Chaotic disintegration of suspension spray by a cross air flow

Belal A. Zaitone, N. V. Doan, Ilia V. Roisman and Cam Tropea
Chair of Fluid Mechanics and Aerodynamics
TU Darmstadt
Petersenstr. 30, 64287 Darmstadt, Germany

Abstract
The aim of this experimental and theoretical work is the characterization of chaotic disintegration of sprays generated by a cross air flow, in particular the description of droplet size distribution, average droplet size and the influence of the various process parameters on spray disintegration. These experiments will serve as a base for the development of a phenomenological predictive model for typical spray parameters, in particular for the mean drop diameter of drops.

Introduction

Spray drying and spray microencapsulation are one of the most widely spread technologies for particle generation in pharmaceutical [1], food [2], detergents and chemical industries [3], and in powder generation for drug delivery [4]. The key element of these technologies is the primary spray atomization. It is well-known that the size distribution of atomized droplets coupled with the operating parameters of the spray dryer can influence not only the size but also the morphology of the particles obtained in spray dryers. The entire spray process consists of multiple physical phenomena: primary atomization, spray transport and wall interactions, as well as single droplet processes, i.e. evaporation during spray transport. The quality of the predictive tools in this field is highly related to the level of physical knowledge of the different elementary phenomena. In order to develop and validate theoretical models, estimation of the size of drops generated as a result of the jet disintegration is essential. The effect of the properties of the feed fluid such as initial solid concentration, surface tension, density and rheology on the size distribution of the spray is investigated in this article which is based on [5].

Materials and Methods

An experimental rig has been built (see Fig. 1) to study chaotic disintegration of suspensions and other complex liquids. The liquid jet is ejected from a pressurized reservoir through a nozzle. The jet is then disintegrated by a continuous gas cross flow hitting it near the exit of the nozzle, as shown in Fig. 2. The geometry is chosen to be generically relevant to a wide variety of industrially applied atomization technologies. An optical system consisting of a high speed camera with back-lighting is used to capture the shadow images of the disintegrated spray. The images are analyzed to calculate average droplet size and droplet size distribution.

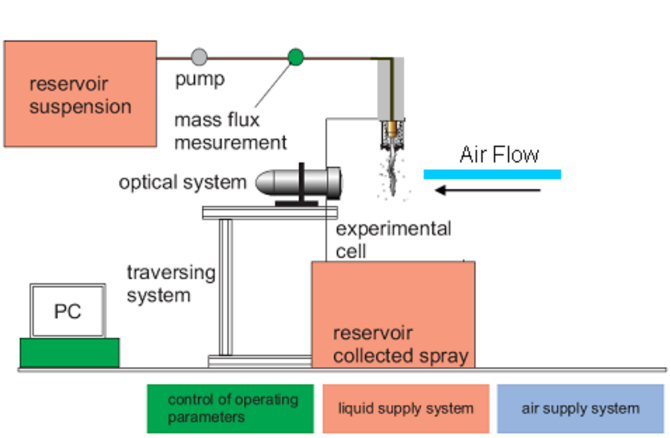

Figure 1. Experimental setup

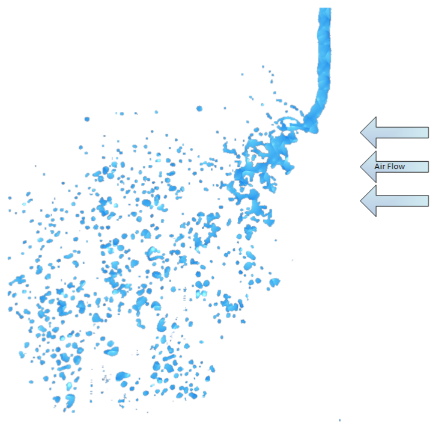

Figure 2. Schematic illustration of jet disintegration

The atomization process and the formation of the drops occur in a very small scale. Therefore a high level of magnification is needed to record the images of spray. In order to obtain a sufficient amount of information about the spray, the investigated area was enlarged by moving the camera position along the vertical axis, thus, creating a band of images along the spray propagation. The distance of the band from the air flow nozzle was fixed throughout the whole experiments (see Figs. 3 and 4), the flow conditions remain then equal for all test series. Analysis of the images was conducted for single recording positions as well as the whole band. The images were analyzed by an automatic image processing algorithm (in house developed) which calculates the mean diameters based on equation 1 as well as the drop size distributions. D_{ab} represents the mean droplet diameter, whereas a and b are parameters to calculate the diameter which fits best to the investigated field of application.

