Droplet Clustering in Sprays

Jens Heinlein[1], Udo Fritsching[2]

1: University of Bremen, Badgasteiner Str. 3, 28359 Bremen, Germany, heinlein@iwt.uni-bremen.de
2: University of Bremen, Badgasteiner Str. 3, 28359 Bremen, Germany, ufri@iwt.uni-bremen.de

Abstract

Experimental characterization of spatial and/or temporal drop distributions in sprays is typically based on single point statistics characterizing the droplet properties at discrete points in time or space. Such a description provides a measure of the droplet number density or flux rate. Progress in particle measurement techniques as e.g. in Phase-Doppler-Anemometry has made times series information available for sprays. Here it is possible to distinguish between steady and unsteady sprays by evaluation of the interparticle arrival time statistics at a certain position.
For the determination of the steady and/or unsteady behaviour of a spray, a certain place in the spray formed by the probe volume of the PDA is regarded. Here the interparticle arrival time is determined. Each particle exhibits thus additionally to its characteristics of size and velocity, the interparticle arrival time. In the case of a steady spray the interparticle arrival time obeys a Poisson distribution. A typical example of unsteady behaviour is droplet clustering which is caused e.g. by pulsating decay procedures or particle interaction with large-scale eddy structures. The aim of the investigations is the analysis of such unsteady spray conditions.

Introduction

Sprays often are characterized at a single point in time or space. Such a description provides e.g. a measure of the number density or flux rate of the spray. Phase Doppler interferometry has made times series information available for sprays. Edwards and Marx [1, 2] developed a multipoint statistical description of a spray. Based on this theoretical framework it is possible to distinguish between steady and unsteady sprays by using the interparticle arrival time τ. Steady sprays are defined as those whose interparticle arrival time distribution obey inhomogeneous Poisson statistics. Unsteady sprays are defined as those whose interparticle arrival time distribution do not obey inhomogeneous Poisson statistics. An example of unsteady behaviour is droplet clustering.

Theory

The formalism for determination if a spray is steady or not can be divided into three main steps. First step is to assume that the spray is steady and to calculate the theoretical interparticle distribution function at a certain position. The second step is to measure the interparticle arrival times and to calculate the resulting distribution function. At least these two functions have to be compared [3, 4].
The experimental interparticle time distribution, $h_{\exp}(\tau_j)$, can be determined from a single realization (SR) or multiple short realization that are ensemble averaged (ER). To determine the theoretical interparticle time distribution $h_{th}(\tau_j)$ Edwards and Marx [1, 2] modelled the spray as a marked inhomogeneous, Poisson process. The Poisson process is described by the intensity function, λ, which represents the expected number of particles to be sampled per unit time [6]. The theoretical interparticle function is then compared with the experimental interparticle distribution function and a decision on spray steadiness or unsteadiness is made. The statistical analysis of the Chi – square tests is used to get the significance (confidence), level within which the experimental results can be argued to be the same as the theoretical values. In a Chi- square analysis, the calculation of the random variable χ^2, which measures the proximity of the observed values to the corresponding expected values can determine the validity of the hypothetical model [3]. Once χ^2 has been determined, the hypothetical model can be accepted or rejected depending on the desired significance level [3, 7]. The Chi- square table is used in this process. The smaller the χ^2 value, the better is the agreement between the known data and the proposed model.

Experimental investigations

The experimental facility includes two different atomizers, a fluid supply system and the Phase-Doppler system. To prevent influences of pressure variations from the fluid supply system a pressure vessel is used.
The Phase-Doppler- System is used to acquire droplet size, velocity and arrival time data. The evaluation of the PDA-data takes place in post-processing, what means that first the complete signal is recorded and afterwards the evaluation concerning to the measured particle, their velocity, diameter and arrival time happened in offline-mode. Finding the PDA-typical Doppler-bursts happens in the frequency range, where the signal first is analysed by an FFT-algorithm and if both channels exhibit the same frequency a particle is recognized. In relation to an on-line evaluation the advantage of this method consists of the fact that hereby more particles are recognized.
The PDA is set up in forward scattering or refractive mode with the receiver positioned at 60° from the transmitter axis. The collimating lens focal length was 700mm, the transmitting lens focal length was 1200mm.
Since the aim of this study is to investigate how spray unsteadiness depends on the operating conditions and the break-up process, experiments are performed with two different kinds of nozzles. A pressure atomizer that forms a flat sheet and an air atomising nozzle that forms a full cone spray pattern are used. Measurements are taken at different axial and radial distances from exit orifice of the nozzle to learn more about the relative unsteadiness in various parts of the spray.

