SPRAY FORMATION THROUGH LIQUID SHEET BREAK-UP CONTROLLED BY VIBRATIONAL EXCITATION

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Abstract

The present paper reports about recent progress in the development of a technique for controlling the formation of sprays from fan-shaped liquid sheets produced by flat-fan pressure atomizers. The motivation for the work is the need of many branches of industry to have best controlled sprays for various applications like, e.g., spray coating and spray drying. The technique relies on the vibrational excitation of the liquid sheets emerging from prefilming pressure atomizers. The vibrations produce wave fronts on the sheets which, under suitable conditions, are regular in shape and lead to the disintegration of the sheet into regularly shaped ligaments. These ligaments finally disintegrate into droplets of high regularity which finally form the spray. The aim of the work presented is to establish a compact device for exciting the sheets, to investigate the sheet and ligament formation processes, and to identify the mechanism that forms the droplets by ligament break-up.

Introduction

A large variety of pre-filming pressure atomizers are commonly used for various purposes in industrial production processes, agriculture, and other fields. One group of such atomizers, the flat-fan pressure atomizers, produce fan-shaped liquid sheets, which diverge in flow direction and disintegrate into ligaments due to the Kelvin-Helmholtz instability of the sheet. The drop formation eventually takes place due to the break-up of the ligaments. The global drop size spectrum of sprays from such atomizers is typically quite wide, extending from very small droplets of a few microns to drops of 300 µm or more in size. The details of the spectrum of course depend on the width of the atomizer orifice, the liquid and ambient gas properties, and the operation conditions of the atomizer. It is the aim of the present work to develop a technique for controlling the break-up of the fan-shaped sheets to influence the width of the drop size spectrum and the mean drop size.

In the literature we find only few papers dealing with the vibrational excitation of liquid sheets for controlling their disintegration. The group led by N. Dombrowski worked in this field. Their most important paper on the subject may be [1], where they investigate the effect of nozzle vibrations on the drop size formed by water sheet break-up. Their results show that, at typical frequencies of some kHz, the mean size of the droplets may be affected by the vibrations. It is interesting to note that the frequencies and vibration amplitudes treated in [1] are of the same order as in our work. The authors point out that both forced and natural vibrations may have effects on the sheet break-up. A systematic study on the effects of forced vibrations is not given in the paper.

The present group previously reported on the development of this technique in [2,3]. The results showed that the technique works better for liquids with higher dynamic viscosity than with lower viscosity, and that the technique can force the formation of sprays which consist of streams of practically monodisperse drops. It could be shown that the technique suppresses the formation of small droplets in fan-shaped liquid sheet break-up.

Our present paper introduces a new version of the experimental set-up, which is more compact and suitable for the practical application than the one used earlier for the preliminary investigations discussed in [2,3]. We then present a theoretical approach for calculating the sheet contour and the ligament formation as a function of the operating conditions of the atomizer. Thereafter we present experimental and theoretical results from investigations on the sheet formation and break-up, and on the final process of drop formation by break-up of the ligaments. We also present windows of the liquid flow rate and excitation frequency and amplitude, inside which the technique can be applied. Finally we put together the conclusions from our work.

Experimental Setup and Technique

The setup developed for the production and visualization of sprays under the influence of forced nozzle vibrations is shown in Fig. 1. The essential part of the setup is the shaker Brüel & Kjær 4809, which moves the nozzle at the end of the nozzle holder up and down. The frequency and amplitude of this oscillatory motion of the nozzle may be adjusted by means of the signal generator and a power amplifier Brüel & Kjær 2706 (not shown in the sketch). The liquid is supplied to the conventional flat-fan nozzle from a pressurized vessel via a throttle valve through an elastic hose. The volume flow rate of the liquid through the nozzle is adjusted by the overpressure in the vessel and the throttle valve. The latter is located far enough upstream from the nozzle so that perturbations in the liquid flow die out before the liquid reaches the nozzle. It has been an essential result from our earlier work on this technique that the flow of liquid entering the nozzle must be as smooth and well controlled as possible in order to allow for a regular formation of the sheet and, consequently, of the ligaments which finally disintegrate into the spray droplets.

