Effect of Bell Geometry in High-Speed Rotary Bell Atomization

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Abstract

High-speed rotary bell atomizers are dedicated instruments for high quality application of paints, used mainly in the automotive industry. Atomization is achieved through a well-defined disintegration process of a thin film at the edge of the bell. Based on experimental observations, it is well known, that the bell geometry, i.e. bell diameter and the exact form of the bell edge, corresponds to certain properties of the produced paint film. The approach of the present contribution is to support this empirical knowledge with physical properties, i.e. the disintegration process and the resulting droplet size distribution. Both, Nanolight short exposure and Fraunhofer diffraction are applied to obtain these results. It was found, that the initial idea of the serrations to produce very narrow droplet size distributions, is not achieved. In contrast, the specific geometry of the serrations leads to bimodal droplet size distributions and to an umbrella-shaped outer spray cone consisting of larger droplets. In contrast, unserrated bells produce almost log-normal shaped size distributions. In all cases, the bell speed is the dominant parameter for mean droplet size control. Under the investigated conditions, paint flow rate does not have an important influence.

Introduction

High-speed rotary bell atomizers are used in the painting industry to achieve paint films with high quality properties in terms of levelling, colour and metallic effect. This quality is mainly related to the fine atomization even of high viscous liquids due to very high speeds in conjunction with the thin films disintegrating at the bell edge. Furthermore, reasonable transfer efficiencies are achieved through the electrostatic support of the deposition process.

Practical experiences indicated that certain properties of the paint film, e.g. the metallic effect during base coat application, could be directly related to the geometry of the bell edge. Mainly three different forms are used, i.e. a smooth bell edge without serrations, straight serrations and cross-formed serrations. From a physical point of view, the geometry of the bell edge will directly influence the disintegration process and the subsequent formation of the droplet size distributions. Of course, droplet diameter and droplet velocity will also further influence the deposition process on the target and, hence, the resulting orientation of the flat flakes inside the droplets. To improve the basis knowledge in this field, it is the aim of the present contribution, to map different disintegration figures and size distributions as a function of the application parameters (bell speed, paint flow rate etc.) and the bell geometry (diameter and geometry of bell edge).

Materials and Methods

The investigations were performed using a state-of-the-art rotary bell atomizer supplied by Dürr Systems GmbH. In Fig. 1, the rotating bell is shown, which is driven by a frictionless air turbine. Behind the bell, a series of shaping air nozzles is arranged, re-directing the tangentially accelerated droplets in radial direction towards the target. High voltage was not applied to protect the electronic equipment; furthermore, it was found that high-voltage does not alter the droplet size distributions significantly [1]. The atomizer was mounted on a dedicated paint robot that incorporated all necessary measuring and controlling devices. The installation corresponded exactly to the conditions used in practice and guaranteed the reproducibility of the experiments.

The geometry of the serrated bell edges is shown in fig. 2. A typical pitch of five serrations in 2 mm is observed, with a length of the serrated area of approximately 2 mm. As discussed below, the precision of the serrations in the sub-millimetre, if not in micrometer scale, is of significant importance, as the paint films formed on the bell surface are in a thickness range between 20 and 40 µm at the bell edge [2]. Especially in the case of the crosswise serrations, the axial distance of the machining tool has a significant influence on the bell geometry directly at the location of detachment of the paint film.

As major measurement techniques a so-called Nanolight instrument, delivering a short exposure time of 20 ns, and a Fraunhofer diffraction instrument (Spraytec) were used. The Nanolight performance was enhanced by a special imaging system, applying a large Fresnel lens to increase the size of the spot. Typical frame size was approximately 5x5 mm. The flash was synchronized with the video camera yielding a frame rate of 25 1/s. The

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short exposure time of the flash delivers 'frozen' images of the disintegration process even at the highest bell speeds; a frame-to-frame identification of fluid ligaments or droplets is not possible, however. As typical droplet diameters are in the range of 30 µm and below, the set-up shown in Fig. 3 was found to be a good compromise between speed and frame resolution.

The diffraction instrument to measure droplet size distribution was also arranged very close to the bell edge. As shown in Fig. 4, the distance of measurement volume axis to the bell edge was approximately 10-15 mm to obtain the true droplet production without any significant influence of size dependent aerodynamic separation within the developing spray cone. The instrument was set to have a measurement range between 0,5 and 300 µm.