Pressure atomizer

The pressure atomizer is studied at a constant mass flow rate of 0.003 kg/s at an spray angle of 65°. The experiments are performed with water. Figures 1 and 2 show the spray characteristic of the pressure atomizer. Based on these Figures one can recognize that the spray doesn't exhibit a regular density in every part of the spray. It is rather shown that the spray is more dense in the core regions. Figure 1 and 2 show that the ligaments describe a pronounced undulation before the break-up process occurs.

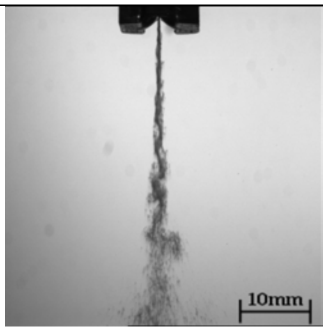

Fig. 1: Side view of the pressure atomizer

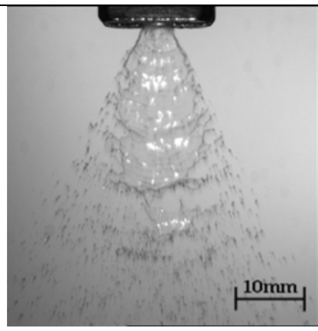

Fig. 2: Front view of the pressure atomizer

Twin-fluid atomizer

The twin-fluid atomizer is operated at a constant liquid mass flow rate of 0.0007kg/s and different air volume flow rates of 0.11, 0.14, 0.18 and 0.22l/s. The experiments are performed with water, the spray angle is 18°. Figures 3 and 4 illustrate the spray characteristic of the twin-fluid atomizer at different air flow rates. Figure 3 shows that the spray doesn't exhibit a homogeneous density which is similar to the pressure atomizer shown in Figures 1 to 2. The highest droplet density here is likewise in the core range. It can be stated however that with increasing the air flow the droplet density distributes itself more evenly. It needs to be mentioned that the atomizer-manufacturer indicated a minimum air flow of 0.18l/s. The operating conditions represented in Figure 3 lies thus below this value.