For visualizing the sheets and sprays, the flow is illuminated from behind by means of a stroboscope. The stroboscope is synchronized with the shaker via a frequency splitter, which produces integer fractions of the signal frequency applied to the shaker and enables a synchronous operation of the shaker and the stroboscope at a constant – and adjustable – phase shift. This technique allows for the production of standing pictures of the sheet disintegration and drop formation processes.

Measurements on the performance of this setup for the present investigations are carried out on the basis of image processing. They concern the sheet opening angle, the diameter of the ligaments, and the size of the droplets. The ligament break-up process was visualized with a high-speed camera Hadland Ultra 8+1, which provides sequences of images of the disintegrating ligaments for observing the break-up mechanism, which was to be identified in the present work.

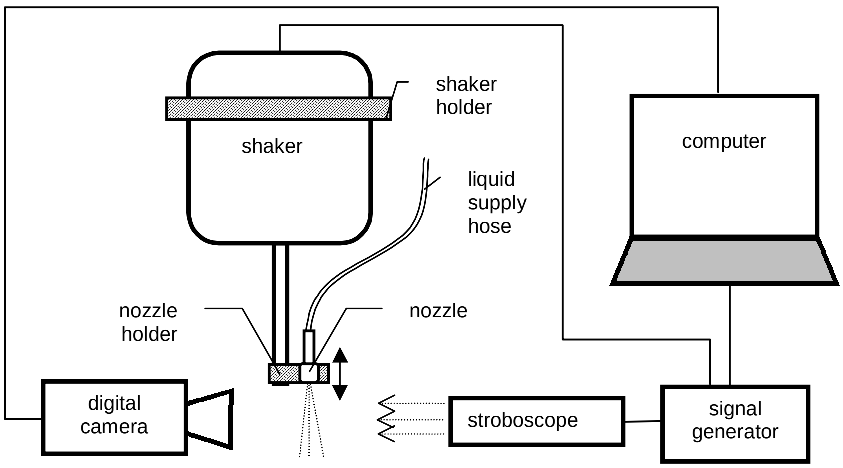

Figure 1. Sketch of the experimental setup for the production and visualization of the sprays under forced nozzle vibrations. The nozzle may be any conventional flat-fan pressure atomizer.

Theoretical considerations

In the present section, we consider theoretically the formation and propagation of the liquid sheet and ligaments. The idea behind the calculations is the treatment of the ligament formation as a process of withdrawal of liquid from the sheet. A photograph of a liquid sheet disintegrating under the influence of axial nozzle vibrations is shown in Fig. 2. The experiment depicted was carried out with water at the flow rate of 11 l/h, at the vibration frequency of 3.2 kHz, the amplitude 0.03 µm, and with the Lechler flat-fan atomizer 632.304 made of brass, which exhibits the orifice slit width of 0.4 mm and the nominal spraying angle of 60°.

We consider the liquid sheet with the opening angle θ and the flow-rate equivalent constant radial velocity V_0. The thickness of the sheet at the radial distance r from the nozzle pole is h, and the flow rate of liquid through the nozzle Q. For a liquid sheet filling the whole opening angle θ, we can express the liquid volume flow rate as

$$Q = V_0 h r \theta \ , \tag{1}$$

and the sheet thickness consequently as $h=Q/(V_0\, r\theta)$. This sheet thickness we will assume to persist in the regions where the sheet has narrowed due to the disintegration, so that it does not fill the whole opening angle any more (see Fig. 2). Therefore the propagation of a fluid element in the radial direction may be expressed by

$$r = r_0 + V_0 t \ , \tag{2}$$

where r_0 is the location on the sheet where it starts to narrow, and t is time. Substituting this into the equation for the sheet thickness, we obtain

$$h = \frac{Q}{V_0 \theta (r_0 + V_0 t)} \ . \tag{3}$$

The arclength of the fluid structures at the distance r from the nozzle pole may be expressed as $l_* = r\theta$, so that we have