Although various paint systems were investigated, the present contribution focuses on automotive clear coat systems having a Newtonian viscosity of 88 mPas. In total, more than 500 different parameter setting were investigated, varying both the relevant application parameters and the geometry of the bells. The investigated geometries and parameter ranges are summarized in table. 1. In the practical application, the smaller bell diameters are mainly used for complex geometries and cases with limiting access, delivering also a smaller spray cone angle compared to bells with larger diameter. To some extent, the bell diameter is also linked to the maximum paint flow rate.

Results and Discussion

As expected, the geometry of the bell edge a significant influence of the primary break-up of the paint film. This clearly indicated by Fig. 5, showing the disintegration process of a smooth, a straight serrated and a cross-serrated bell at a bell speed of 30 000 1/min and a paint flow rate of 400 ml/min. In the inspection of these figures, it should be noted that the magnification varies for better visualization. In general, both types of serrations lead to the expected disintegration figure, characterised by long and stable jets extending up to a length of approximately 10 mm. In fact, it is the purpose of these serrations to force a reproducible and less chaotic disintegration process leading also to more stable and, hopefully, narrower droplet size distributions. For the crosswise serrations, an interesting structure is obtained characterized by the presence of pairs of jets with different diameters. There might be two reasons for this: First, a simple imperfection in the geometry of the serrations that is formed in a 2-step machining process, second, the interaction between the volume forces and the edges of the grooves having different azimuthal angles. It should be noted, that the typical paint film thickness at the beginning of the grooves is less than 40 µm. As the undesirable jet pairing was also depending on the bell used, it is very likely that the machining quality plays an important role.

For the application parameters given in Fig. 5, the disintegration process without serrations may be described as film disintegration. As further indicated by Fig. 6, the extension of the film is strongly depending on the bell speed, nevertheless, even at a speed of 50 000 1/min small films can be still observed. This is in contrast to former investigations [3], in which a critical, *We*-number dependent flow number q_{crit} has been derived above which the transition from jet to film disintegration takes place:

$$q_{crit} = 0.0034 \ln(We) - 0.0404 \qquad (1)$$

Here, *We*- und flow number are defined as follows:

$$We = \frac{\pi^2 D^3 n^2 \rho_L}{\sigma}; \quad q = \sqrt{\frac{2\rho_L}{\sigma \cdot D}} \cdot \frac{\dot{V}}{\pi \cdot D} \qquad (2)$$

According to this model, most of the application conditions should correspond to jet disintegration. It should be noted, however, that eq. 1 has been derived for simple water-ethanol-sucrose mixtures up to viscosities of 40 mPas. Nevertheless, the visualisations clearly indicate film-like structures that disintegrate within a few mm from the bell edge.

It is expected, that the different disintegration processes lead also to different droplet size distributions. A comparison of volume weighted size distributions of the three different bell geometries at a paint flow rate of 400 ml/min and bell speeds of 20 000 and 40 000 1/min is provided by Fig. 7. Obviously, the change in the bell speed yields significantly different results, not only in terms of the absolute droplet sizes but also in terms of the shape of the droplet size distributions. At a speed of 20 000 1/min, which is at the low limit of the value range used in practice, all three bells deliver monomodal distributions with a slight 'hump' at approximately 20 µm for both serrated bells. At high speed, however, the size distributions of the serrated bells are fully bimodal. This is expected from the cross-serrated bell, leading to a pair of jets with different diameters from each groove, but less expected in the case of the straight serrations. However, in a very detailed inspection of the disintegration images, only visible directly on a high resolution computer screen, some thin filaments are visible besides the dominant jet, also emerging from each groove.

