ILASS–Europe 2017, 28th Conference on Liquid Atomization and Spray Systems, 6-8 September 2017, Valencia, Spain
http://dx.doi.org/10.4995/ILASS2017.2017.4650

Numerical and Experimental Investigations on Rotary Bell Atomizers with predominant Air Flow Rates

Nico Guettler[1]*, Stephan Paustian[1], Qiaoyan Ye[1], Oliver Tiedje[1]
[1]Fraunhofer Institute for Manufacturing Engineering and Automation, Stuttgart, Germany
*Corresponding author: Nico.Guettler@ipa.fraunhofer.de

Abstract
For high-quality spray painting of small parts, a rotary bell atomizer with a narrow spray pattern is used in the automotive industry. The required unusual high shaping air flow rate yields in an atomization process predominated by a pneumatic atomization and rather than by a rotary atomization, called hybrid bell atomizer in this article. Numerical and experimental investigation on typical high-speed rotary bell atomizers, with rotation type of high rotational speed 40000-60000 rpm of the bell, were already successful demonstrated. For these high-speed rotary bell atomizer for painting bigger areas the ratio between tangential velocity at the bell edge and axial shaping air velocity at the bell edge is in the range of 0.8 and 4, depending on the process parameter. At the hybrid bell atomizer (10000-20000 rpm), this ratio is between 0.2 and 0.4.
The first step of the present study includes the theoretical characterization of spray cone velocity profile using two definitions of swirl-number compared to experimental measurements of particle velocities using Laser-Doppler-Velocimetry (LDV). This study was carried out on varying shaping air settings and rotational speeds. The results show that the the swirl of the main airflow field is dominated by the secondary airflow, which is induced coaxial in an angle of 45°. The influence of the circumferential speed of the bell cup on the swirl of the main airflow field plays a subordinate role, so the resulting spray pattern is only weakly influenced by the number of revolutions of the bell-cup.
In the second step, the hybrid bell atomizer was examined numerically. In order to implement the hybrid atomization concept in the simulation correctly, methods for creating droplet initial conditions in the trajectory calculation was developed. The simulation results were verified through comparisons of calculated and measured velocity profiles inside the spray cone and calculated and measured film thickness distributions on the work piece. In the present investigations of the atomizer, it has been demonstrated numerically and experimentally that the airflow field of this hybrid bell atomizer is strongly impacted by the secondary shaping air and both the circumferential speed of the bell cup and the direct electrostatic charge on the bell have only a minor effect on the generated spray pattern and the resulting transfer efficiency.

Keywords
Rotary bell atomizer, Spray painting, Atomization characteristics, Numerical Coating, Swirl-number

Introduction
High-speed rotary bell-cup atomizers are widely used in automotive painting industry and increasingly replacing the pneumatic atomizers in high-quality coating processes. The application range of rotary bell-cup atomizers includes large-area coating processes, such as hoods and car roofs, as well as areas for detailed coatings, such as door extensions.
Previous studies on atomization technology in the automotive industry have been performed on pneumatic atomizers and high-speed rotary bell atomizers. In particular, numerical studies on electrostatic effects on high-rotary bell-cup atomization have been carried out intensively in recent years [5, 6, 8, 9].
The high-speed rotary bell atomizer investigated in this study is predominantly used for detailed coating processes. In order to produce a narrow spray cone, a high axial velocity of the shaping air, which is defined by an airflow coaxial with the bell-cup, is required. This unusually strong axial shaping air velocity and a small diameter of the bell leads to an rotary atomization process with pneumatic behavior. For this reason, this class of high-speed rotary bell atomizers is referred as hybrid bell atomizers.
In the present study, the effects of the strong axial shaping air are investigated experimentally and numerically and a new method for creating the droplet initial conditions adapted to the strong shaping air is presented and validated.

Material and methods

Experimental setup

In order to investigate the characteristics of a hybrid atomizer with predominat airflow rates, a detailed study was performed at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart, Germany. The hybrid bell atomizer investigated in this study is the Dürr ECOBELL 2 HD. The experiments were carried out in a environmentally controlled paint booth with an fixed ambient temperature of 23 °C, a relative humidity of 60% and a vertical booth airflow of 0.3 m s^{-1}.