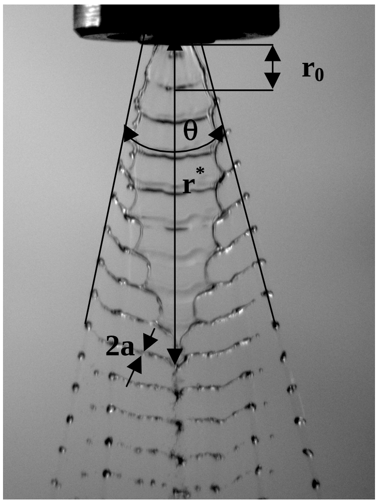

Figure 2. Photograph of a liquid sheet of water at the flow rate of 11 l/h, influenced by vibrations with the frequency 3.2 kHz and the amplitude 0.03 µm. Lechler flat-fan atomizer 632.304 with slit width of 0.4 mm.

$$l_* = (r_0 + V_0 t)\theta \quad , \tag{4}$$

while the width of the sheet persisting at the same distance r from the nozzle pole is denoted by l. The velocity of withdrawal of the ligament from the sheet we consider as constant and calculate it as

$$U = \frac{dl_*}{dt} = V_0\theta \quad . \tag{5}$$

We now consider the liquid volume entrapped between two wave fronts, which is given by the expression Q/f. The rate of volume withdrawal from the sheet by the ligament formation process we express as $\pi a^2 U$, which, due to Eq. (5), is equal to $\pi a^2 V_0 \theta$. In each moment we can describe the volume of liquid entrapped in the remaining sheet between two ligaments by its width l, its thickness h, and its length V_0/f in the radial direction, so that we get lhV_0/f for this remaining sheet volume. This expression we rewrite to obtain

$$l\frac{V_0}{f}\frac{Q}{V_0\theta(r_0 + V_0 t)} = \frac{Ql}{f}\frac{1}{\theta(r_0 + V_0 t)} \quad . \tag{6}$$

The volume balance of liquid is given by the fact that the liquid withdrawn from the remaining sheet reduces the remaining volume with ongoing time. The balance reads

$$\frac{d}{dt}\left[\frac{Ql}{f}\frac{1}{\theta(r_0 + V_0 t)}\right] = -\pi a^2 V_0 \theta \quad . \tag{7}$$

Integrating this equation under the assumption that the radius a of the ligament is constant in time, we obtain

$$\frac{l}{r_0 + V_0 t} = -\pi a^2 V_0 \theta^2 \frac{f}{Q} t + \frac{l_0}{r_0} \quad . \tag{8}$$

We calculate the initial value l_0 of the sheet width using the equation

$$Q = l_0 h_0 V_0 \quad . \tag{9}$$

Furthermore we know that the initial sheet thickness h_0 must be given by the equation $h_0 = Q/(V_0\theta r_0)$. This finally yields the expected relation

$$l_0 = \theta r_0 \quad . \tag{10}$$

From Eqs. (8) and (10) we obtain for the width of the remaining sheet between two ligaments the expression

$$l(r) = r\theta - \pi a^2 \theta^2 \frac{f}{Q} r(r - r_0) \quad . \tag{11}$$

This result can readily be compared with the result from visualization experiments on the disintegrating liquid sheet. It predicts that the width of the sheet decreases parabolically with the radial distance r from the nozzle.

Another sheet property of interest for our technique is the break-up length, i.e., the length of the coherent sheet to full break-up into ligaments, denoted r_* in Fig. 2. The radial distance from the nozzle pole to the position where the sheet is fully disintegrated is reached when the length l of the remaining liquid sheet has become zero. This requirement leads us to the expression

$$r_* = r_0 + \frac{Q}{\pi a^2 \theta f} \quad . \tag{12}$$

This equation can be used for calculating the ligament diameter if the distance $r_* - r_0$ is measured as a function of the opening angle of the sheet and of the other relevant parameters. The ligament diameter $d_l=2a$ then reads

$$d_l = 2\sqrt{\frac{Q}{\pi\theta f\left(r_* - r_0\right)}}\ , \tag{13}$$

which can be calculated for known values of $r_* - r_0$ and θ obtained by image processing with known Q and f. At the same time we can measure the ligament diameters on the images directly and depict both values in a diagram for comparison. We will see in the following section that, obviously, our above calculations were carried out under the right assumptions.