It should be noted that these distributions are obtained directly at the bell edge. Hence, it can be expected that the bimodal character of the size distributions disappears further downstream due to aerodynamic interactions. As indicated by numerical simulations [4] both aerodynamic and electrostatic effects lead to droplet size dependent separation effects inside the spray cone with larger droplet sizes being mainly present near the edge of the spray cone. Consequently, two separate spray cones are observed at certain application conditions, an inner cone consisting of small droplets and an outer umbrella-shaped cone of larger droplets. Truly, this effect is undesirable. One major aim of the serrations, to obtain specifically narrow size distributions, is not achieved at all. This conclusion is further confirmed by the variations of the relative span given in Fig. 8. The relative span defined as $(D_{v0,9}$-$D_{v0,1})/D_{v0,5}$ and indicates the relative width of the volume weighted size distribution. In the case of the smooth bell, the span is almost constant at values around two, whereas the smooth bells lead to increasing span factors at increasing bell speeds due to the formation of bimodal distributions at decreasing volume median.

For all geometries, the bell speed has the most significant influence on mean droplet diameters. This is clearly shown by Fig. 9, comparing the measured Sauter mean diameters for the three different bell geometries as a function of the bell speed at paint flow rates of 200 ml/min an 500 ml/min, respectively. It is interesting to note, that the two serrated bells have almost identical mean diameters, whereas the unserrated bell produces smaller droplets especially at lower bell speeds. This is consistent with the experimental observations of the disintegration process. At low speeds, the serrated bells produce very long stable filaments, disintegrating at several mm form the edge. It is also interesting, that the differences diminish at bell speeds above 50 000 1/min. In fact, this speed is the standard value used in the practical application in the moment.

Finally, the experimentally observed Sauter mean diameters are compared with an empirical correlation that has been developed for a smooth bell [3] in a so-called transition mode. According to eq. 3, the Sauter mean diameter is only depending on the We-number, i.e. the paint flow rate does not have any effect.

$$D_{32} = 0.034 \cdot We^{-0.47} \tag{3}$$

It should be noted, that this equation has been derived from measurements with simple water-sugar-alcohol solutions up to viscosities of 40 mPas. As shown by Fig.10, the correlation underestimates the measured Sauter mean diameters by approximately 40 %, almost independent form the bell speed. As the general trend is consistent, it would be possible to adapt eq. 3 to paint results easily. However, additional measurements with paint systems with varying viscosities are required to build up a more robust database. In addition, more information is necessary to verify the influence of the suspension character of the clear coats on the atomization process.

Conclusions

The present paper presents only an excerpt of results obtained with a state-of-art high-speed rotary bell atomizer used for painting purposes in the automotive industry. Here, the major focus lies in the application of an almost Newtonian clear coat with three different bell geometries, i. e. a smooth bell and two serrated bells with straight and cross-wise serrations. The results can be summarized as follows.

- For the smooth bell, film disintegration is dominant with shortening film lengths at higher bell speeds.
- Both serrated bells provide long and stable filaments, disintegrating in several mm distance from the bell edge.
- The cross-serrated bell produces nice pairs of jets from each groove, having different diameters. The straight serrated bell has also a “twin-jet” disintegration figure, but with a larger difference in diameter.
- Consequently, both serrated bells produce bimodal size distributions, especially at higher bell speeds.
- The smooth bell delivers well-defined log-normal (“natural”) size distributions.
- In all cases, the bell speed is the dominant parameter for the resulting mean diameters. Interestingly, the smooth bell gives the smallest means, especially at lower bell speeds. The mean diameters of the serrated bells are almost identical.
- The aim of the serrations to have well reproducible narrow size distributions is not achieved. In contrast, the distributions are wider than the distributions from the smooth bell.
- An empirical model that has been developed for smooth edged bells and simple solutions, underestimates the Sauter mean diameters of the clear coat paint by approximately 30 – 40 %. Additional measurements are necessary to improve the model and fit it to Newtonian paint systems.

Nomenclature

D	bell diameter [m]
D_{32}	Sauter mean diameter [m]
n	bell speed [1/s]
m	mass [kg]
q	Flow number [-]
We	We-number [-]

ρ density [kg/m^3]

σ surface tension (N/m)

Subscripts
crit critical (used in connection with flow number)
L liquid

References

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[4] J. Domnick, A. Scheibe, Q. Ye: The electrostatic spray painting process with high-speed rotary bell atomizers: Influences of operating conditions and target geometries, 9th Int. Conference on Liquid Atomization and Spray Systems, July 2003, Sorrento, Italy

