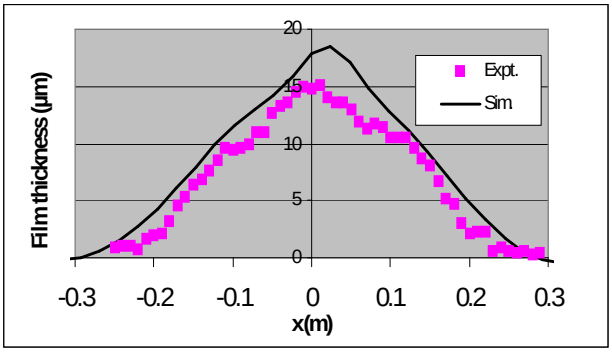


Figure 14: Dynamic film thickness distribution with 0.15 m/s traversing velocity - droplet injections very close to the nozzle.

As discussed above, the results shown in figs. 13 and 14 have been obtained by applying the integral droplet size distribution originally measured at an axial distance of 50 mm downstream the nozzle at an inlet plan 3 mm below the nozzle. While the initial axial velocities were taken from the simulated local air velocities, the initial radial component has to be estimated. Apart from the film thickness profiles, an additional justification for this approach may be achieved through the comparison of measured and simulated mean droplet diameter profile at an axial distance of 50 mm. The result of this comparison is shown in Fig. 15, indicating a nice agreement between measurement and simulation. The simulated diameter profile is a combined result of the initial conditions assumed and the interaction between the air flow field and the droplets in the region between 3 mm and 50 mm distance from the nozzle.

Summary and outlook

In this paper, the numerical simulation of the spray coating process using a pneumatic atomizer has been presented. The compressible airflow was calculated starting at the outlet plane of the nozzles. Hence, the effect of variations of the airflow rates on the flow field can be determined without additional experimental efforts.

Specific attention was paid to the influence of the simplified inlet conditions of the liquid phase on the film thickness distribution on the work piece. It was found that the droplet characteristics obtained through Fraunhofer diffraction could be used as initial conditions, despite the integrating character of the measurements. In addition, the initial droplet velocities can be taken from the airflow simulation.

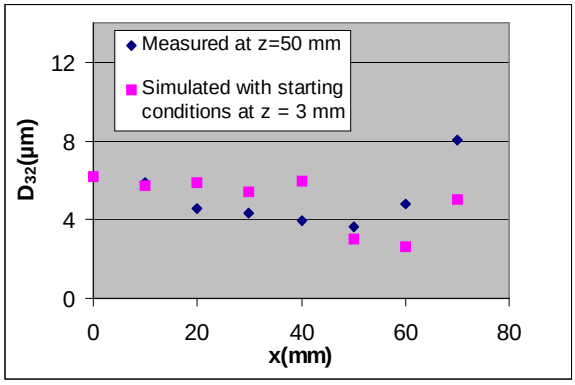


Figure 15: Comparison between measured and calculated mean diameter profile at z = 50 mm

It was also found, that the initial conditions of the droplets necessary for the simulation of the liquid phase can be taken very close to the nozzle. The calculated film structure on the work piece and the transfer efficiency agreed quite well with the measurement.

Nevertheless, additional investigations with different atomizer airflow rates are necessary to verify the approach used in this phase of the investigations. Moreover, a droplet collision model should be considered in the future especially in the case of droplet injections quite close to the nozzle, since the local droplet concentrations might be high enough to affect the final spray structure.

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