Experimental results and comparison with theory

We investigated the process of sheet formation, propagation and break-up, we looked at the process of ligament formation, and finally investigated the process of ligament break-up into drops. In this sequence, which corresponds to the physical process in the experiment, we present our results, partly in comparison with theory.

Sheet formation, propagation and break-up

Under conventional conditions of operation of flat-fan atomizers, one expects the formation of a fan-shaped liquid sheet. In our earlier publications [2,3] we showed that flow rates through flat-fan atomizers required for their conventional operation are far too high to achieve the control effect on the drop formation we presently want. For our technique to work properly, we must avoid the dynamic interaction of the liquid sheet with the gaseous ambient medium. In order to do this, we keep the liquid flow rate (or the Weber number) small enough to ensure a good efficiency of our vibrational control of the sheet disintegration. It was shown in [3] that, under such flow conditions, the sheet does not spread monotonically, but contracts by the surface tension. Only when the vibrations are applied does the sheet spread monotonically. The opening angle formed under excited conditions is depicted in Fig. 3 as a function of the product of frequency and amplitude of the forced nozzle vibrations. We see that the opening angle converges to a single value for all frequencies investigated, once the product $s_0 f$ has assumed a sufficiently large value. This value of the opening angle is about 20° smaller than the nominal spraying angle of 60° of the nozzle. This is due to the fact that in our measurements we took the angle between straight lines through the boundary drops in the sprays as the angle θ, which is somewhat smaller than the angle of the sheet we would measure close to the nozzle exit. These measurement results are an important basis for the further analysis of the spray formation process.

As a next issue we look at the length $r_* - r_0$ of the intact sheet downstream from the nozzle as a function of the operating parameters. In Fig. 4 we see that the measured quantities depend linearly upon each other for all flow rates and liquid properties involved. It is a plausible result that the intact sheet length tends to decrease as the opening angle increases, since the increased opening angle accelerates the sheet break-up due to the larger velocity of liquid withdrawal.

The evolution of the liquid sheet width as a function of the radial distance from the nozzle pole was predicted by Eq. (11) to be parabolic. Figure 5 depicts a comparison of a calculated sheet contour with a result from the visualization. It is seen that the parabolic curve represents the sheet contour quite well. We can conclude from this agreement that the above calculations are reasonable.

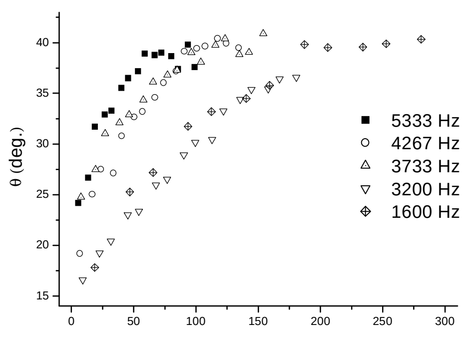

Figure 3. Opening angle of the sheet as a function of amplitude and frequency of nozzle vibrations (Q=11 l/h, 25% wt. glycerol in water, nozzle Lechler 632.304).

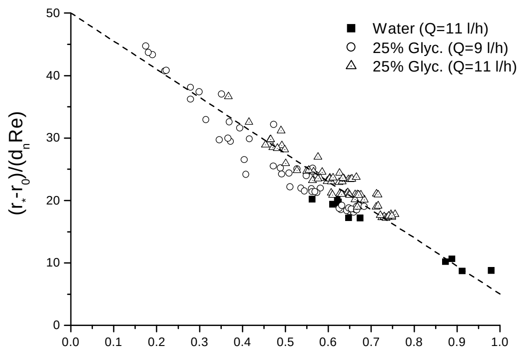

Figure 4. Non-dimensional sheet length to complete break-up as a function of the opening angle of the sheet for two different liquids and two flow rates (d_n – nozzle slit width, Lechler 632.304).

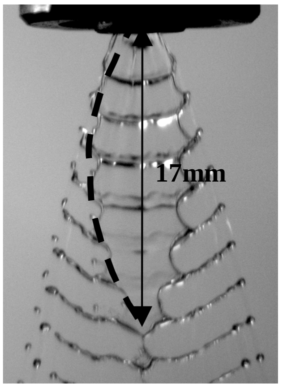

Figure 5. Water sheet at Q=11 l/h, f=4.267kHz, s_0= 0.03 µm with nozzle Lechler 632.304 in comparison with sheet contour calculated by Eq. (11).