Table 1: Investigated bell geometries and parameters

Bell diameter	45 - 65 mm
Bell material	Stainless steel
Bell edge	Smooth/straight serrations/ cross serrations
Liquid flow rate	100 – 500 ml/min
Bell speed	10000 - 60000 1/min
Bell edge velocity	23 - 205 m/s

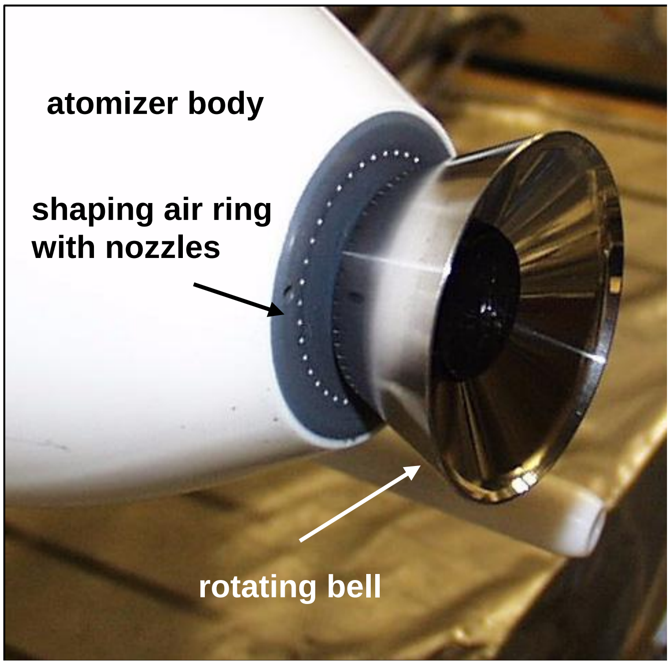

Figure 1: High-speed rotary bell

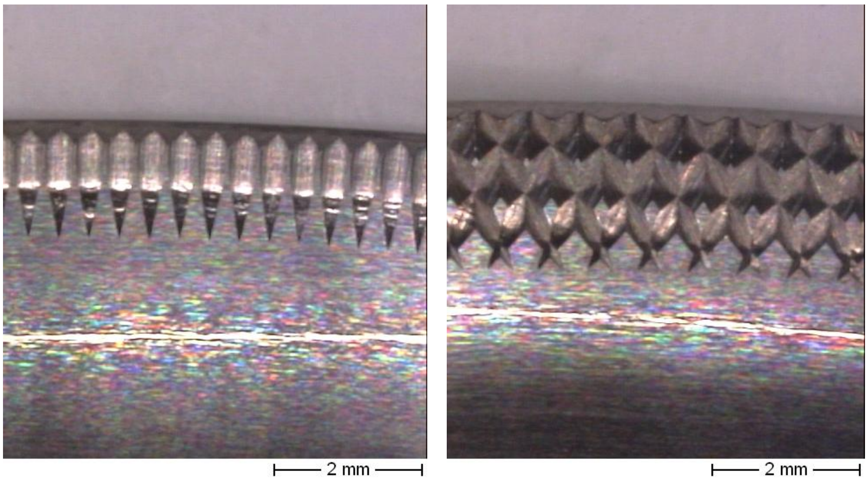

Figure 2: Bell edge geometry with straight serrations (left) and crosswise serrations (right)