The Dürr ECOBELL 2 HD hybrid bell atomizer, shown in figure 1, consists of 60 shaping air tubes with a diameter of d_{SA}=0.6 mm. Thirty shaping air tubes are arranged perpendicular to the bell edge whereas 30 shaping air tubes are arranged with an given angle of 45°. Both the perpendicular, which is referred as shaping air 1 and the angular shaping air tubes (shaping air 2) are arranged at the back of the bell cup in an annular fashion. The bell cup has a diameter of 38 mm and a serrated section at the edge of the bell cup.
In the present study, two basic shaping air settings, which have the same amount of 600 l_s/min as defined by ISO2533, were examined. A basecoat with a non-volatile content of 44.4m%, a wet density of ρ_{wet}=1136.1 kg m^{-3} and a dry density of ρ_{dry}=1820 kg m^{-3} was used as coating material.

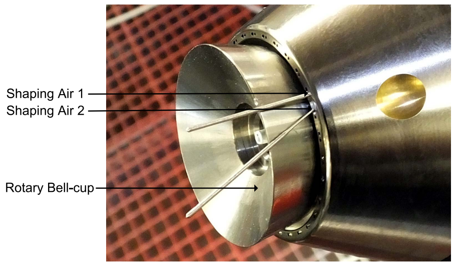
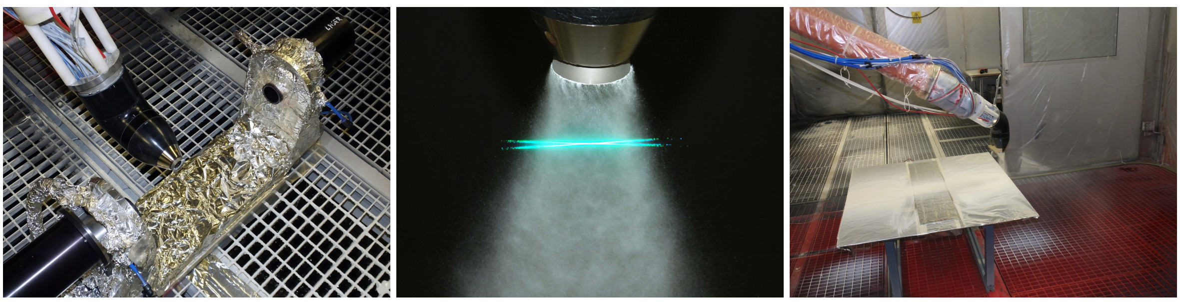


Figure 1. Rotary bell atomizer ECOBELL 2 HD (Dürr AG, Bietigheim-Bissingen), needles in a drilling of shaping air 1 and 2 are used to show the direction of the air outlets

Table 1. Design of Experiment

	shaping air 1 l_s/min	shaping air 2 l_s/min	rpm min^{-1}	paint massflow ml min^{-1}	high voltage kV
E01	200	400	10000	300	0/30
E02	200	400	15000	300	0/30
E03	200	400	20000	300	0/30
E04	400	200	10000	300	0/30
E05	400	200	15000	300	0/30
E06	400	200	20000	300	0/30

The characterization of the hybrid bell atomizer and typical quantities for coating applications are determined by means of the particle size distribution, the droplet velocity using Laser-Doppler-Velocitmetry, the coated film thickness profile and the transfer efficiency. The particle size distribution is determined by use of a SPRAYTEC RTS 5001 from Malvern Instruments. The measurement technique of this device relies on Mie-scattering and Fraunhofer-diffraction. The particle size distributions were measured in a horizontal measurement setup (see figure 2a) at a defined distance of 50 mm to the bell edge.
The droplet velocity in the spray cone is determined by means of 2-dimensional Laser-Doppler-Velocimetry using a laser power of 400 mW. The investigations are based on a rasterized scanning of the spray cone in the x- and y-direction of 30 mm at intervals of 5 mm and a distance from the bell edge of z=50 mm (see figure 2b). The coated spray pattern were recorded at a distance to the bell edge of z = 180 mm, which is a typical distance in industrial coating applications. The hybrid bell atomizer was driven at a speed of motion v_{robot}=300 mm s^{-1} (see figure 2c) and the resulting dry film thickness profile was measured in a transverse direction to the motion of atomizer using magnetic inductive measuring equipment. The transfer efficiency is determined as the ratio of the mass of the dry coating material deposited on the test sheet and the mass of the solids contained in the coating material, which is sprayed by the rotary bell atomizer. The speed of motion for determining the transfer efficiency is set to v_{robot}=200 mm s^{-1} according to DIN EN 13966-1.



