High-speed rotary bell atomization of Newtonian and non-Newtonian fluids

J. Domnick
University of Applied Sciences Esslingen, Germany
joachim.domnick@hs-esslingen.de

Abstract

The present contribution deals with the effect of different rheologies of paint materials on high-speed rotary bell atomization. Namely, a solvent based, almost Newtonian paint (automotive clear coat) is compared with a waterborne, non-Newtonian paint (automotive base paint). For both systems Sauter mean diameters around 10 µm are obtained at practically relevant application parameters, confirming the efficiency of the atomization process. However, the Newtonian clear coat with a constant viscosity around 85 mPas delivers a finer spray, although the shear-thinning base coat system has a significantly smaller apparent viscosity at high shear rates. The obtained mean diameters are only partly confirmed by former investigations using water-alcohol-sucrose mixtures up to viscosities around 40 mPas. Although the general dependencies might be very similar, the absolute Sauter mean diameters are theoretically underestimated by a factor of 2. More investigations are necessary to consider the effect of polymeric components and solid content.

Introduction

High-speed rotary bell atomizers have been used in the automotive industry for more than 20 years. They deliver paint film qualities, which are equivalent to the well-known high pressure paint spray guns. In typical installations, these atomizers are mounted on robots to achieve the required flexibility of the adaptation between work piece geometry and atomizer movement. Due to the additional electrostatical support, very high transfer efficiencies can be achieved.

It should be considered, that paint atomization is one of the most challenging applications of atomizers with respect to the stability and reproducibility of the atomization process. Single big droplet events may indispensably destroy the quality of the paint film, which has, in some applications, initial thicknesses in wet state of less than 50 µm. Moreover, the leveling of the paint film and the final film formation depends on the effective viscosity of the deposited paint material, which is related to the solvent evaporation during the droplet lifetime.

In summary, the properties of the paint droplets, i.e. droplet size distribution and droplet velocity, are crucial for the final quality of the paint film. This contribution focuses on the effect of the paint properties, or, more precisely, the rheology of the paint, by comparing Newtonian solvent based materials with non-Newtonian water based systems. The latter materials are usually highly shear-thinning and thixotropic.

Experimental Methods

The investigations have been performed with a Dürr-ECOBELL high-speed rotary bell atomizer that has been used in many other related investigations before. Although this atomizer is available since more than 10 years, it still represents in its main functional parts the state of the art. In Fig. 1, the rotating bell as the major component is shown, which is frictionless driven by an air turbine. In the atomizer version shown, high voltage is directly applied to the bell. Behind the bell, the atomizer body is equipped with a certain number of shaping air nozzles. Together with the electrical field, the shaping air flow deflects the initial tangentially directed propagation of the paint droplets in axial direction towards the work piece.

Bell speed and paint flow rate are the most important parameters of the application. In the present investigations, the bell speed has been varied between 10 000 and 60 000 1/min and the paint flow rate between 100 and 600 ml/min. Below, it will be shown that the bell speed, for a given diameter of the bell, represents the most effective way to tailor the properties of the spray. In the present investigations, the bell diameter was kept constant at 65 mm.

Two major optical measuring techniques were used to investigate the disintegration process and the properties of the size distributions. Qualitatively, the disintegration process was visualized using a Nanolight 18 ns flash and a video camera in a standard inline arrangement as depicted in Fig. 2. The Nanolight performance was enhanced by a special imaging system, applying a large Fresnel lens to increase the size and the quality of the illuminated area. The short exposure time of the flash delivers ‘frozen’ images of the disintegration process even at the highest bell speeds.