$$D_{ab} = \left(\frac{\sum N_i D_i^a}{\sum N_i D_i^b} \right)^{\frac{1}{(a-b)}} \tag{1}$$

In this study both, the arithmetic mean diameter and the Sauter mean diameter were calculated, also known as D_{10} and D_{32} [6]. To ensure that the number of identified drops is high enough for the mean diameter, a total number of 5000 images were recorded at every position. Both pure liquid water and polymer solution (Polyvinylpyrrolidone) at initial polymer concentrations of 1%, 2%, 5% and 10% have been investigated at cross air flow velocities of 100m/s and 125m/s. Different polymer concentration were chosen to investigate the influence of surface tension and viscosity. Both of these properties change with increasing concentration. A variety of nozzle geometries has been tested with diameters of 0.5mm, 0.63mm, 0.8mm and 1.05mm. Smaller nozzle diameters were susceptible to clogging.

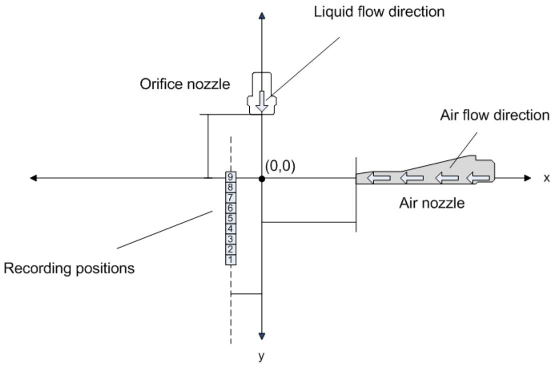

Figure 3. Experimental setup - front view

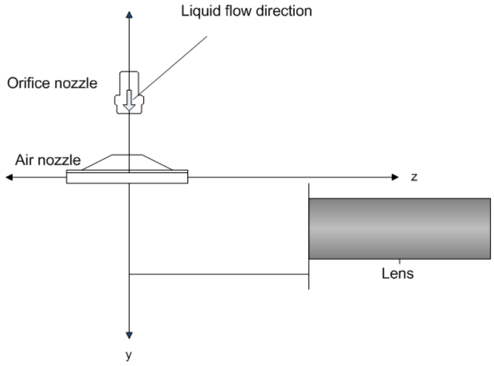

Figure 4. Experimental setup - side view

Results and Discussion

The experimental results were analyzed taking into accout; size distribution, mean droplet diameter and morphology of the atomized spray. The following sections explain these individually.

In this study mainly the primary drops were investigated . These primary drops form when the cross air flow hits the liquid jet. It can be assumed that the percentage of secondary drops is very small. Droplets that remain in the air flow are carried away and also remain subject to strong aerodynamic forces. A further disintegration is thus very likely to occur.

Morphology* generally refers to the doctrine of forms. In this study the term is used to describe the shape of the observed structures that form in consequence of the atomization process. A qualitative analysis of single shots and recording sequences represented the first step of the data evaluation. It is apparent that areas with different flow conditions exist. The recording positions that are on the same level as the air nozzle, are located directly in the airflow, or close to its area of influence. In contrast, it can be seen that a few millimeters below the nozzle hardly any direct influence of the airflow remains. Therefore ligaments and droplets shape resulted is a function of the recording position. They differ in shape, size and number. In addition the amount of diffuse structures which are located outside the focal plane varies. Figure 5 shows an example of the most frequently observed structures. Stable droplets, where the disintegration is complete, take a circular form, figure 5 a). They show no interaction with the surrounding air and their size can vary several times over within a test series. Drops, which are still under the influence of the flow, show an oscillating elliptical shape, caused by the reaction of the surface tension to the deformation by the air flow, Figure 5 b). The next group includes large-scale structures, which shapes resemble dumbbells. These are characterized by mass gatherings on both ends and a lateral contraction in the middle, figure