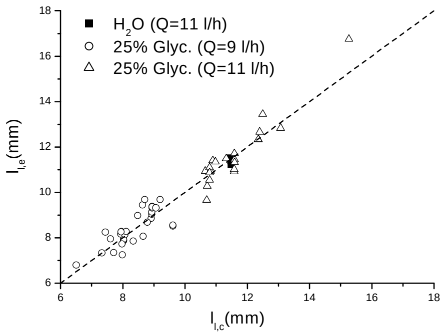

Figure 6. Comparison of ligament length as measured directly and as calculated from measured experimental parameters by Eq. (14).

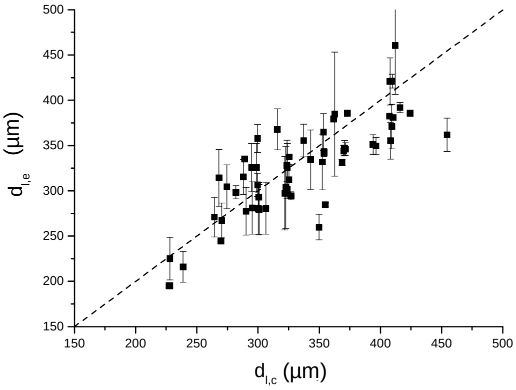

Figure 7. Diameter of ligaments as measured and calculated for 25% wt. glycerol in water at the flow rates Q = 9 and 11 l/h.

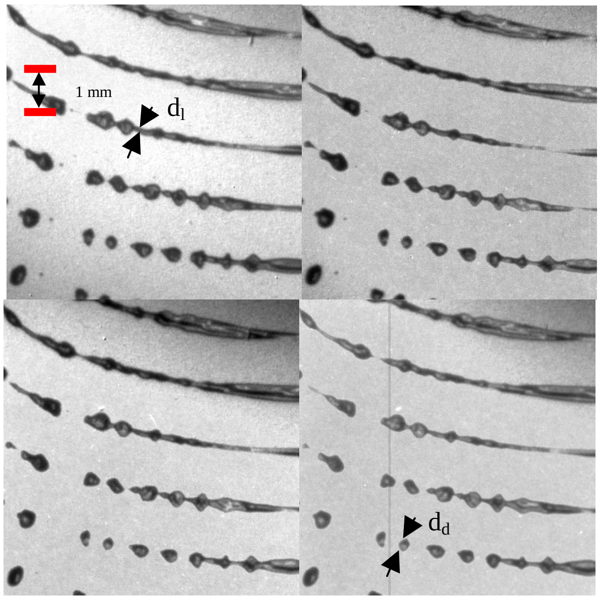

Figure 8. Visualization of the disintegration of ligaments formed by forced sheet disintegration (water flow rate 20 l/h, excitation frequency 4.8 kHz, excitation amplitude 0.03 µm, time between two images 166.6 µs, nozzle Lechler 632.364, manufactured from PVDF, slit width 0.6 mm).

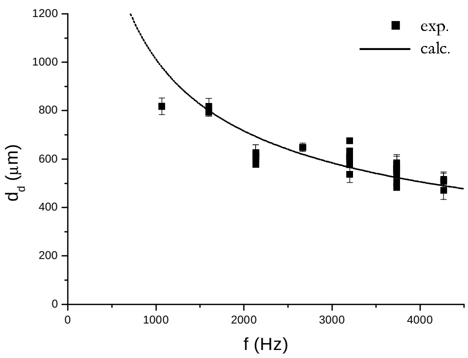

Figure 9. Drop size as a function of the excitation frequency for 25 %wt. glycerol in water.