(a) Measurement of particle size distribution (b) 2-dimensional Laser-Doppler-Velocimetry (c) Spray pattern and transfer efficiency

Figure 2. Setup for the experimental investigation the hybrid bell atomizer

Numerical setup

The numerical investigation of the hybrid bell atomizer was carried out using the commercial computational fluid dynamics software ANSYSFluent. For this purpose, the hybrid atomizer was positioned in a fluid domain with the dimensions of 240 mmx1100 mmx1100 mm (height x width x depth). The distance of the plate to the bell edge is equivalent to the experimental investigations, z=180 mm. Above the hybrid atomizer, a velocity inlet of v_{in}=0.3 m s^{-1} was defined as the inlet boundary condition, which represent the downdraft air velocity in the painting booth. The boundary conditions for the shaping air are defined by a massflow inlet, which can be calculated from the measured volumetric flow rate and the definition of a standard liter according to ISO2533.

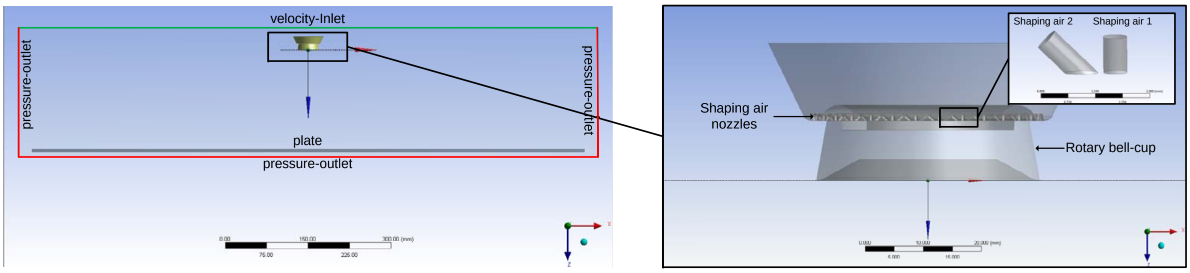


Figure 3. Geometrical model used in the simulation for the Dürr ECOBELL 2 HD

First a grid sensitive study was performed, from which a full structured hexahedral mesh yields in both most stable and most precise results (see figure 4).

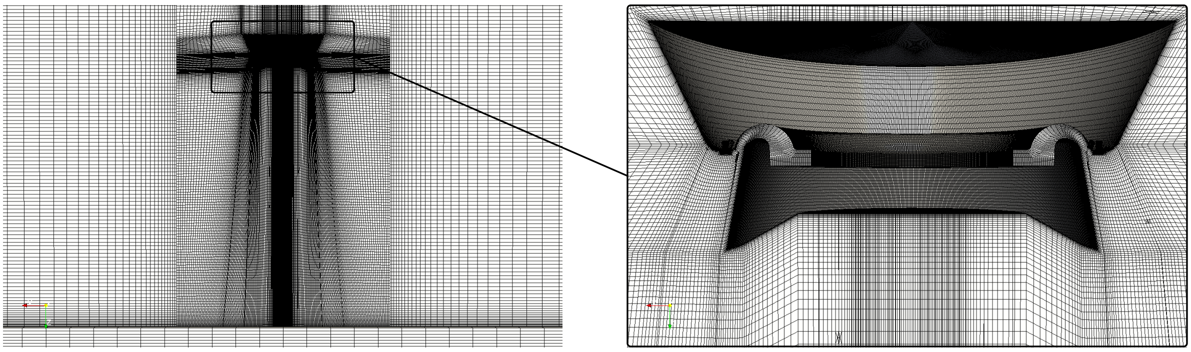


Figure 4. Full structured hexahedral grid with an total amount of 20M cells

For the calculation of the airflow field at this strong shaping air, turbulence models were compared using a k-ϵ, k-ω and a Reynolds Stress turbulence model. Scalable wall function was applied - if available at the turbulence model. In addition compressibility effects insight the shaping air tubes were also taken into account through the turbulence models.
The motion of paint droplets are represented by inert particles computed through FLUENT discrete-phase-model. The discrete-phase-model (DPM) is an Lagrangean model for calculating the trajectories of particles through the computational domain. To capture the effects of particle on the flow field, the interaction to the continuous phase was enabled. Turbulence effects on particle trajectories are included by means of stochastic tracking using a random-walk model. As a result of which the paint mass flow and the particle size distribution are known, the mass flow can be determined at each injection point for each particle size class.
Furthermore, electrostatic effects in the simulation were taken into account by a two-way coupling of both the continuous phase and the motion of particles and electrostatic field. For more details on this topic the reader is referred to *Kulkarni et al.* and *Ye et al.* [5, 6].