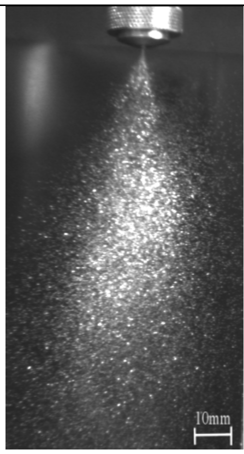

Fig. 3: air atomizer at an air flow rate of 0.11l/s

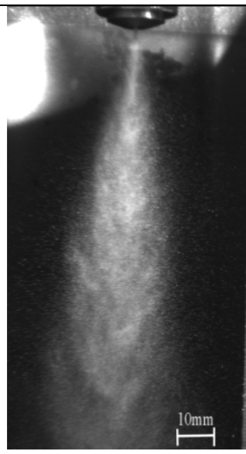

Fig. 4: air atomizer at an air flow rate of 0.18l/s

Results for the pressure atomizer

One method of presenting the measurement data is as interparticle time distribution functions. Representative interparticle time distributions have been plotted in Figures 5 and 6 to illustrate the comparison between experimental data and steady interparticle time distribution. The data shown in Fig. 5 were taken 30mm downstream from the atomizer on the spray centreline and the data shown in Fig. 6 were taken 125mm downstream from the atomizer at a radial distance of 20mm from the spray centreline. The indicated axial and radial locations refer here and in the following text always to the front view (Fig.2) with the nozzle exit as point of reference. The vertical bars represent the experimental data, while the solid curve represents the theoretical result. The error bars show the expected deviation of the theoretical results due to the random nature of a theoretical spray. The most important information is that at the shortest interparticle arrival times. While in Figure 5 the experimental interparticle time distribution differs for the first bin from that of the steady theoretical case only by 0.75 deviations it differs in Figure 6 by more then 4 deviations for this bin. This suggests that while the two results shown in Figure 5 are nearly the same the two results shown in Figure 6 are significantly different. To show that the results are not due to random fluctuations the Chi square value is calculated for both data series. While for Fig. 5 a chi value of $\chi^2 = 0{,}3$ shows that the difference between the two distribution function could be possible due to random fluctuations, for Figure 6 the Chi square value of $\chi^2 = 42$ shows that there is practically no chance for the two distributions to be different due to random fluctuations.

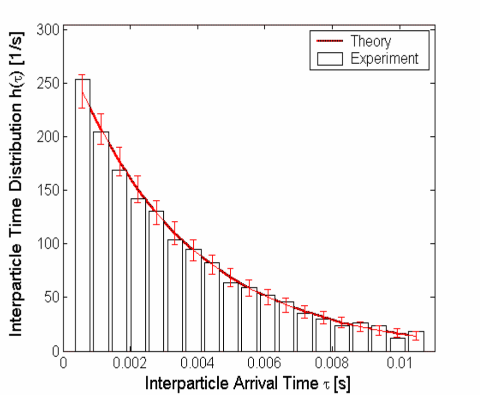

Fig. 5: Experimental and theoretical interparticle time distribution versus interparticle arrival time. Taken 30mm downstream on the centreline

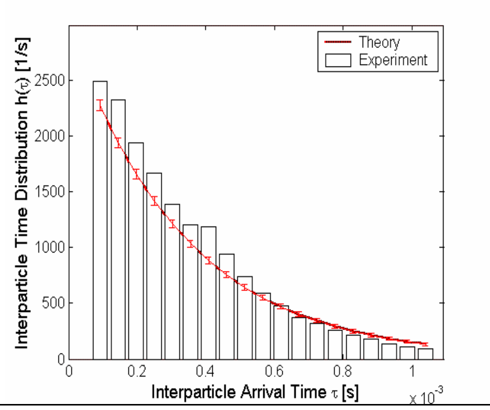

Fig. 6: Experimental and theoretical interparticle time distribution versus interparticle arrival time. Taken 125mm downstream at a radial distance of 20mm

Here the magnitude of the experimental time distribution is much greater than the steady theoretical interparticle time distribution for the short interparticle time bins. This indicates that there is a higher probability for having shorter interparticle arrival times. In other words, droplet clustering occurs in this spray. This indicates that the spray at this location is unsteady.

To make a comparison of spray steadiness of the results at different locations dependent on the radial and axial location in the spray representative interparticle arrival-time bins are compared. Spray steadiness/unsteadiness is presented in terms of the chi square value and number of deviations between theoretical (steady) and experimentally measured interparticle droplet size distribution at the shortest interparticle time.

Figure 7 shows the number of deviations and Figure 8 shows the chi square value for all measured axial and radial location of the spray of the pressure atomizer.

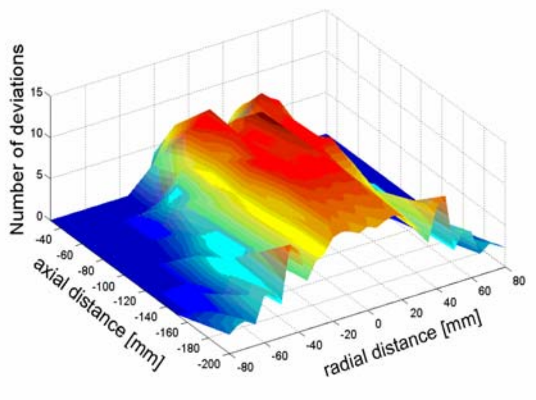

Fig. 7: Number of deviations versus radial distance for different axial distances

