Analysis of time-dependent spray structures in spray processes in enclosures with square cross sections

A. Lampa* and U. Fritsching
Department of Process Engineering and Particle Technology
University of Bremen
Bremen, 28359, Germany

Abstract

Spray processes are influenced by the interaction of the spray flow and the surrounding spray chamber. Spray chamber designs may have a significant influence on the recirculation and re-entrainment of spray droplets. Flow structures induced by different spray chamber geometries also affect the local concentration of droplets. In this paper the influence of different conical spray chamber designs with square cross sections on unsteady flow structures in the spray of twin-fluid atomizers is discussed. Since the product properties of a spray process highly depend on the local mass and heat transfer within the spray, particle trajectories as well as local droplet concentrations have to be assessed. Both phenomena are reviewed experimentally by using Particle Imaging methods in planar light sheets of the spray. The effect of coherent flow structures on the local particle concentration is the central point in this investigation.

Introduction

Unsteady phenomena in sprays greatly affect the outcome of the spray process. In this paper the large-scale movement of the jet and the ambient air as well as local clustering of droplets in a spray is analysed. In enclosed spray processes flapping accompanied by precession of the spray may occur. The strength and the size of the entrainment and recirculation movement influence the retention time of particles and are therefore analysed. Additionally the meso-scale clustering of droplets within the spray cone is reviewed quantitatively. The interactions of particles with large-scale eddy structures within the gas are discussed. A Particle Imaging method is applied to planar light sheets in the spray to examine the correlation between particle concentration and the local flow characteristics. The Particle Image method can be described as a combination of 2D-Particle-Image-Velocimetry measurements and image analysis techniques to investigate the concentration patterns of the spray droplets (Figure 1).

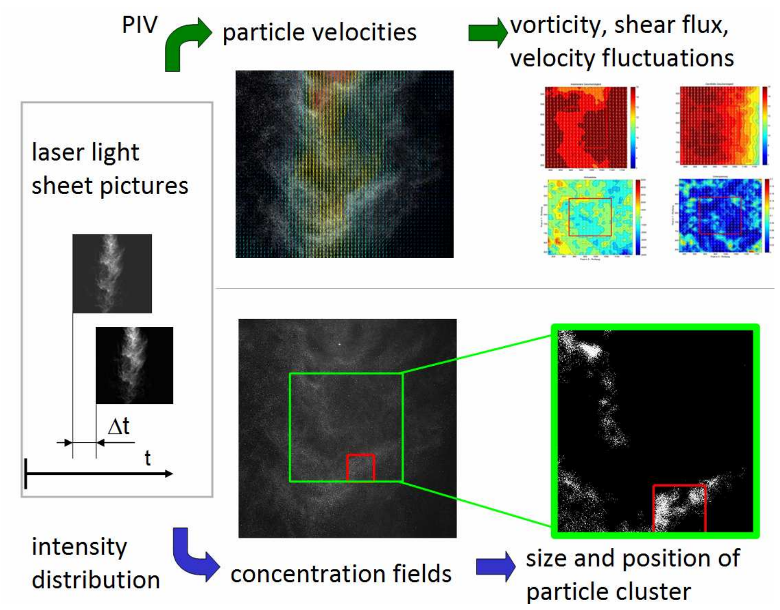


Figure 1. Particle Imaging method: local droplet velocities and concentration fields

* Corresponding author: lampa@iwt.uni-bremen.de

The following parameters of the spray process are changed systematically to estimate their influence on the time-dependent structures of the spray:

- conical spray chamber design with square cross sections
- twin-fluid atomizer type
- loading of spray

Instabilities in the gas flow, caused by high shear rates in the boundary region of the spray for example, have a great influence on the formation and transport of particle clusters. There are several hypothesis why clusters in particulate systems occur (see also [1], [4]). Here only the large coherent flow structures are analyzed. The method to quantify the inhomogeneities within the spray is derived from Garncarek [2]. In this work a practical approach with midscale laboratory equipment has been performed to induce more application-like conditions.

Materials and Methods

The outer spray chambers cross-sectional area is 1 m^2 (Figure 2). In the center of this chamber the conical, transparent spray chambers are built-in. The spray is removed from the chamber by a vacuum outlet. The bottom side of the transparent spray chambers is open to minimize the influence of the vacuum on the spray flow. The flow rates of air and water are controlledby the respective pressures and metered by appropriate flow meters.