Results and discussion

Investigation of Velocity Profile and Particle Velocity

At rotary bell atomizers the velocity profile as well as the geometrical profile of the spray cone are controlled via the volume flow rates of the shaping air and the speed of the bell cup. At hybrid bell atomizers a strong axial velocity component prevails at the bell edge, but is supplemented by a tangential velocity component with increasing shaping air 2. Thus, with increasing the angular shaping air the flow field leads into a swirling flow. Due to the design and the manner of function of rotary bell atomizers, a swirl can be caused either by circumferential speed of the bell cup or by angular shaping air. In order to investigate the influence of the swirl generation, two swirl-numbers are defined in this study. First of all, the swirl-number from the rotating bell-cup is examined, whereby the swirl-number S_{cup} is defined according to *Stevenin et al.*[1]. The swirl-number S_{cup} is defined as the ratio of the bell edge tangential velocity $U_{tan,cup}$ to a characteristic value of mean velocity in the axial direction $U_{ax,mean}$[1]. Based on the results from numerical study, the characteristic mean velocity in axial direction was calculated over an area-weighted average in a annular plane at $z = 0$ with an approximated flow thickness of 1 mm at the bell edge.

$$S_{cup} = \frac{U_{cup,tan}}{U_{ax,mean}} = \frac{d_{cup}\pi n}{U_{ax,mean}} \tag{1}$$

Due to the predominant axial airflow velocity, the swirl-numbers caused by the circumferential speed of the bell cup are weak to moderate (see table 2). The swirl-numbers are in a range of $0.2 < S_{cup} < 0.42$, where the flow field in the vicinity of the axis of symmetry is decelerated, but a vortex breakdown is not achieved. In swirling flows a vortex breakdown is defined as an abrupt change of flow structure, where reversed axial airflow near the axis of symmetry can be observed. In the present study the definitions swirl-number and vortex breakdown are used to describe flow field on rotary bell atomizers with predominant airflow rates.

Table 2. Swirl-number induced by rotational bell-cup

Experiment	Swirl-Number S_{cup}	Experiment	Swirl-number S_{cup}
E01	0.21	E04	0.17
E02	0.31	E05	0.25
E03	0.42	E06	0.34

However, this type of definition of the swirl-number induced by the bell cup is only a local average of the circumferential and axial speed, which, in addition, does not take account of swirl from the angular shaping air 2. A much more common definition of a global swirl-number, which also includes the influence of tangential shaping air, was provided by *Chigier and Beer et al.*. They defined the swirl-number as the ratio between the axial flux of the tangential momentum to the axial flux of the axial momentum [2]. In the present study, the swirl-number was investigated numerically and the influence of the swirl formation by the adjustment of the angular shaping air 2 as well as the circumferential speed was investigated. For the determination of the swirl-number at a given distance of z=50 mm ($z/d_{cup} = 1.3$) to the bell edge, integration over a circular plane with a characteristic length R is executed [4]. At this given distance, the airflow velocities are below Mach-number Ma = 0.3, which is why a constant density ρ of the air can be assumed.

$$S = \frac{1}{R}\frac{\int_A \rho U_{ax} U_{tan} r dA}{\int_A \rho U_{ax}^2 r dA} \tag{2}$$

This definition of the swirl-numbers (see table 3) show that the influence of the angular shaping air 2, which causes a strong tangential impulse, clearly dominates the swirl formation. Due to the fact that the bell is rotating against the angular shaping air direction, the swirl-number decreases with increasing rotation.

Table 3. Integral swirl number calculated in the plane z = 50mm

Experiment	Swirl-Number S	Experiment	Swirl-Number S
E01	1.006	E04	0.244
E02	1.001	E05	0.239
E03	0.996	E06	0.234

The comparison of the two tested shaping air settings shows that the critical swirl-number of 0.6 is exceeded in experiments E01 to E03. If the swirl-number exceeds this critical value, a vortex breakdown occurs. The vortex breakdown describes the reversal of the axial flow direction in the vicinity of the symmetry axis due to a prevailing negative axial pressure gradient which is greater than the axial kinetic forces. In order to determine the magnitude of the vortex breakdown and the effect on its flow profile, the spray cone was examined by means of Laser-Doppler-Velocimetry (LDV) in the plane z=50 mm. The seeding required for the LDV are directly used from the sprayed paint material. In this way the measured velocities represent the integral droplet velocities in the spray jet.