Quantitative droplet size measurements were made with a Malvern Spraytec Fraunhofer type particle sizer, yielding a 400 µm size range with a 200 mm receiving lens. The axis of the measuring volume of the Spraytec, having a diameter of 9 mm, was positioned at a distance of approximately 10 mm from the bell edge to be able to detect the true droplet production of the atomizer (Fig. 2). This is of specific importance as Fraunhofer diffraction instruments measure a concentration weighted size distribution that is affected by the presence of size/velocity correlations. On the other hand, the visualizations shown below indicate the formation of the final droplet size distribution just a few millimeters away from the bell edge. The shaping air flow rate was simply adjusted to minimize the pollution of the optical system. From numerical simulations of the flow field in the vicinity of the bell edge it could be concluded that the effect of the shaping air on the atomization is negligible. Similarly, the effect of the applied voltage on the atomization process was neglected.

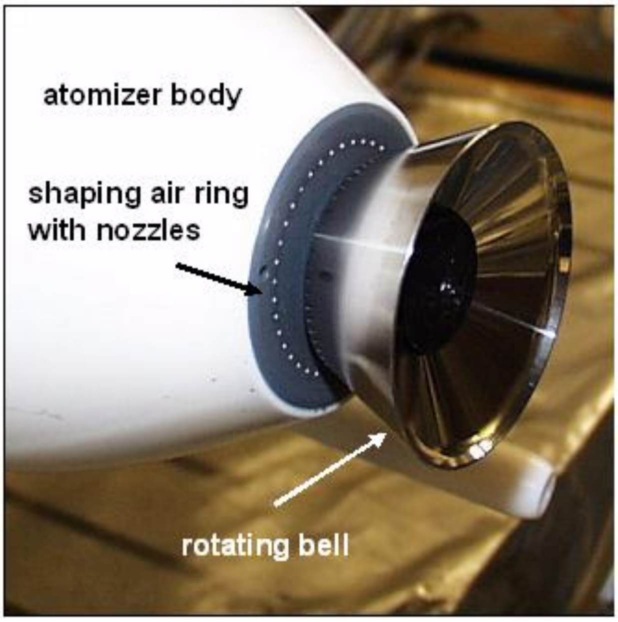

Fig. 1: High-speed rotary bell

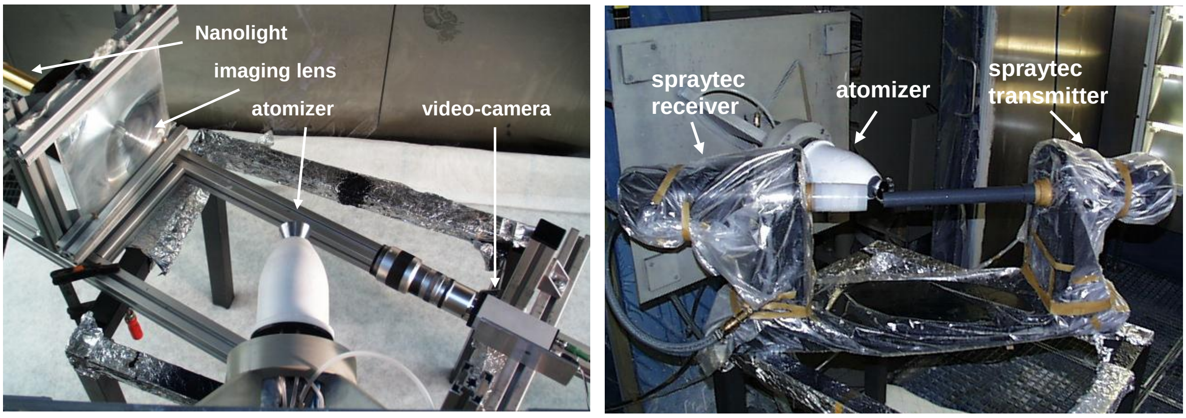

Fig. 2: Set-up of the visualization system (left) and the SPRAYTEC Fraunhofer diffraction (right)

The investigations have been performed with paint systems typically used in OEM painting lines in the automotive industry. More precisely, water based paints for the base coat layer, yielding color and effect within the multi-layer paint system, and solvent based clear coats have been compared. The rheologies of typical representatives of these paint families are shown in fig. 3. Viscosity measurements have been performed using standard rotational viscometers (cone-plate geometry) in a shear rate range between 1 and 2000 1/s. Of course, higher shear rates would be required to further characterize the rheology, especially of the water based systems. This is still under investigation. So far, it was found that the specific material properties of paint, especially the presence of solid particles, set limits in the application of viscometers. Also, dedicated instruments for elongational viscosity measurements such as the stretching filament system [1] cannot be applied to real paint systems.