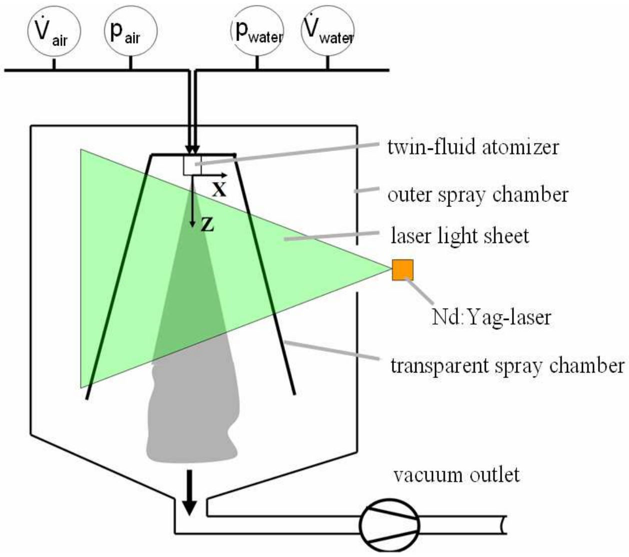
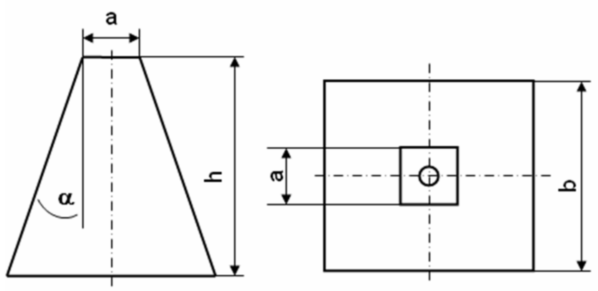


Figure 2. Experimental setup and coordinate system

The investigated spray chamber designs vary in the size of starting cross sections and opening angles (Figure 3). The chambers are made of acrylic glass plates with a thickness of 3mm.



Variant	**a** / mm	α/°	**h** / mm	**b** / mm
V1	200	10	900	513
V2	200	15	900	666
V3	400	10	900	713

Figure 3. Spray chamber designs

In order to estimate the effect of the disintegration process on the formation of particle inhomogeneities, an external and an internal mixing twin-fluid atomizer are analyzed. Both nozzles produce fine water droplets with particle diameters $d_{50,3} \approx 10\ \mu m$. The mass flux of water is kept constant, while the atomizer gas pressure is varied (Table 1) to investigate the influence of the gas phase on the particle trajectory and the structure of the particle collectives.

Table 1. Parameters for external mixing twin-fluid atomizer

p_{air} / bar	p_{water} / bar	$\dot{V}_{N\,air}$ / lmin^{-1}	$\dot{V}_{water}$ / lmin^{-1}	$\dot{m}_{air}$ /gmin^{-1}	$\dot{m}_{water}$ / gmin^{-1}	$\mu = \frac{\dot{m}_{water}}{\dot{m}_{air}}$
0.5	0.7	8.49	0.1	10.18	100	9.82
1	0.7	15.5	0.1	18.6	100	5.38
2	0.7	28.28	0.1	33.9	100	2.95
3	0.7	39.84	0.1	47.8	100	2.09
4	0.7	52	0.1	62.4	100	1.60

A dual-cavity Nd:YAG laser (65 mJ/pulse at 532 nm) is used to illuminate the droplets within the center plane of the spray (Figure 2). The CCD-camera recording the light scattered by the particles has a 12 bit image sensor with 2048 x 2048 pixels. The laser sheet has a thickness of approximately 1 mm at the centre of the images. A small laser light thickness is needed to focus the laser light properly, yielding enough intensity in wide light sheets. If the laser sheet thickness is extended multiple scattering within the spray cone can be observed. This leads to the blurring of particle collectives. Image analysis of particle clusters requires an optimized laser light intensity. There must be a minimum of intensity to illuminate the particles for the PIV method and there must be enough light to detect particle concentration differences. On the other hand a maximum of intensity leads to multiple scattering effects resulting in blurring, which prevents PIV and cluster recognition from being applicable. Requirement for a narrow laser sheet is that the time difference between two images is kept short. Otherwise out-of-plane losses of particles take place which falsify the PIV measurements. In this setup a time difference of 100 µs was chosen. The temporal resolution of the camera is 7.4 Hz, which is too low to track the dynamics of the spray. Therefore only qualitative statements on the oscillation behaviour for example can be made.