*derived from Greek $\mu o \rho \varphi \acute{\eta}$, morphé = shape, form and $\lambda \acute{o} \gamma o \varsigma$, lógos = word, study, research

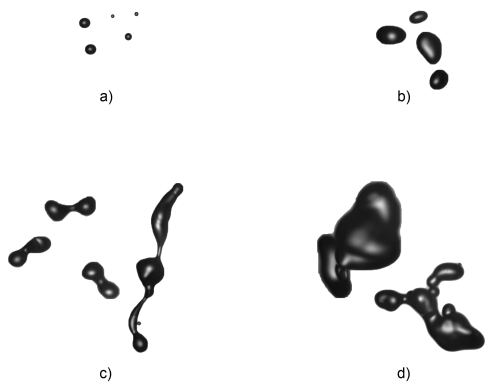

Figure 5. Morphology of identified liquid structures: a) round droplets b) elliptical droplets c) barbell shaped droplets d) irregular structures

5 c). It is expected that these structures are in an intermediate unstable stage and will disintegrate further into two or more separate drops. The previously described structures possess a certain degree of symmetry. In addition, there are also irregular clusters and string-like structures, figure 5 d).

Independent from the experimental parameters the recording position is the most important factor in regard to the morphology of the droplets. It is common for all test series that very few and relatively small drops can be found at the level of the air nozzle. Also the number of diffuse structures is very large and dominant. The reason for this observation is the direct influence of the airflow. Velocity measurements with a Pitot tube and an estimation of the drop velocity confirm that the air and droplet velocity in X-direction reaches its highest value at this position. The estimation of the drop velocity was achieved by means of a simplified two image process, in which the movement of the drop center was observed in two succeeding images and converted into the velocity. The observed droplets were atomized completely and are now transported downstream in an almost horizontal flow line. This observation is confirmed by the estimated velocity components in X- and Y-direction. Because of their small size, even small deviations of the flow line in the Z-direction result in leaving from the focal plane, causing an increased number of diffuse structures.

If one moves further away from the airflow in Y-direction, an increase in the number of drops and drop size can be detected. At first the shape of the drop shows no change. Only when a position is reached where the air velocity decreases significantly this instance changes. Depending on the experimental parameters this point is reached at a distance between 1.5cm and 2.5cm below the air nozzle. At this position, string-like ligaments can be observed for the first time. These are of very chaotic nature and vary greatly in size and shape. The number and size of the ligaments increases when moving further downwards. The image section is now dominated by these large-scale structures and the number of unfocused particles decreases strongly, until only very few large drops can be observed at the lowest recording position. These ligaments are formed in areas where the impact of the air flow is too low to spur on a further disintegration. Once these ligaments have been moved away from the liquid jet by the airflow, they move down rapidly due to their large size and then become far away from the influence of the airflow.

Drop size distribution

The droplet size distributions are compared at various operating parameters. The droplet size distributions that were determined during this study show only a portion of the overall spectrum.

Examination of the droplet size distributions confirm previous observations regarding the influence of the recording position on the resulting droplets. As the distance increases from the air nozzle, the diameter of the drops increases. This can be seen in the histogram by an expansion of the distribution and significant shift to larger average diameters. Both pure water and polymer solutions show the same behavior. Figures 6 and 7 show a comparison of the histograms.

Aerodynamic forces are necessary to break up the stable liquid jet which is held together by surface tension forces. An increase in aerodynamic forces should therefore favor the disintegration process. A comparison of histograms at different air velocities as depicted in Figure 8 clearly shows that, its increases from 100m/s to 125m/s at the nozzle exit cause the mean of the droplet size distribution to be reduced by about 100μm. Simultaneously