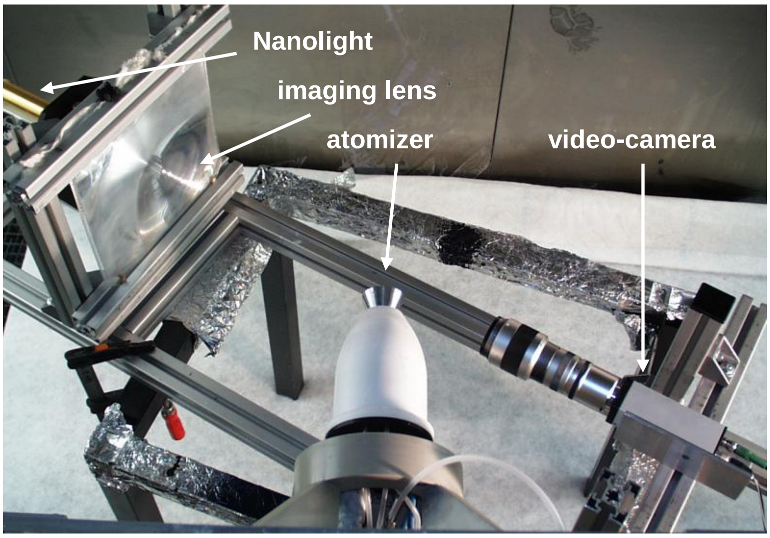

Figure 3: Set-up of the visualization system

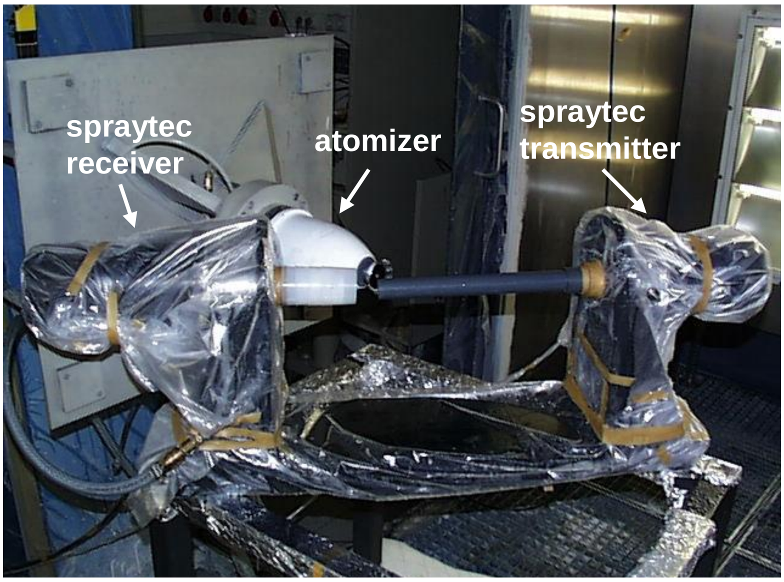

Figure 4: Set-up of the SPRAYTEC droplet sizer system

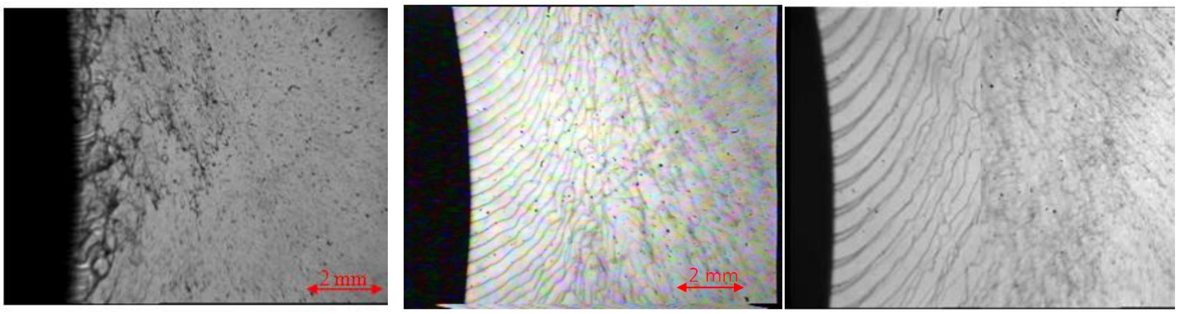

Figure 5: Disintegration process of an unserrated (left), a straight (center) and a cross serrated bell (right), bell speed 30 000 1/min, paint flow rate 400 ml/min