Unsteady particle clusters are determined quantitatively by evaluating the spatial inhomogeneity within planar light sheets. First of all it is necessary to distinguish the particle clusters from the background noise. Common image processing techniques are used for filtering. For 8 bit grayscale images the following methods are applied:

- gamma correction
- bandpass filtering
- local statistical filtering (Wiener filter)
- conversion to binary picture

The result is a binary picture with segregated particle clusters (Figure 1). These particle structures are processed with the Garncarek-algorithm (Figure 4) defined by Czainski [2].

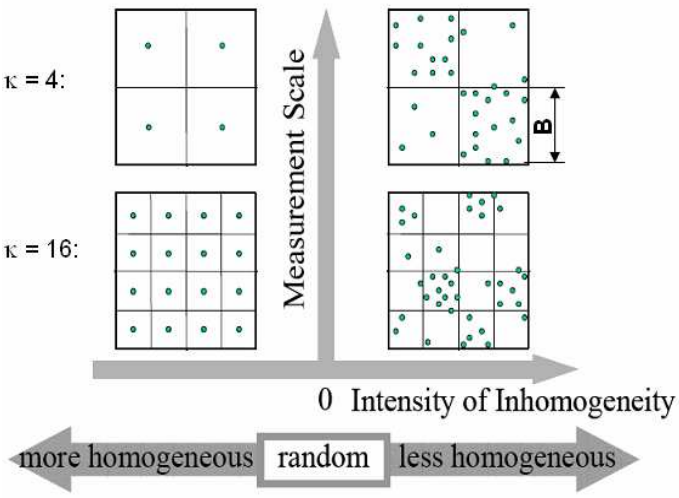


Figure 4. Garncarek-algorithm (Kuno et al. 2007)

The inhomogeneity index H is the central quanitity in this algorithm. The inhomogeneity index is defined as the ratio of the distribution of objects in a specific state and the distribution of objects in a random state. The inhomogeneity index increases when there are structures in the spray that show clustering (Figure 4). The inhomogeneity index is dependent on a certain measurement scale κ. The inhomogeneity index H is expressed as follows

$$H(\kappa, n) = \left(\frac{n(n-1)}{2(\kappa-1)}\right)^{0.5} \left(\frac{1-n-\kappa}{\kappa-1} + \frac{\kappa}{n(\kappa-1)} \sum_{i=1}^{\kappa} n_i^2\right), \tag{1}$$

where n is the the sum of all grey or binary values within the processed picture and κ is the scale on which the inhomogeniety index is evaluated (Figure 4). For each interrogation window with the side length $B = L/\sqrt{\kappa}$ the sum of gray values n_i is counted. H is a scalar value for the inhomogeneity in the whole picture. For the variation of B the inhomogeneity index H yields a maximum where the characteristic cluster size $B_{Cluster}$ can be found (Figure 5). The accuracy of the cluster scale detection in sprays will be discussed in the next section.

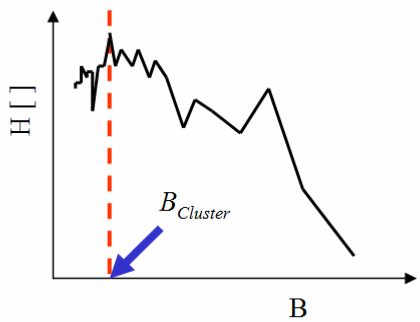


Figure 5. Characteristic scale within a spray

Once the mean cluster size in a picture is determined, a cluster with the characteristic scale $B_{Cluster}$ is picked out and the information from the instant velocity fields from PIV measurements are evaluated at the position of the cluster.

Results and Discussion

In the spray zone close to the boundary, complex interactions between gas and particles take place. The velocity field of the particles is highly time-dependent (Figure 6). The spray cone flow shows characteristic flapping combined with a precession movement. Flapping can be estimated by PIV measurements, while precession can only be recorded qualitatively by high-speed videography.