In spite of this, so far, limited results, the strong shear-thinning character of the water based paint systems becomes evident. Also, it can be seen that the apparent viscosity of the shear thinning paints at higher shear rates falls significantly below the viscosity of the investigated Newtonian systems. Moreover, there are significant thixotropic and other dynamic effects expected, which are not taken into account. The static surface tensions of the considered paints range between 27,5 und 30,0 mN/m, i .e. differences are only marginal.

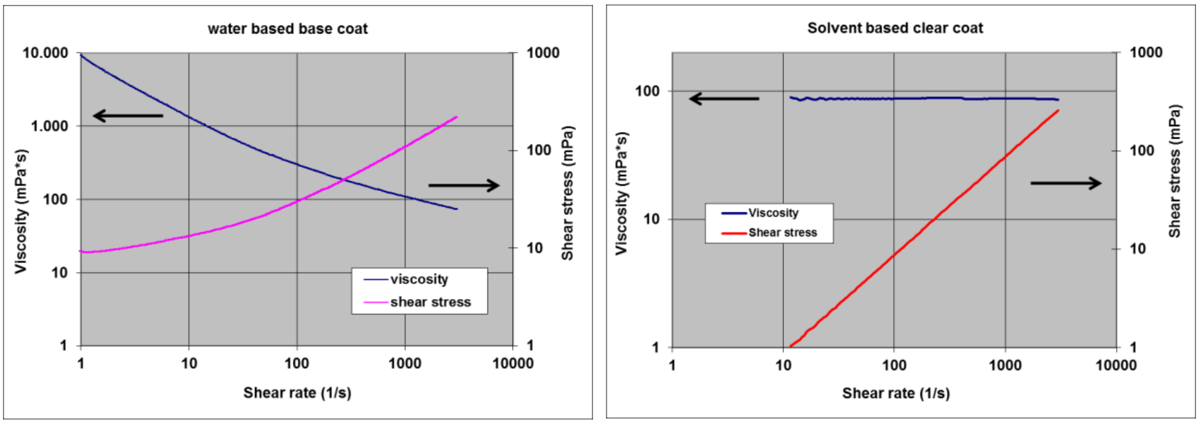

Fig. 3: Flow and viscosity curves of base coat (left) and clear coat (right)

Results and Discussion

The investigations that are further presented were obtained using unserrated bells, i. e. bells with a smooth surface up to the bell edge. Depending on the application and the paint system, both geometries i. e. serrated and unserrated bells are used in practice. In the unserrated case, the paint film remains undisturbed, developing local thicknesses and velocity profiles on the bell surface given by the external and viscous forces acting on the film. The calculated film thicknesses at the bell edge range between 15 und 35 µm, depending on the paint flow rate, the bell diameter and the bell speed [2]. As shown before [3], there are 2 different disintegration processes. In jet disintegration mode, individual jets are formed at the bell edge, which further disintegrate into droplets at a certain distance from the edge. In sheet mode, a sheet or film is formed at the bell edge, which in a first stage disintegrates into tangentially oriented filaments and further into droplets. The dominant mode is mainly given by the *We*-number and a flow number *q*. A critical flow number has been experimentally found above which the sheet mode is present.

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

We-number and flow number *q* are defined as follows:

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

In figs. 4 – 6, the disintegration processes of Newtonian clear coat (left) and shear-thinning base coat (right) at bell speeds of 10 000, 30 000 and 50 000 1/s are compared. The paint volume flow rate was kept constant at 400 ml/min. The general trend indicated by eq. 1 is confirmed, i. e. at constant flow number the extension of the sheet emerging from the bell edge reduces with increasing *We*-number and there is a transition to jet disintegration mode. According to eq. 1, sheet disintegration should be dominant at a bell speed of 10 000 1/s and jet disintegration at a bell speed of 50 000 1/s. At 30 000 1/s, disintegration should comply with a certain transition mode between sheet and jet mode.