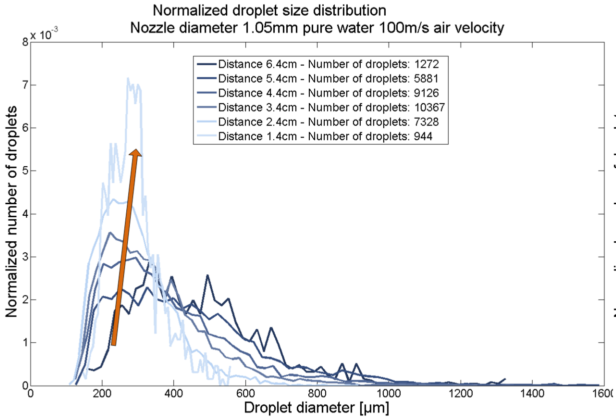

Figure 6. Histogram comparison - Influence of recording position for pure water - distance from air nozzle increases in arrow direction

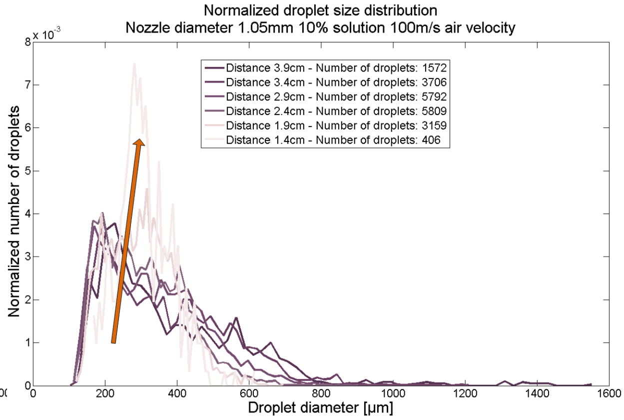

Figure 7. Histogram comparison - Influence of recording position for 10% solution - distance from air nozzle increases in arrow direction

the width of the distribution is strongly reduced.

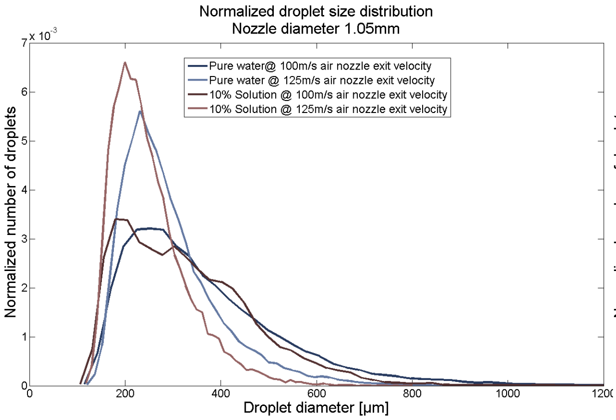

Figure 8. Histogram comparison - Influence of air velocity on entire band

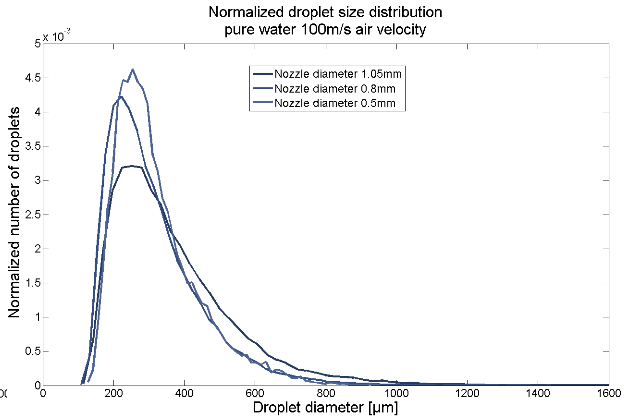

Figure 9. Histogram comparison - Influence of nozzle diameter on entire band

A smaller nozzle diameter should have a similar effect on the droplet size distribution, the capillary force is proportional to the jet/nozzle diameter. Figure 9 shows that the change of the distribution caused by reduction of the nozzle diameter is less drastic than by increase of air velocity, but still recognizable. This is seen when reducing the nozzle diameter from 1.05mm to 0.5mm.

Figure 10 shows histograms of different solutions with different initial concentration which are compared under the same operational conditions. Contrary to expectations the droplet size distribution show only minimal changes. A tendency of reduced maximum drop diameters and increased mean diameters with higher concentrations can be seen.