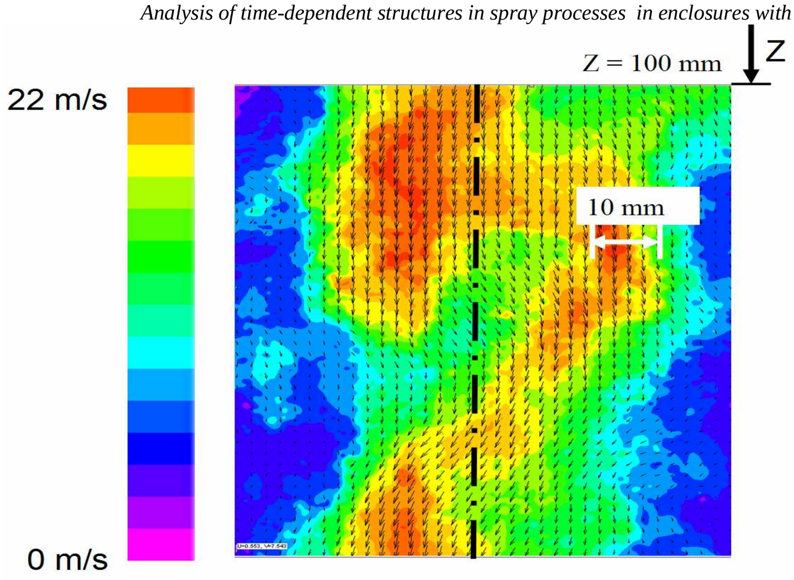


Figure 6. Instantaneous particle velocity field, p_{air} = 4 bar, variant V2

The strength of these effects is mainly dependent on the nozzle type, the air pressure and the spray chamber design. Before discussing the influence of these parameters on the inhomogeneity of the spray and the characteristic scale of the cluster the unsteady behaviour of the jet is briefly reviewed. Most stationary results can be found for Variant V3. This means that the oscillation amplitude is low and no large scale destabilization of the jet takes place. For Variant V2 one gets a high oscillation amplitude and destabilization of the jet, which in some cases leads to the transport of particle clusters into the recirculation area (Figure 7).

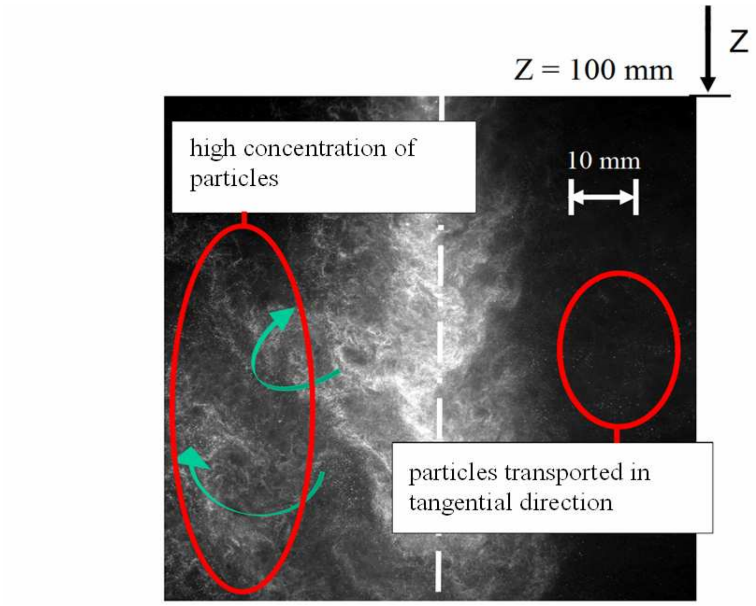
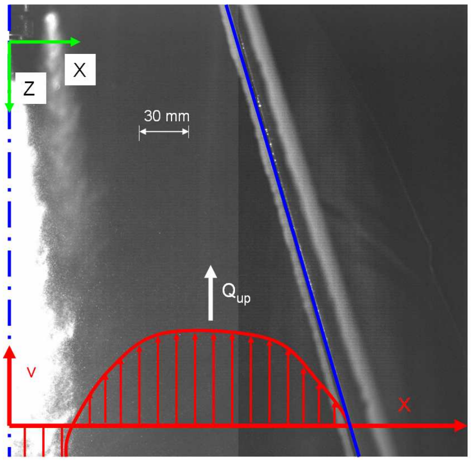


Figure 7. Transport of particles clusters into recirculation area, variant V2

In most cases the droplets at the spray cone edge are re-entrained (Figure 7). But once the oscillations are large enough the particles remain in the recirculation area and are transported upwards to the nozzle. This effect has great influence on the distribution of the retention times of the particles. Especially the retention time of larger particles could be increased because they have a larger centrifugal moment which keeps them in the recirculation area. The re-entrainment at the top may lead to undesired product properties. To get a stationary spray flow the starting cross section should be as large as possible. This geometry is already being used by default in most spraying processes. Variant V1 with a smaller opening angle, but with the same starting cross-sectional area as variant V2, shows less destabilization of the spray flow.