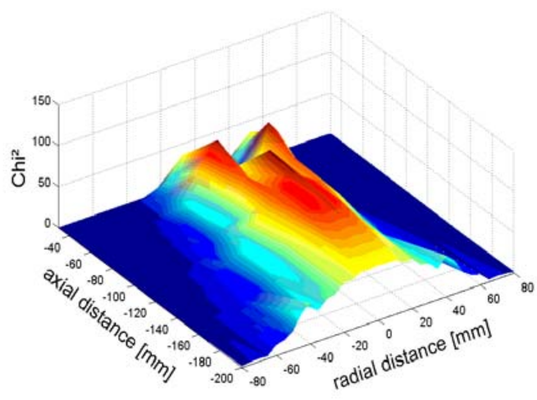

Fig. 8: Chi square value versus radial distance for different axial distances

The data represented in Figure 7 shows regions in the spray in which the number of deviations has large values especially near the nozzle exit. The number of deviations for the spray centre line is rather small, the maximum can be found next to the spray centre. With increasing axial distance from the nozzle exit, also the number of deviations increases. After a certain distance these values are large over a wide radial range in the spray centre (approx. ±20mm). However, the number of deviations decreases to the edge of the spray and reaches there a minimum over the entire represented axial range.

If one compares the values for the determined Chi-square value, represented in Figure 8, the same behaviour can be seen here. The largest Chi-square value can be found within a range at the spray centre and the value decreases to the edge of the spray where it reaches a minimum.

To make a decision on spray steadiness/unsteadiness it's necessary to combine these two results. Therefore, the regions in the spray where a large number of deviations can be found in combination with the height of the Chi-square value are to be examined. As both parameters show a good agreement in their behaviour, it results that for the mentioned range where a large number of deviations is determined, the Chi- square value reaches the critical value. This indicates that for these mentioned ranges there is a high probability that droplet clustering occurs and the spray is unsteady.

The observed trend that droplet clustering is most intense in the region between the spray boundary and the spray centre is also observed by Hodges et al [5]. They expected that only the smallest droplets, having relatively small Stokes numbers, follow the gas- phase turbulence, and the larger droplets with high momentum and large Stokes number tend to be unaffected by the gas-phase flow. This would be in good agreement with the local drop size distributions for the used pressure atomizer because the smaller droplets are inside the spray rather than at the edges of the spray. To give an exact statement about this influence, the interparticle arrival time analysis has to be done for different drop size and velocity classes. Figure 9 shows the number of deviations for the spray centre line for different drop size classes. The sizing of the drop size distribution took place with an increment of $\Delta d = 10\mu m$. Additionally to the subdivision of the drop size distribution also the velocity distribution was subdivided in classes and the interparticle analysis for these classes has been made. The resulting Chi-square values are shown in Figure 10.

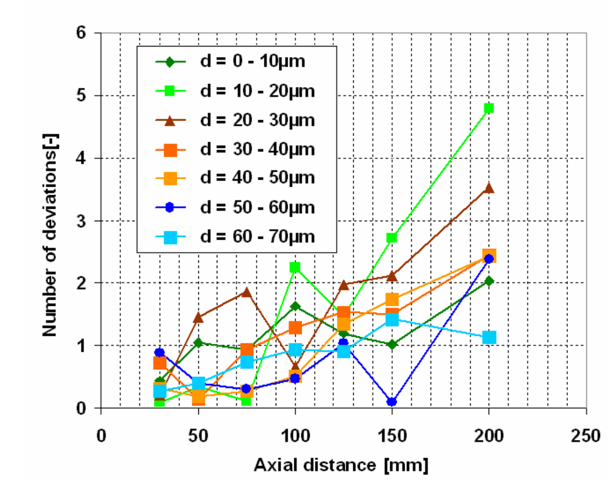

Fig. 9: Number of deviations versus axial distance for different drop size classes