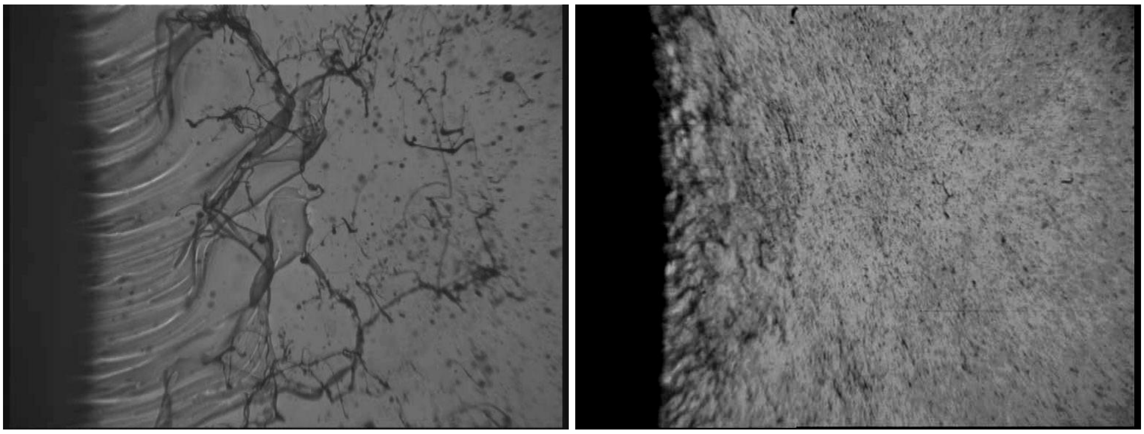

Figure 6: Disintegration process of an unserrated bell at bell speeds of 10 000 1/min (left) and 50 000 1/min (right), paint flow rate 400 ml/min

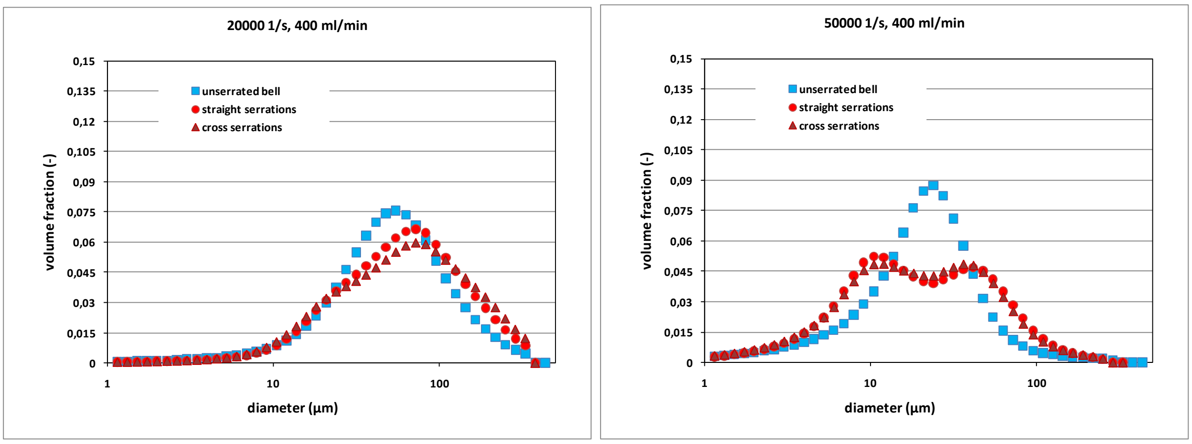

Figure 7: Comparison of the droplet size distributions at a paint flow rate of 400 ml/min and bell speeds of 20 000 1/min (left) and 50 000 1/min (right)