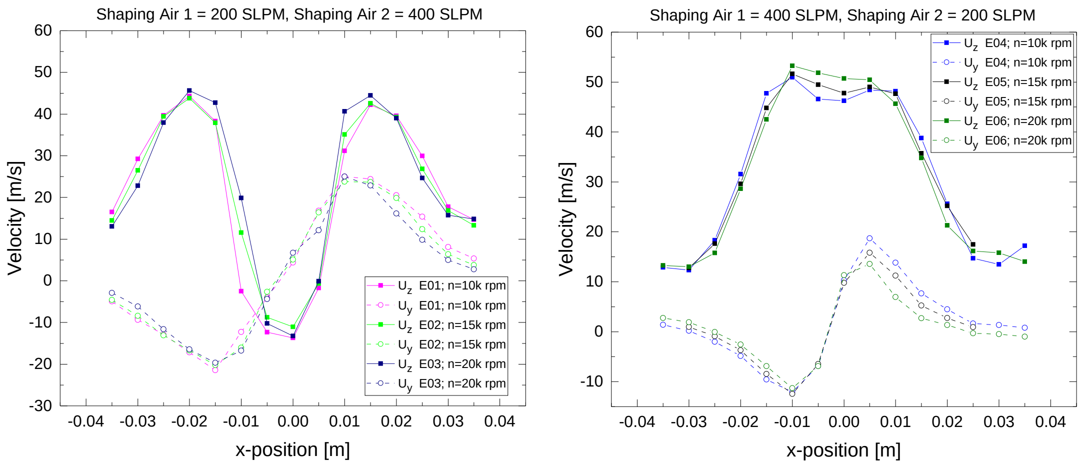


Figure 5. Experimental results of LDV measurements

The particle velocities of the investigated process parameters, as shown in the figure 5, show that the reversal axial flow direction is very pronounced due to the strong swirl in cases E01-E03. In the cases E04-E06 with a calculated swirl-number of approximately S=0.2, a slight deceleration occurs in the vicinity of the axis of symmetry. The experimental flow profile shows a good confirmation of the integral swirl-number. The determination of the swirl-number on high-speed rotary bell atomizers is an important dimensionless quantity for the design of shaping air process parameters and can be used for the analysis of the stability of the coating processes.
In the introduction the term "‘hybrid bell atomizer"’ has been defined, which states that predominant airflow rates have a significant impact on the atomization mechanisms. The dominant axial velocity is demonstrated experimentally and confirmed the characteristics of the particle velocity of a pneumatic behavior.

Numerical Investigation of hybrid bell atomizer

In the following section, the hybrid bell atomizer is numerically investigated on the basis of the process parameters E01 and E04 and a new approach to calculate the initial particle conditions for the discrete phase model is presented. Previous investigations on high-speed rotary bell atomizers used the k-ϵ realizable turbulence model [5, 6]. The high-speed rotary bell atomizers studied by *Kulkarni et al.* and *Ye et al.* were based on a weak axial flow velocity and can not be compared with the flow profiles in this study. As a result a turbulence study was performed using the k-ϵ realizable, the k-ω SST and the Reynolds-Stress model baseline were compared. The results of the axial U_z and tangential U_{tan} airflow velocities are compared to the particle velocities from the LDV measurements. The experimental uncertainty is shown in the following figure 6.

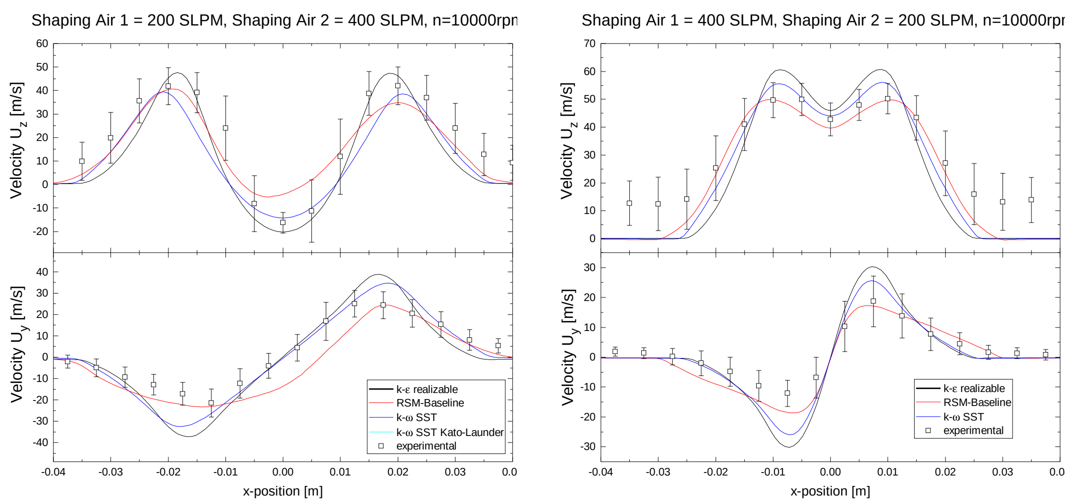


Figure 6. Results of turbulence study compared to the LDV measurement data on the experiment E01 (left) and E04 (right)

The k-ϵ realizable turbulence model produces the highest values of axial airflow velocity with the smallest diameter of the spray cone. The Reynolds-Stress-Baseline turbulence model shows very good results in the tangential velocity in the case E04, but no stable solution could be achieved within the case E01. The k-ω SST turbulence model has very good velocity values, both in the axial as well as the tangential direction. Furthermore the k-ω SST turbulence

EDITORIAL UNIVERSITAT POLITÈCNICA DE VALÈNCIA

model shows good stability as well as symmetry of the spray cone, which is why this turbulence model is used for further investigations.