Despite the varying quality of the images and the transparency of the paint material, significant differences between clear coat and base coat can be obtained. Nominally, both materials have very similar surface tensions and, hence, at identical atomizer parameters, very similar *We*-numbers. However, in the case of the base coat larger sheet like structures can be observed only at the smallest bell speed. Therefore, additional effects must be taken into account, which are not included in eq. 1 that promote jet disintegration.

At this point, it should be reconsidered, that the most significant difference between the two paint materials observed so far is their viscosity at high shear rates. As the film thicknesses at the edge of a smooth bell are estimated to be between 15 and 35 µm at velocities between 1,5 and 2,5 m/s [2], the corresponding flow rates are beyond $1 \cdot 10^4$ 1/s. In this shear rate range, the apparent viscosity of the base coat material is expected to be below 20 mPas and, hence, significantly smaller than the viscosity of the clear coat. Consequently, the paint films of the base coat on the bell surface should have lower thicknesses and higher mean velocities, leading to additional, mostly *Re*-number driven effects on the disintegration process. This is not considered in eq. 1.

The discussed differences in the disintegration processes of the various paint materials should also be reflected by the results of the droplet size measurement. In fig. 7, the obtained size distributions at a paint volume flow rate of 400 ml/min and bell speeds of 10 000 and 50 000 1/min, respectively, are compared. Clearly, the base coat paint produces coarser and slightly narrower size distributions, although its apparent viscosity at high shear rates is significantly smaller. However, this result is, at least to some extent, consistent with the observations throughout the disintegration visualizations. Here, the base coat paint produces a larger number of elongated ligaments, which survive also further downstream at larger distances from the bell edge. It may only be estimated, that the Non-Newtonian base coat exhibits a certain viscoelastic behavior, hindering the disintegration of these structures. As the basic organic binders of the paints are very similar, this behavior may be related to rheological additives in the water based paint, which are included in the paint recipe to avoid runs and sags on vertically orientated surfaces after film formation. Interestingly, the solid particles with diameters between 5 and 20 µm, which are present in the base coat, do not lead to an increase in the number of small droplets. These particles may act as break points throughout the disintegration process.

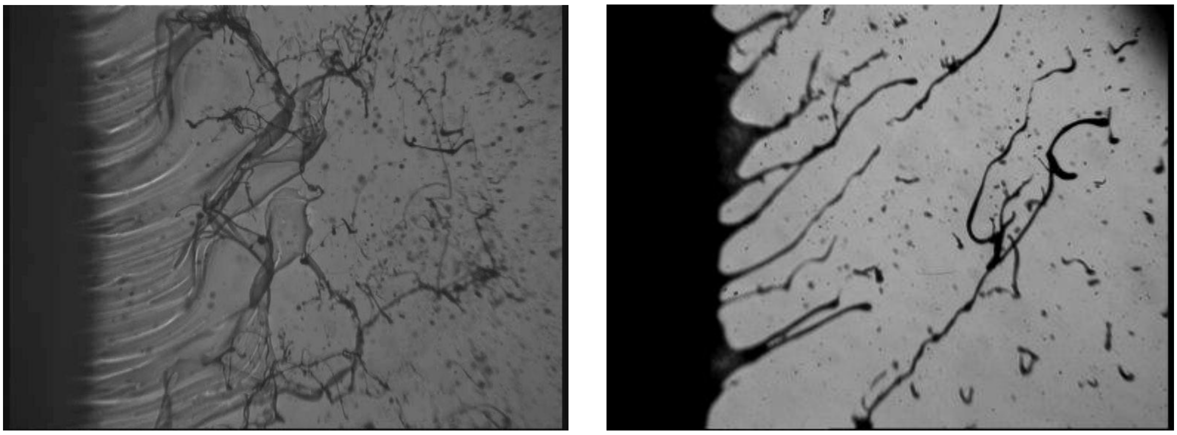

Fig. 4: Disintegration process of clear coat (left) und base coat (right) at 10 000 1/s and 400 ml/min

