The vibrational excitation of conical liquid sheets for the control of spray formation

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The present paper reports about progress in the development of a technique for controlling the disintegration of conical liquid sheets and the resultant formation of sprays by vibrational excitation of the atomizer. For this work, a "conical sheet generator" was specially designed and manufactured in order to have sheets with well controlled opening angle and thickness at the orifice. The conical sheets are excited by liquid flow pulsations resulting from the axial vibrations of the sheet generator, as previously done with flat-fan sheets. The sprays obtained with this technique are composed from monodisperse drop streams with very narrow drop size spectra. Similar to what was seen in flat-fan sheets excited by nozzle vibrations, the shape of the sheet is influenced by inertial forces, while the drop formation mechanism is capillary. The drop formation can be described by the Rayleigh approach. The ranges of flow rates, excitation frequencies, and nozzle vibration amplitudes suitable for application of the technique are quantified. Conical sheets produced by commercial pressure-swirl atomizers are also investigated. The results show that the influence of the nozzle vibrations moves the global drop size spectra in these sprays towards smaller drop sizes.

1. Introduction

In three previous publications at ILASS Europe conferences, Brenn and co-workers (2000, 2001, 2002) showed that liquid sheets produced by commercial flat-fan pressure atomizers can be forced to break up into regularly shaped ligaments by the influence of axial vibrations of the atomizer. These ligaments then break down into droplets by the Rayleigh mechanism, so that sprays composed of nearly monodisperse drop streams may be formed. It was shown in the earlier work that the properties of these sprays depend on frequency and amplitude of the vibrational excitation of the atomizer, the properties of the liquid, and the geometry of the nozzle. Such sprays may consist of relatively large droplets. The drop size, however, of course depends largely on the width of the orifice slit. On the basis of these results we now investigate the influence of nozzle vibrations on liquid sheets with other geometries also, such as conical sheets in the present paper. We will show that the above technique can be applied to these sheets also, resulting in the formation of conical sprays with well defined drop size spectra. The technique is additionally applied to commercial pressure-swirl atomizers. The influences of axial vibrations of these atomizers on the liquid sheet formation and breakup are quantified.

2. Conical sheet generator

For the purpose of producing conical liquid sheets with controllable properties, a "conical sheet generator" was constructed. The device, shown in Fig. 1, is made of brass and consists of a body (1), a conus (2) with a stem (3), and a distributor (4) with screw (5). The liquid is supplied to the device through the distributor (4). The opening angle of the conus is 60°, its diameter at the orifice is 12mm. The width of the annular slit from which the liquid emerges can be adjusted by varying the axial placement of the conus on the stem. The slit width suitable for application of our technique is limited to values between a minimum and a maximum, given by the dominance of surface tension or inertial forces on the liquid sheet. Around the circumference of the body of the device, four screws are placed for adjusting the conus into a position coaxial with the body.

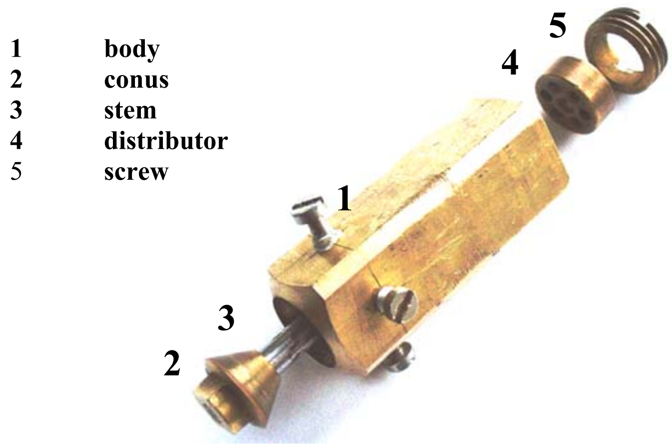


Fig. 1 The conical sheet generator developed for the present experiments.