Mean droplet diameter

Mean droplet diameter D_{10} (arithmetic mean) and D_{32} (Sauter diameter) have been calculated according to eqn. 1. An evaluation of the curves in Figures 11 and 12 confirms the previously mentioned correlations between the recording position, air velocity and the mean droplet diameter. It can be noticed that an increasing distance from the air nozzle cause the mean droplet diameter for this selected test series to increases up to 25% for D_{10} and 74% for D_{32}. The influence of the air velocity can be also clearly seen. An increase of the velocity by 25 % leads to a reduction of the average diameter of 31% (D_{10}) and 39% (D_{32}).

The influence of the mass concentration and the nozzle diameter are depicted in Figure 13, the regression lines clearly show the downward trend in correlation with increasing concentrations. The deviation of the calculated values of the regression line can be accounted to measurement variations, which are reinforced by the chaotic

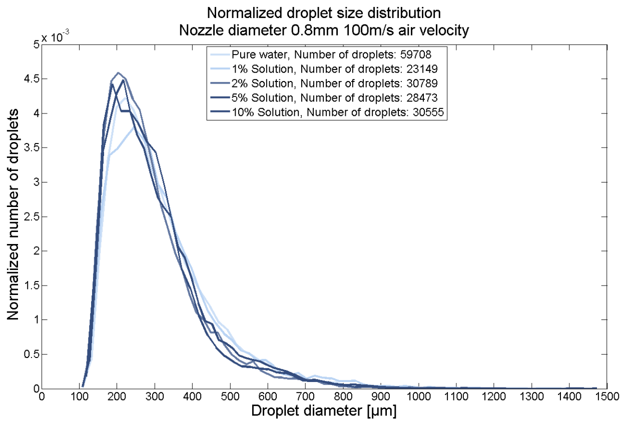

Figure 10. Histogram comparison - Influence of polymer concentration on entire band

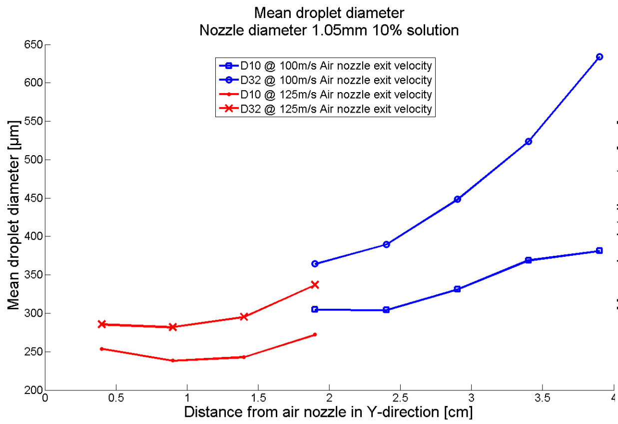

Figure 11. Developing of mean diameters in dependence on recording position

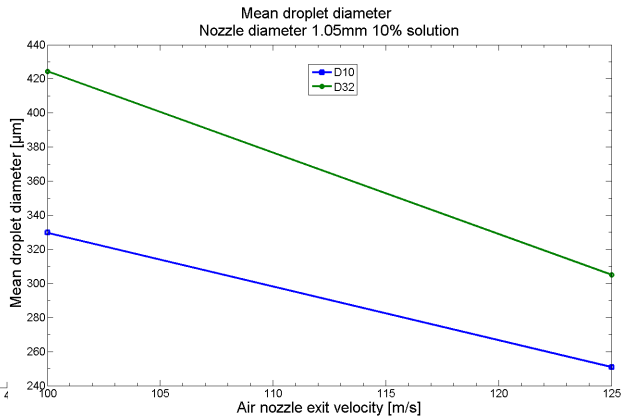

Figure 12. Developing of mean diameters in dependence on air velocity

nature of the atomization process. The amount of deviation varies from test series to another but has no influence on the principal course.

Figure 14 shows the mean drop diameter as a function of the nozzle diameter, it does not seem to exhibit any clear regularity. A possible explanation is that the spray shape changes with the nozzle diameter whereas the experimental setup and recording positions are fixed. This leads under certain circumstances to the analysis of different relative parts of the spray causing conflicting results.