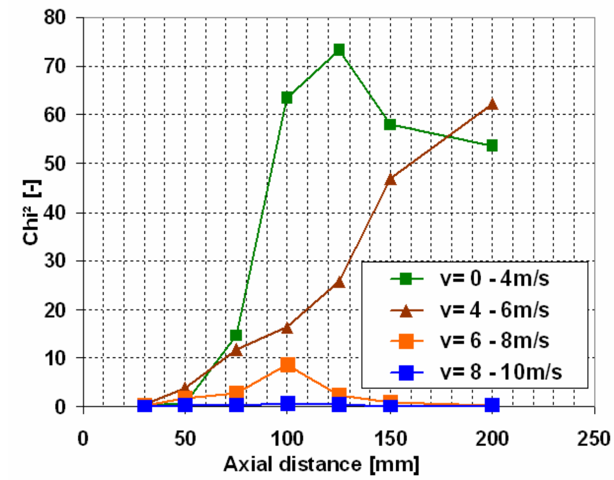

Fig. 10: Chi square value versus axial distance for different velocity classes

Figure 9 illustrates that with increasing axial distance also the number of deviations increases. The largest number of deviations can be found for the diameter range from 10µm to 20µm. With increasing droplet size smaller values for the number of deviations can be determined. Only the results for the first seven diameter classes are represented here for the reason of clarity. The results for the other classes follow the shown trend and just take smaller values. This result is in agreement with the observation made before. However, including the results of the associated Chi-square analysis into this considerations, it can be determined that these Chi-square values are all below a critical value. That means that a tendentious course appears here but that this effect is not significant and may be due to random fluctuations.

In contrast to this the result for the analysis of the velocity classes is different. Figure 10 shows that the two lowest velocity classes show large Chi-square values. With increasing velocity these values get substantially smaller (and for the reason of clarity are no longer represented here for the upper velocity classes). The pertinent values for the number of deviations show this trend likewise. In this case also a large value for the number of deviations can be determined for the lower two velocity classes. That means that clustering is expected for droplets, whose velocity is in the lower velocity range. Both curves describe first the same trend that with increasing axial distance also a higher probability for the presence of clustering exists. During that probability increases for the velocity classes of v = 4 - 6m/s, this probability starts to decrease for the class of 0 – 4m/s from an axial distance of approximately 125mm.

Results for the twin-fluid atomizer

For each operating condition and/or air flow the spray is analysed at different axial and radial locations. Figure 11 shows the number of deviations and Figure 12 shows the chi square value for all measured locations of the spray at an air flow rate of 0.14l/s.

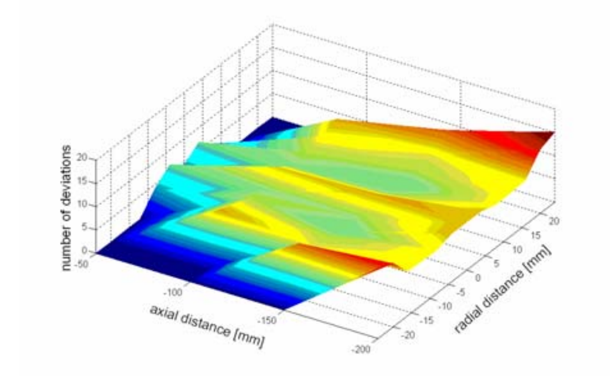

Fig. 11: Number of deviations versus radial distance for different axial distances