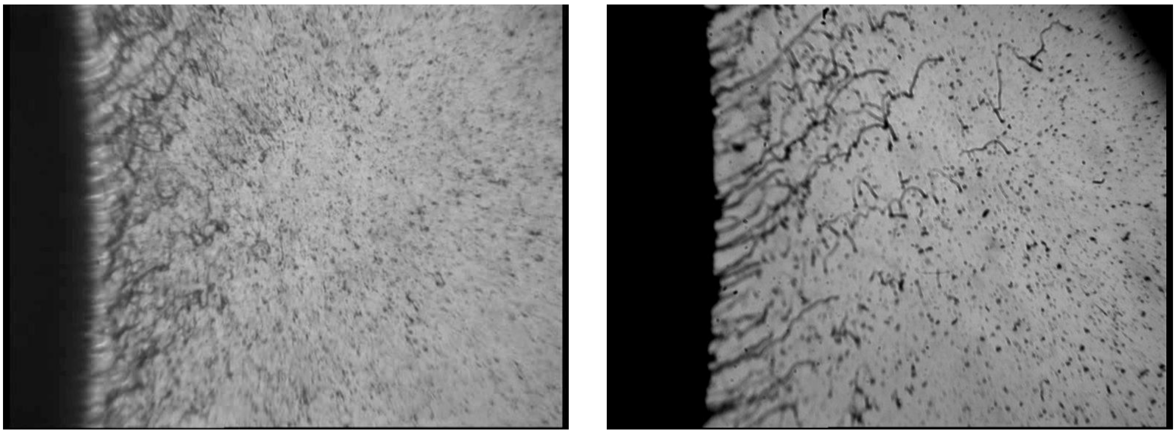

Fig. 5: Disintegration process of clear coat (left) und base coat (right) at 30 000 1/s and 400 ml/min

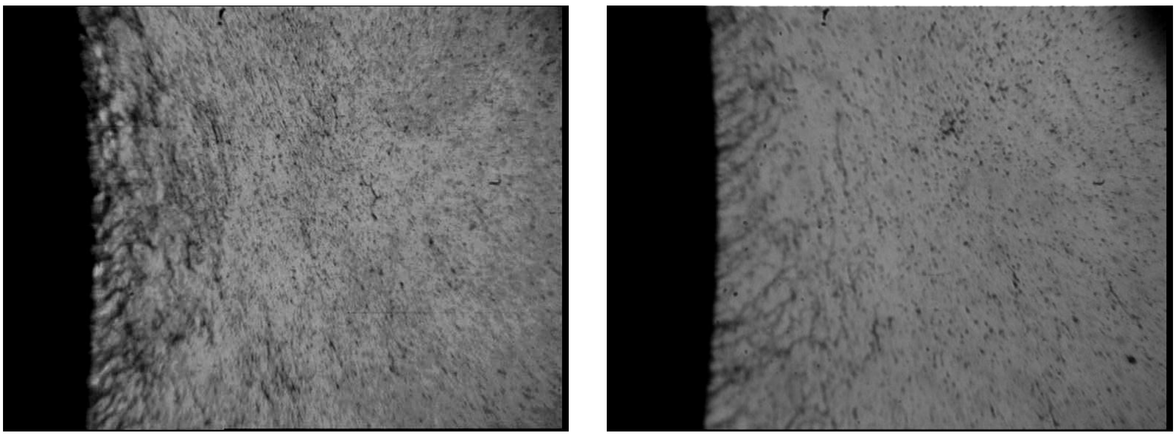

Fig. 6: Disintegration process of clear coat (left) und base coat (right) at 50 000 1/s and 400 ml/min