Since the droplet break process at the bell edge is not simulated, experimental data on the particle size distribution (see figure 7) were used in this study. As *Husam et al.* has already been extensively studied, the resulting spray pattern depends on the number of injection points, the position of the injection points and the initial particle velocity. A obvious approach for the particle injection of high-speed rotary bell atomizers is to set the position of injection points as close as possible to the bell edge. However, this position also depends on the applied grid, which should refined until a very close position can be reached. In this study, 120 injection points with an axial offset of 0.0001 m and a radial offset of 0.0002 m were defined in an evenly fashion with respect to the bell edge. In order to implement the strong influence of the shaping air realistically into the particle injection velocities $U_{P_{ax,tan,rad}}$, the data of the simulated air velocity in the injection plane were interpolated to the injection points.

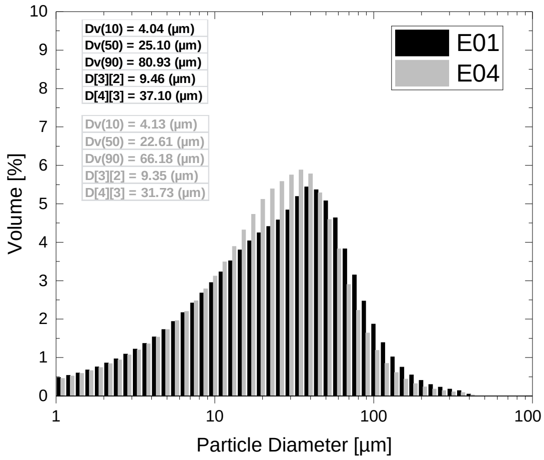
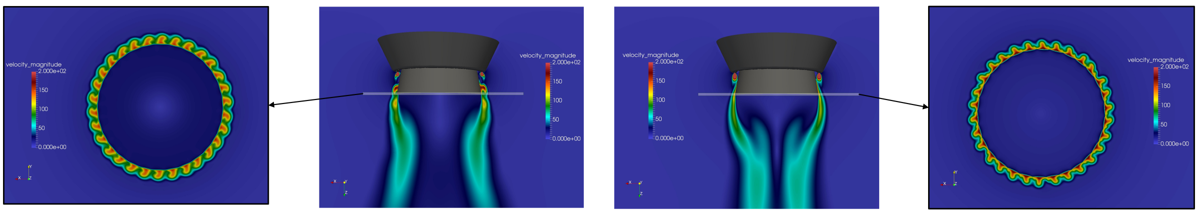


Figure 7. Results of measured particle size distribution at z=50 mm



(a) Case E01 (b) Case E04

Figure 8. Velocity magnitude both at injection plane and at the center of the hybrid bell atomizer

Subsequently, the initial particle velocity $U_{P_{ax}}, U_{P_{tan}}, U_{P_{rad}}$ was calculated using the following equation. The tangential initial particle velocity is composed of the tangential air velocity in this equations, as well as the circumferential speed $U_{cup_{tan}}$ of the bell edge.

$$\begin{pmatrix} U_{P_{ax}} \\ U_{P_{tan}} \\ U_{P_{rad}} \end{pmatrix} = \begin{pmatrix} \alpha_{ax}\; U_{ax} \\ \alpha_{tan}\; U_{tan} + \beta_{tan}\; U_{cup_{tan}} \\ \alpha_{rad}\; U_{rad} \end{pmatrix} \tag{3}$$

Due to the opposing tangential velocities from the swirl-forming shaping air to the circumferential speed of the bell edge and the defined injection particle position close to the bell edge, the tangential airflow velocity component was eliminated. Therefore, the calculation of initial particle conditions is based on the circumferential speed of the bell edge, the axial and the radial airflow velocities.