To quantify the influence of the atomizer parameters and the spray chamber geometry on the entrainment and recirculation movement, the axial component of the upwards directed air volume flow has been determined at a specific cross section (Figure 8). The basis for the measurement of the air flow rate is the evaluation of the velocities of the particles beyond the spray plume with PIV. Most particles outside the spray cone act like tracers since their maximum Particle Stokes number is estimated smaller than 0.1.

The results for the average volumetric flow rate show that an increase of the atomizer air pressure leads to a larger volumetric flow rate as expected. Moreover the spray chamber with the largest cross-sectional area (V3) gives the highest volume flow recirculation. Especially in this case the recirculation gas flow rate is in the order or even exceeding the atomizer gas flow rate. However the spray chamber with the smallest cross-sectional area does not induce the lowest recirculation of air volume flow rate. The reason might be that the recirculation zone of variant V2 is smaller or is shifted to a different position.



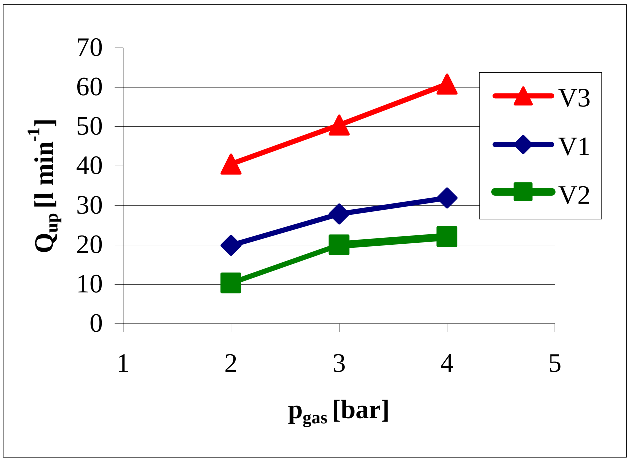
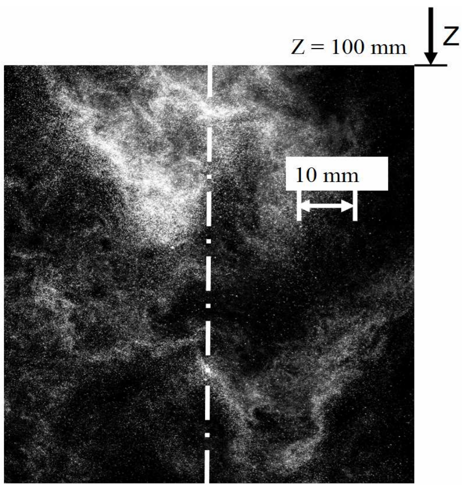


Figure 8. Averaged recirculating air volume flow rate at Z = 190 mm for different spray chamber geometries

The influence of the spray chamber design is in this case more dominant than nozzle parameters. One can say that a reduction of the cross-sectional area leads to less recirculation, but on the other hand an increasing destabilization of the spray plume can be reported, when the expansion angle is bigger. Further studies could reveal whether there is an optimum for specific spray setups. A numerical review dealing with similar questions can be found in [6].

The resulting coherent structures of the spray result in an inhomogeneous distribution of the spray droplets. A comparison between the cluster structures and the instantaneous velocity fields of the particles (Figure 9) for instance shows that particles in a cluster have a higher velocity than the particles around the clusters. This has also been found by Aliseda [1].