The overall effect of the most important application parameters, i. e. bell speed and paint volume flow rate, on the measured Sauter mean diameters are summarized in Fig. 8. For the considered high-speed rotary bell atomization, the paint volume flow rate has only a weak effect on the produced droplet size distributions, which is also consistent with former investigations [4]. This is probably one of the most important advantages of this type of atomizer, as paint films of different thicknesses can be applied at constant quality of atomization. For the atomization, the bell speed turns out to be the most significant parameter, resulting in a high flexibility, as the bell speed is easily adapted to the application and the material.

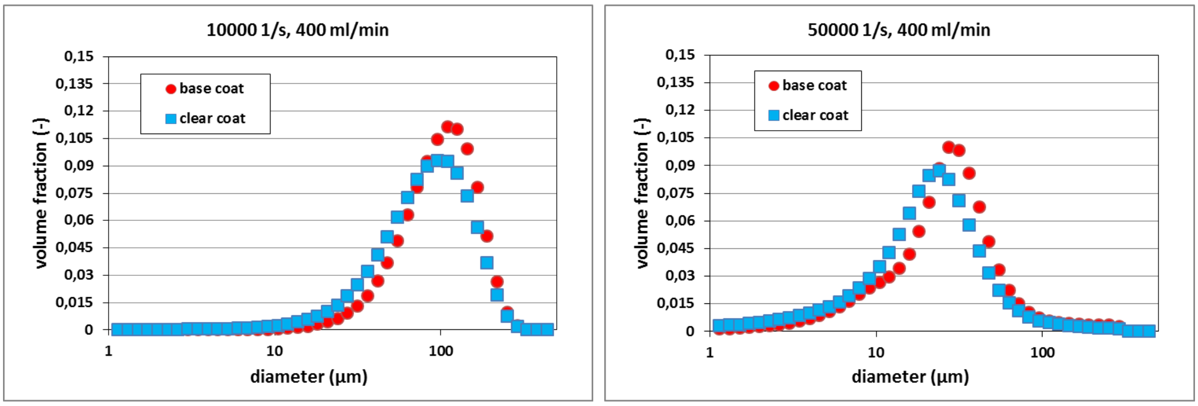

Fig. 7: Comparison of measured volume weighted droplet size distributions at a paint flow rate of 400 ml/min and bell speeds of 10 000 1/s (left) and 50 000 1/s (right)

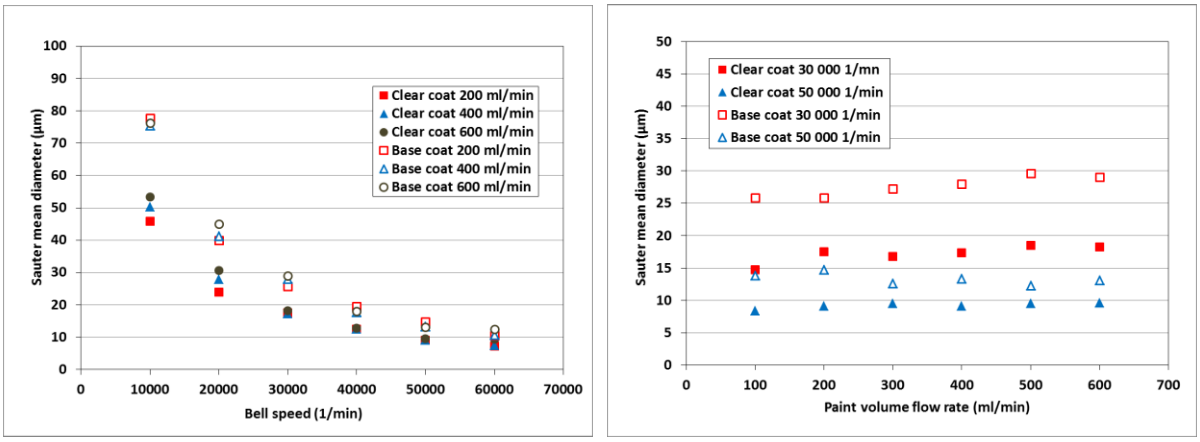

Fig. 8: Effect of bell speed (left) and paint volume flow rate (right) on the Sauter mean diameter