Conclusions

In summary, the atomization of primary droplets using a cross air flow is highly dependent on the velocity of the airflow and the mass concentration of dissolved solids as well. The surface tension, the curvature radius or diameter, and the air velocity which is proportional to the aerodynamic force or pressure can be identified as the main influence parameters. The change of air velocity has the most distinct impact on the atomization process. It allows both a variation of the mean droplet diameter as well as the droplet size distribution. The variation of mass concentration and thus the surface tension only had an effect on the mean droplet diameter. If a modification of the mean droplet diameter at fixed size distribution is desired the manipulation of the concentration should be considered as an approach. However, it should be noted that high concentrations increase the risk of nozzle clogging.

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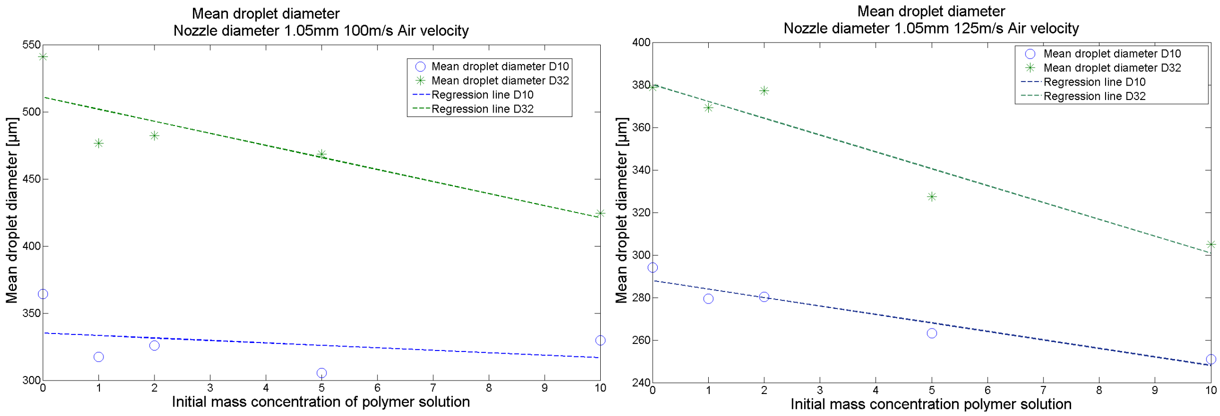

Figure 13. Developing of mean diameters in dependence on initial mass concentration

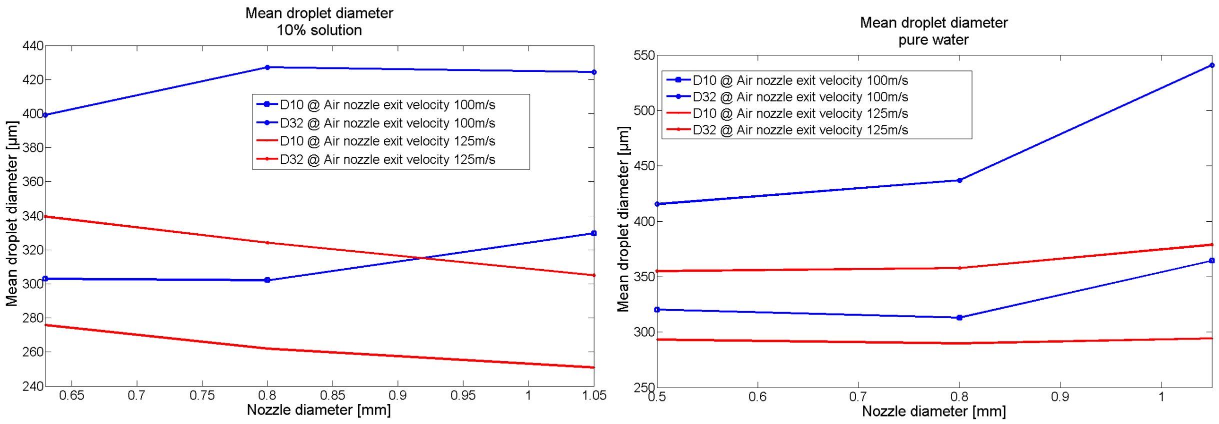

Figure 14. Developing of mean diameters in dependence on nozzle diameter

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