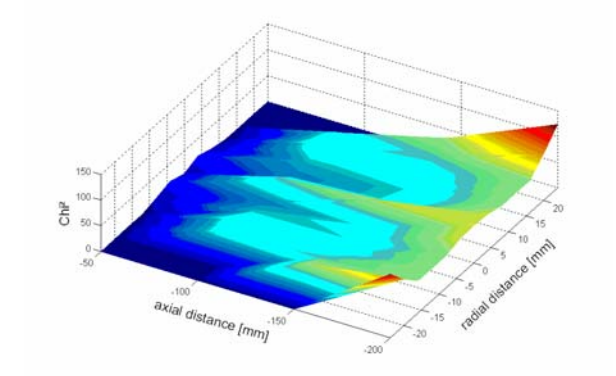

Fig. 12: Chi square value versus radial distance for different axial distances

The results represented in Figures 11 show that in the region close to the nozzle exit nearly the same behaviour can be determined as for the pressure atomizer. Also here the maximum number of deviations can be found next to the spray centre line and reaches there a minimum. However, from a certain distance (approx. 100mm) one can recognize that the maximum value can be found at the edge of the spray, which shows a completely different behaviour from the pressure atomizer. At the same time, on the spray centre line this value increases and the range between the spray centre and the spray edge is characterized by rather small values. For the values of the Chi-square analysis in Figure 11 the same behaviour as for the number of deviations is likewise observed. For a statement on spray steadiness/unsteadiness it's also here necessary to combine the two results. For small axial distances relatively high numbers of deviation can be found but the associated Chi-square values are however so small that these effect can be due to random fluctuations. For larger axial distances it behaves differently. While at small axial distances the Chi-square value for the spray centre line is still relatively small, it starts to increase with increasing axial distance. With increasing the axial distance a higher probability for the occurrence of cluster exists. The same effect can be determined at the edge of the spray, since with increasing axial distance both the number of deviations and the Chi-square value reach very high values. Here a very high probability exists to have small interparticle arrival times. That indicates that droplet clustering occurs and that the spray started to be unsteady from that mentioned locations. Like initially mentioned Figure 11 and 12 show exemplarily for all four investigated operating conditions the temporary behaviour of the spray. However the described trend concerning the steadiness/unsteadiness was observed at all operating conditions. Possible differences were to be determined in the absolute amount of the two regarded parameters, significant differences on the temporal behaviour could thereby not be determined. The observed trend of increased unsteadiness for droplets at the edge, or shear layer, of the spray is thought to be due to the effect of intermittency and shear layer vortex roll-ups, which causes the spray to exhibit more droplet clustering.

Conclusion

The unsteadiness of two different sprays is studied using the multipoint statistical model for an ideal spray. Spray unsteadiness is illustrated and the dependence on the operating conditions and spatial locations is reported.

The two examined atomizers show thereby different results in their temporal behaviour. While for the pressure atomizer clustering takes place rather within the mid area of the spray, this effect takes places at the air atomizer rather within the outside spray area. For both atomizers clustering increases and/or begins only at increasing axial distances. In a droplet cluster a locally high droplet number density exists which results in relatively short interarrival times. Although droplet clustering occurs even in steady sprays as a consequence of the random character of the droplet flux, in this discussion the term clustering applies to those situations for which the interarrival times differ in a statistically significant fashion from the steady Poisson statistics.

Next step for following investigations is to vary the drop size depending interparticle arrival time analysis and characterisation of the existing clusters, e.g. with frequency analysis.

Nomenclature

d	droplet diameter, m
ER	pertaining to ensemble-average realizations
h_{exp}	experimental interpartical time distribution, 1/s
h_{th}	steady theoretical interparticle time distribution, 1/s
λ	intensity function, 1/s
SR	pertaining to single realizations
τ_i	interparticle time gap j, s
v	velocity, m/s
χ^2	Chi- square value, dimensionless

References

[1] Edwards, C.F.; Marx, K.D.: Multipoint Statistical Structure of the Ideal Spray, Part I: Fundamental Concepts and the Realization Density, Atomization & Sprays 5 (1995), 435 – 455

[2] Edwards, C.F.; Marx, K.D.: Multipoint Statistical Structure of the Ideal Spray, Part II: Evaluating Steadiness Using the Interparticle Time Distribution, Atomization & Sprays 5 (1995), 457-505

[3] Luong, J.T.K.; Sojka, P.E.: Unsteadiness in Effervescent Sprays, Atomization & Sprays 9 (1999), 217-257

[4] Edwards, C.F.; Marx, K.D.; W.K. Chin: Limitations of the ideal phase-doppler system; Extension to spatially and temporally inhomogeneous particle flows, Atomization & Sprays 4 (1994), 1 – 40

[5] Hodges J. T.; Presser C.; Gupta A.K.; Avedisian C.T: Analysis of Droplet Arrival Statistics in a Pressure- Atomized Spray Flame, 25th Int. Symp. On Cumbustion, pp. 353 – 361, Pittsburgh, PA, The Combustion Institute, 1994

[6] Roismann I.V.; Tropea C.: Drops distributions and flux measurements in sprays using phase Doppler technique, 10th Int. Symp. on Appl. of Laser Techn. to Fluid Mech., Lisbon 2000

[7] Heinlein J.; Fritsching U.: Detection and evaluation of droplet concentration variations in sprays, DFG- Priority Program Atomization and Spray Processes, Dortmund, 2004