Table 4. Inlet coefficient, determined by fitting to the spray pattern

Case	α_{ax}	α_{tan}	α_{rad}	β_{tan}
E01	0.3	0	0.2	0.9
E04	0.4	0	0.15	0.9

In order to validate the new approach the experimental data of the particles velocities as well as the spray pattern are used. At the beginning, the numerically iterated air flow velocities were compared to the particle velocities and the k-ω turbulence model was choosen. Since the impact of the paint droplets on the airflow is known, the velocity of the particles in the simulation and in the experiment are compared. In order to obtain a representative amount of particle streams in the simulation, the measurement area is was set to 25 mm^2 with the origin of the LDV measurement points.

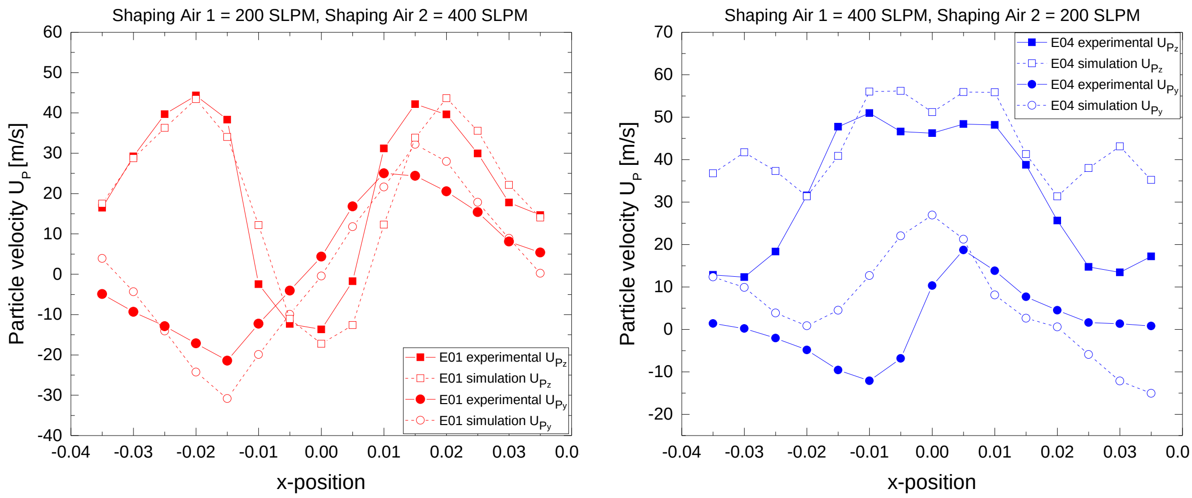


Figure 9. Comparison of simulated and experimental particle velocities

The results from the numerical investigation show very good agreement with the experimental data in experiment E01 and confirms that the selected method of particle injection works very well. In the case of E04, larger deviations in the simulated particle velocity occur, especially in the outer regions of the spray cone. It is known that the large particles concentrate in the outer regions of the spray cone and have higher velocities due to the high momentum. Furthermore, the initial particle velocities leads to a concentration of large particles with an diameter above d_P>100 µm in this region which results in a higher simulated particle velocity. Nevertheless, the injection method shows very good results for hybrid atomizers with predominant airflow rates.

Investigation on Application Specific Values

Important quantities for the characterization of atomization and application processes in the coating technology are the resulting spray patterns (dry film thickness profile) and the magnitude of transfer efficiency (TE). The dry film thickness profile is measured transversely to the direction of motion of the hybrid atomizer and is predominantly used to calculate the overlap respectively the distance between to parallel painting robot paths. The transfer efficiency is defined as the ratio of the paint mass deposited on the object to the sprayed paint mass. The use of rotary bell atomizers for detailed coatings requires a narrow spray pattern, which is realized by the strong axial shaping air. In this case, the film thickness profiles have a structure very similar to the velocities measured by means of LDV. The higher the swirl-number, both the more the spray pattern is enlarging and the deeper the valley in the vicinity of the symmetry axis. The influence of the circumferential speed of the bell cup on the change of the film thickness profile at given shaping air setting is not significant for current coating processes. The use of direct charging support also leads to an insignificant change in the film thickness profile. The simulated spray pattern also shows good agreement with the experimental data in both cases E01 and E04.