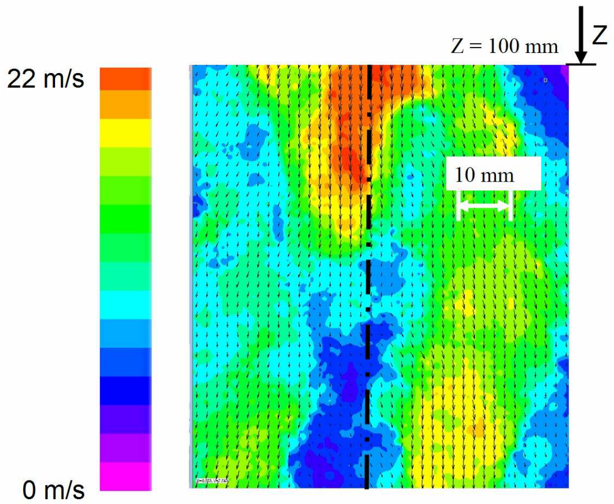


Figure 9. Instantaneous cluster structures and velocities of particles, p_{gas} = 4 bar, variant V2

The Particle Imaging method has been used to find out whether the particle cluster properties differ from the mean state of the spray at the cluster's position. The properties that are examined are velocity, shear rate flux and vorticity. It has to be stated that only the motion of the particulate phase can be tracked in the present measurement approach.

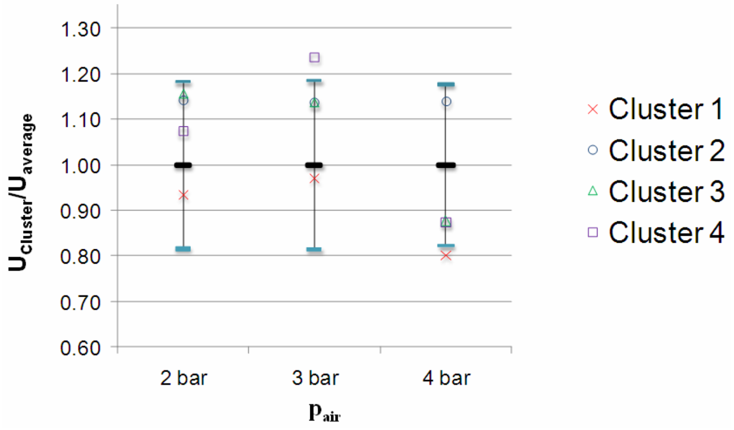


Figure 10. Comparison between cluster velocity and mean velocity at 4 cluster positions within the spray, variant V1

The result is that clusters are not significantly faster than the average particle flow at the cluster's position. This might be due to the fact, that the spray flow itself is strongly unsteady in space and time. Thus the validity of average values is limited. This is also expressed by the large error bars in Figure 10. Similar results can be found for the analysis of the shear rate and the vorticity.

For the nozzle parameters it shows that the inhomogeneity of the spray and the cluster scale (Figure 11) increases slightly with increasing gas flow rate. The inhomogeneity of the spray is thereby more affected than the cluster scale. This may be because of the increasing backscattering intensities of the particles within the clusters with increasing atomizer air pressure. The cluster tend to be more segregated from the ambient particle structures, which raises the inhomogeneity index. The cluster size is only scarcely influenced by this effect. An additional evaluation of inhomogeneity and cluster scale in sprays can be found in [5].

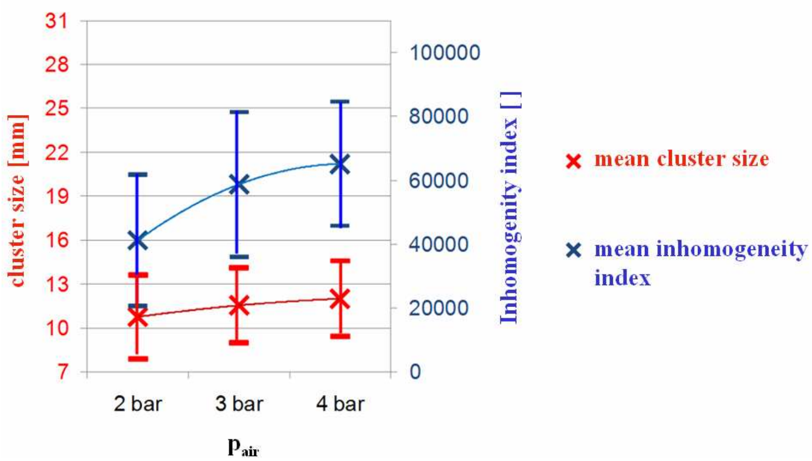


Figure 11. Cluster size and atomizer pressure, variant V1

Particle clusters tend to differ in size and shape. This is obvious when looking at Figure 8 and considering the standard deviation in Figure 11. Stretching of clusters (Figure 9) does not significantly increase the cluster size detected by the Garncarek method. This method is based on quadratic interrogation windows and is therefore only accurate for quadratic or circular cluster shapes. Despite of this the inhomogeneity index and the cluster scale are simple quantitative measures suitable to detect particle inhomogeneities relevant for the optimization of spray processes.