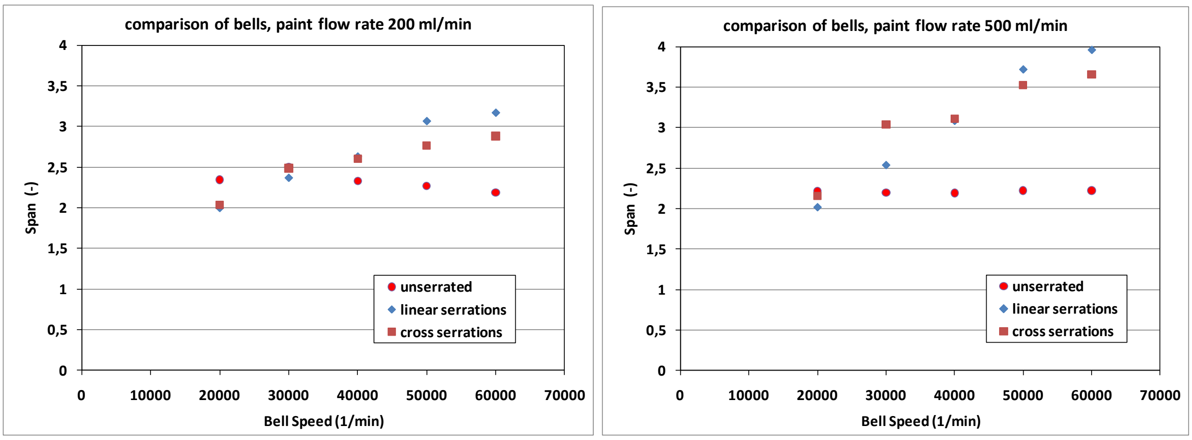

Figure 8: Comparison of the relative span of the size distributions at a paint flow rate of 400 ml/min and bell speeds of 20 000 1/min (left) and 50 000 1/min (right)

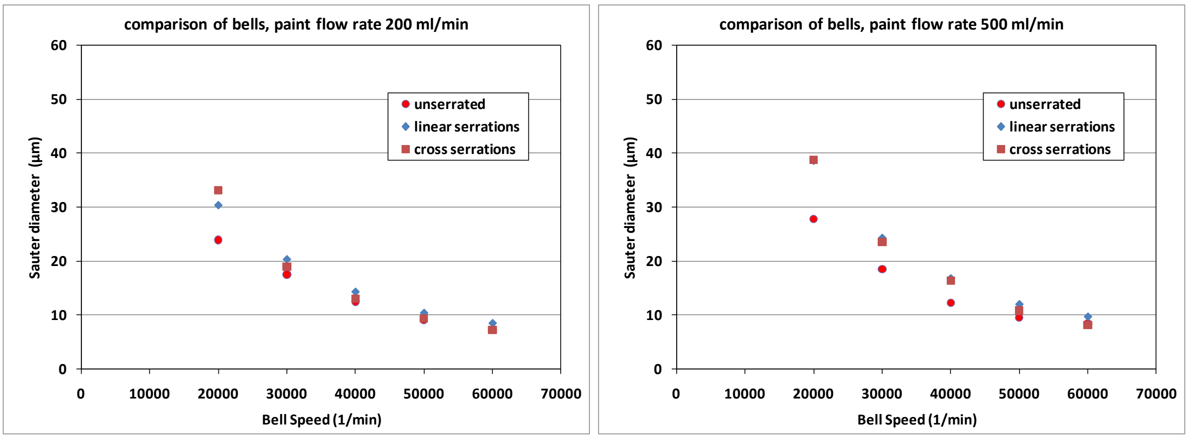

Figure 9: Evolution of the Sauter mean diameter as a function of bell speed at a paint flow rate of 200 ml/min (left) and 400 ml/min (right)

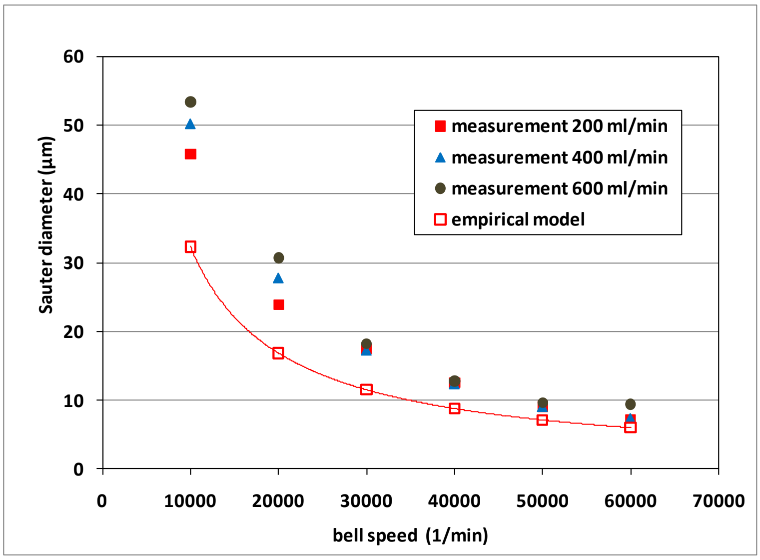

Figure 10: Comparison between measured and estimated Sauter mean diameter (unserrated bell)