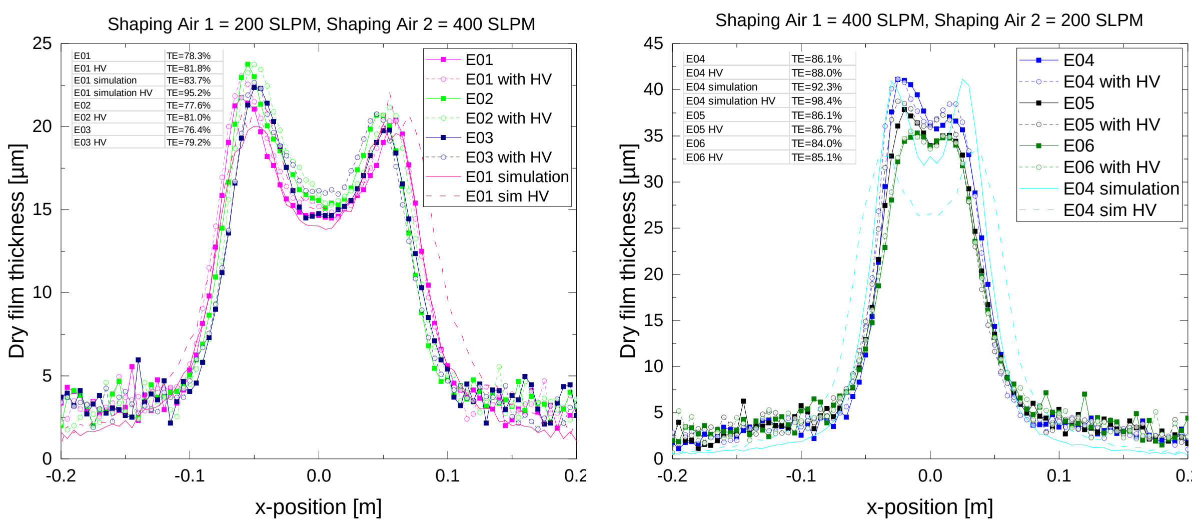


Figure 10. Results of film thickness profile and transfer efficiency

For the calculation of the film thickness profile using direct charging, the same initial particle velocities were used and a constant initial Rayleigh-limit of 5% was assumed [5].
The transfer efficiency, shown in the left upper corner of figure 10a and 10b, shows the same dependencies as the spray pattern. Especially the predominant airflow leads to the fact that further process parameters plays only a subordinate role. Particularly in experiments the direct electrostatic charging shows only a small increase in the transfer efficiency of 1-5%.

Conclusions

Rotary bell atomizers for detailed coatings requires an unusually strong axial shaping air velocity. This leads to the fact, that other process parameter, such as the number of revolutions of the bell cup and the direct electrostatic charge plays a only subordinate role. The description of these predominant shaping airflow rates was carried out using two definitions of a swirl-numbers. Very good agreement could be achieved via an integral description of the swirl-number. The vortex breakdown arising from a critical swirl-number of $S = 0.6$ was calculated theoretically and measured experimentally. Adapted to the prevailing shaping air, a new method for calculating the initial particle velocities for the discrete-phase model of the commercial CFD code FLUENT was presented. The validation of this injection method shows very good coincidences, both in the particle velocities, as well as the resulting film thickness profiles and transfer efficiencies measured in an industrial paint booth.

Acknowledgements
This research was supported within the project »SelfPaint« by Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.

Nomenclature

S_{geo}	geometrical Swirl-Number
S	integrated Swirl-Number
d_{cup}	bell-cup diameter [m]
d_P	particle diameter [m]
n	number of revolutions [rpm]
U	air velocity [m s^{-1}]
U_{mean}	area-weighted average velocity [m s^{-1}]
U_P	initial particle velocity [m s^{-1}]

References

[1] Stevenin, Ch., Béreaux, Y., Charmeau, J.-Y., Balcaen, J., 2015, *Journal of Fluids Engineering*, 137.
[2] Beer, J.M. and Chigier, N.A., 1972 , *Combustion Aerodynamics*, Applied Science Publishers Ltd.
[3] Sheen, H.J.,Chen, S.Y., Huang T.L., 1996, *Experimental Thermal and Fluid Science*, (12), 444-451.
[4] Vondál, J., Hájek, J., 2012 *Chemical Engineering Transactions*, 29, 1069-1074
[5] Kulkarni, J., and Watve, A., May. 2008, 21st Annual Conference on Liquid Atomization and Spray System.
[6] Ye, Q., Pulli, K., Steinhilber, and Scheibe, A., July. 5.-6. 2007, 3rd European Automotive CFD Conference.
[7] Wiedemann, A., 2001 *Mehrkomponenten-Laser-Doppler-AnemometerMessungen in einer drallbehafteten Rohr- und Brennkammerströmung*
[8] Husam, O., Adamiak, K., Castle P., Fan, H., Simmer, J., Nov. 13.-19. 2015, *International Mechanical Engineering Congress and Exposition*.
[9] Mark, A.,Andersson, B., Tafuri, S., Engström, K., Söröd, H., Edelvik, F. and Carlson, J.S., 2013, *Atomization and Sprays*, 23.

EDITORIAL UNIVERSITAT POLITÈCNICA DE VALÈNCIA