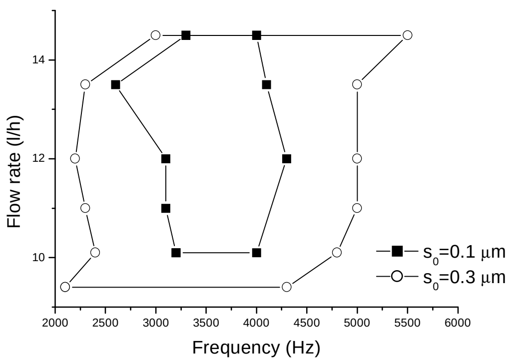

Figure 10. Parameter window for application of the present technique with water (nozzle Lechler 632.304).

Ligament formation

The ligaments are formed by withdrawal of liquid from the narrowing liquid sheet. The ligaments can be characterized by their cross-sectional radius and their final length achieved at the end of the intact sheet length r_*. This length is predicted by Eq. (4) for the case $r=r_*$, where we denote it l_l, as per

$$l_l = r_0\theta + \frac{Q}{\pi a^2 f} \ . \qquad (14)$$

In this equation we can again introduce the measured values of r_0, θ, Q, a and f, to calculate l_l, and, on the other hand, we can measure l_l directly on the images under the given conditions. The comparison of these two data sets for the ligament length is depicted in Fig. 6. We see that the results agree well. The same applies to the diameter of the ligaments, which are depicted as measured and calculated via Eq. (13) in Fig. 7.

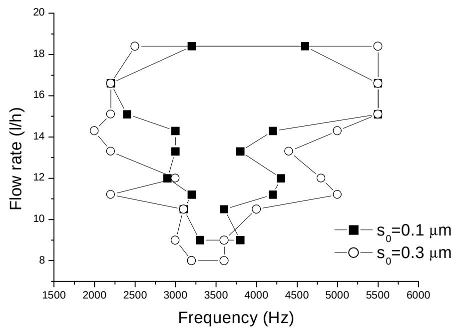

Figure 11. Parameter window for application of the present technique with 25% wt. glycerol in water (nozzle Lechler 632.304).

Drop formation by ligament break-up

The final step to drop formation is the disintegration of the ligaments into droplets. This process we visualized using the high-speed camera Hadland Ultra 8+1. An example of the disintegration of ligaments for a water sheet formed at the flow rate of 20 l/h through the nozzle Lechler 632.364 (made of PVDF) is shown in Fig. 8. Time increases from left to right on the images in steps of 166.6 µs. On the images we measured the ligament and droplet diameters. We assumed beforehand that the mechanism that leads to the break-up of the ligaments may be the Rayleigh mechanism. For this case we know that the mean drop size we can expect must be about 1.9 times the ligament diameter, since the most unstable wavelength of a disturbance is about 4.5 times the ligament diameter [4]. An evaluation of about 10 measured values yielded the result that, on average, we get a nondimensional drop size $d_d/d_l = 1.82 \pm 0.32$. This result lies well inside the expected range for the Rayleigh mechanism, which is therefore clearly identified. In addition to this finding, it is of interest to quantify the influence of the excitation frequency on the drop size produced. This dependency is depicted in Fig. 9 for 25 % wt. of glycerol in water at the flow rates between 9 and 11 l/h and the amplitude of the vibrations ≤ 0.05 µm. We see the expected trend of the drop size to decrease with increasing frequency at the given conditions.

Operation windows

Finally we investigate the parameter windows inside which the presented technique of forced sheet disintegration works. The criterion for the workability is the regularity of the wave fronts and ligaments formed. The results for two values of the nozzle oscillation amplitude s_0 and for two different liquids are shown in Figs. 10 and 11. We see that the windows are wider for the liquid with the higher viscosity, particularly in terms of the flow rate, and also wider for the higher vibration amplitude, which is in agreement with earlier observations.

Conclusions

A technique for the controlled formation of flat-fan sprays from conventional pressure atomizers by forced sheet disintegration is presented. The technique relies on the formation of regularly shaped ligaments from wave fronts on the liquid sheets, and on the Rayleigh-type break-up of the ligaments into droplets. The technique is suitable for producing sprays with very narrow drop size spectra (shown in our earlier work [3]), and it allows the drop size to be controlled by the excitation frequency. Future work will include the investigation of conical sheets under the influence of nozzle vibrations and will represent the parameter windows in a universal form.

Acknowledgements

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References

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