The other factor to influence particle clusters is the spray chamber design. An increase of the cross-sectional area leads to a slight increase of the particle cluster size (Figure 12). The raise of the inhomogeneity index is a most interesting fact. It is presumed that the complex interaction between the spray plume and the spray chamber walls are taking place, leading to differently

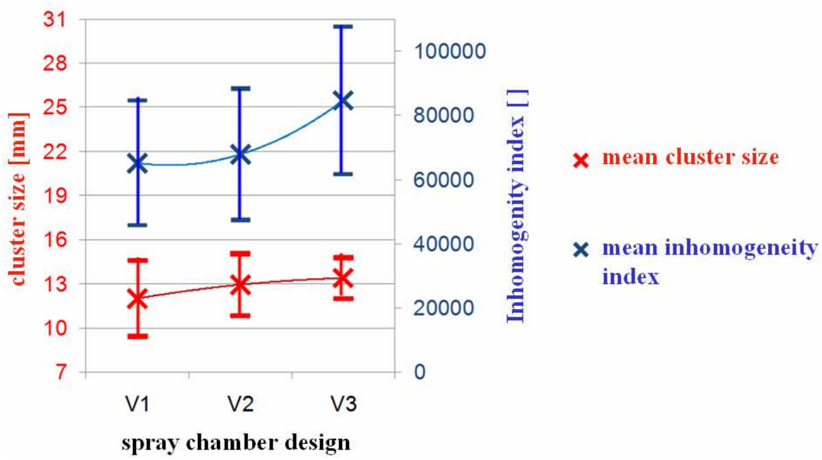


Figure 12. Cluster size and spray chamber design, p_{gas} = 4 bar

There is no strong trend to be found when the influences on the cluster size are examined. Same thing can be assessed for the atomizer typ. The internal and external mixing atomizers show very similar particle cluster structures. The only difference for these two atomizers is that the internal mixing atomizer requires less air volume flow to achieve same quality of atomization. This leads to a different entrainment and recirculation movement and less destabilization of the jet in spray chambers with small cross-sectional areas.

Conclusion

The cluster formation, the entrainment flow and the recirculation movement in sprays have great influence on the particle retention time, heat- and mass transfer and the agglomeration of particles in spray processes. The product properties are thereby dependent not only on the nozzle parameters but also on the spray chamber design. By means of Particle Image methods several results for the spray flow in conical spray chambers have been found:

- the spray flow structures are highly time-dependent (flapping, precession, ..)
- the spray chamber design greatly effects the entrainment and recirculation movement
- the cluster size depends on the spray chamber design and the nozzle parameters
- the mean cluster velocity is faster than the velocity of ambient particles
- the state of the cluster does not differ significantly in one direction from the averaged local spray quantities
- no significant influence of atomizer type on cluster formation is found.

References

[1] Aliseda, A., Cartellier, A., Hainaux, F., and Lasheras, J.C., *Effect of preferential concentration on the settling velocity of heavy particles in homogeneous isotropic turbulence*, J. of Fluid Mechanics Vol. 468: 77-105 (2002).

[2] Czainski, A.: *Quantitive Characterization of inhomogeneity in Thin Metallic Films Using Garncarek´s Method*, J. Phys. D: Appl. Phys. 27: 616-622 (1994).

[3] Hayakawa, S., Okajima, S., and Tokuoka, N., *The study of spray structure by numerical simulation – The effect of interaction between droplets on spatial inhomogeneity*, Proceedings of 22th ILASS, Europe Meeting 2008, Como Lake, Italy.

[4] Heinlein, J., and Fritsching U.: *Droplet clustering in sprays*, Experiments in Fluids, Vol. 40: 464-472 (2006).

[5] Kuno K., Tokuoka N., *Transition of Spatial Inhomogeneity of Droplets in Spray*, Proceedings of 21th ILASS, Europe Meeting 2007, Mugla, Turkey.

[6] Scholler, M., and Fritsching, U., *Oscillating Jet Flow in Enclosures with Non-circular Cross Section* , Int. Journal of Flow Control, Vol. 1, No. 2.: 167-173 (2009).