Finally, the observed Sauter mean diameters will be compared to the results of an empirical correlation that has been derived from measurements using water-sucrose-alcohol solutions [1]. In the case of jet disintegration, the following correlation between Sauter mean diameter and the relevant non-dimensional numbers has been postulated:

$$D_{32} = 0.60 \cdot Re^{0.056} \cdot We^{-0.58} \cdot q^{0.41} \tag{3}$$

In fig. 9, measured and theoretical mean diameters are compared as a function of the bell speed for three different paint volume flow rates, i. e. 200, 400 und 600 ml/min. Although the general trend, i. e. the dependency of the mean values on the bell speed, is very similar, the empirical model underestimates the mean diameters by almost 50 %. So far, it can only be concluded, that the model that has been developed for rather simple liquids with viscosities up to 35 mPas cannot be extrapolated to paints with viscosities above 80 mPas. Moreover, it is definitely not possible to apply the above model to water based systems having apparent viscosities at high shear rates around 20 mPas. The mean diameters delivered by the model are by far too small.

Summary and Conclusions

For both, Newtonian solvent based paints and non-Newtonian water based systems the high-speed rotary bell atomizer delivers a very fine atomization that is almost independent from the paint volume flow rate. At parameters relevant for the practical application, i. e. bell speed above 50 000 1/s, Sauter diameters below 10 mm may easily be achieved. This spray quality is one of the key features for the excellent paint film quality that is obtained. At this point, the present investigations present an approach to estimate the spray quality as a function of the rheology of the different paint materials. Unfortunately, the disintegration and atomization process of original paint material does not correspond to the results of correlations that have been obtained earlier with simple, easy to handle liquids such as water-sucrose-alcohol mixtures. While the disintegration process of Newtonian paints confirms, to some extent, the expectations, the disintegration of non-Newtonian paint is characterized by a more stable jet disintegration process window and the formation of durable elongated ligaments. Compared to the empirical model, the paint materials deliver much coarser sprays with higher mean diameters. In addition, the non-Newtonian paint produces significantly larger mean diameters, although its apparent viscosity at higher shear rates is far smaller than the viscosity of the Newtonian material. More investigations are necessary to evaluate potential viscoelastic or any other complex rheological effects of the paint. The presence of viscoelastic effects are also indicated by the long ligaments that are observed. However, it should be noted that some of the existing instruments to measure more complex rheological properties such as the will not work with real paint materials.

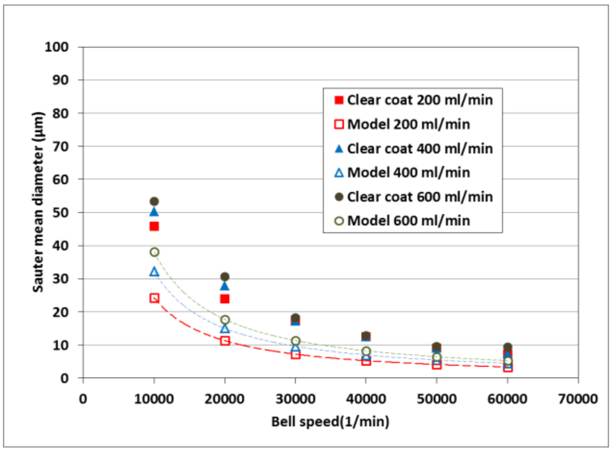

Fig. 9: Comparison between measured and calculated (eq. 3) Sauter mean diameters

Acknowledgements

The present work has been partly supported by the Deutsche Forschungsgemeinschaft through grant No. Do 251/10-1 and 2. This support is gratefully acknowledged by the author.

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