3. 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. 2. The essential part of the setup is the shaker Brüel & Kjær 4809. On its moving part, the conical sheet generator is mounted so as to enable a forced sinusoidal axial motion of the sheet generator with adjustable frequency and amplitude. The shaker is operated with a signal generator and a power amplifier Brüel & Kjær 2706. The liquid to be investigated is supplied to the sheet generator from a pressurized vessel through a plastic hose. The liquid flow rate is adjusted by varying the driving overpressure in the vessel. For visualizing the breakup processes, the sheets and sprays are back-lighted by a stroboscope. The stroboscope is synchronized with the signal generator 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 – but adjustable – phase shift. This technique allows for the production of standing pictures of the sheet disintegration and drop formation processes. The breakup processes were visualized with a high-speed camera Hadland Ultra 8+1, which provides sequences of images of the disintegrating sheet for observing the breakup mechanism. It was one purpose of the present work to identify the physical nature of this mechanism. Measurements of the drop size distribution were carried out using a DANTEC two-component phase-Doppler anemometer in standard configuration. The amplitude of the sheet generator vibrations as a function of signal frequency and voltage amplitude applied was determined by measuring the velocity of the sheet generator motion using a DF-LDA system. In all experiments presented here, water was used as the test liquid.

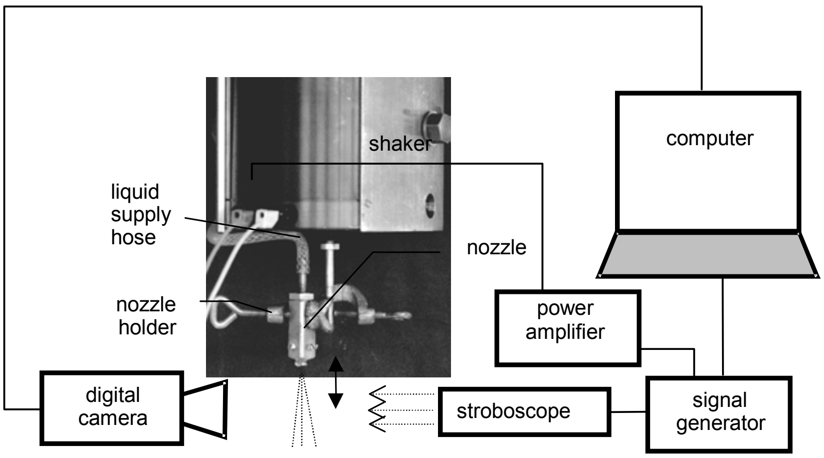


Fig. 2 Sketch of the experimental setup for the production and visualization of conical sprays by forced vibrations of the conical sheet generator. Other types of pressure atomizer may also be used.

4. Experimental results

According to the physical behavior of the liquid sheet, two different regimes of the flow may be identified by their Weber numbers. These regimes quantify the dominance of either surface tension or inertial forces. When the flow rate through the sheet generator is low, the surface tension force dominates, and a closed "water bell" as shown in Fig. 3 is formed. An increase of the flow rate, so that a threshold Weber number is exceeded and the inertial forces dominate, leads to the formation of an open conical sheet, as seen in Fig. 4. This is observed in the present case for sheet velocities U of about 5 m/s with an initial sheet thickness of 100μm, corresponding to We=35. The spray flow cross section exhibits the shape of a circular ring, so that it is axially symmetric. A typical drop size distribution, which turns out the same for each point around the circumference of the ring, is shown in Fig. 5.

When the conical sheet generator is excited with low amplitudes s_0 less than 0.25μm in the water bell regime, waves may be formed on the surface of the water bell, as shown in Fig. 6. An increase of the amplitude above 0.25μm forces the water bell to open and disintegrate into the form of streams of nearly monodisperse droplets, as shown in Fig. 7. Typical sets of drop size spectra measured with PDA in this kind of spray are shown in Fig. 8.

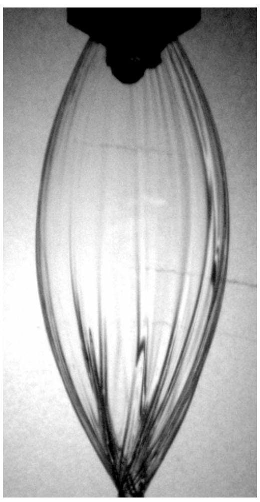


Fig. 3 Closed water bell (We<35).

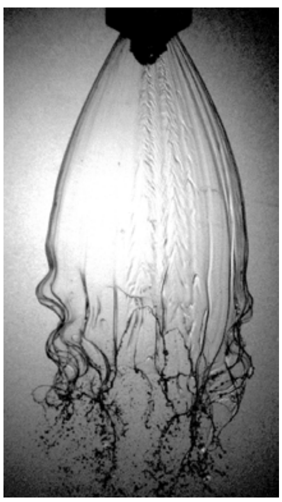


Fig. 4 Open water bell (We>35).

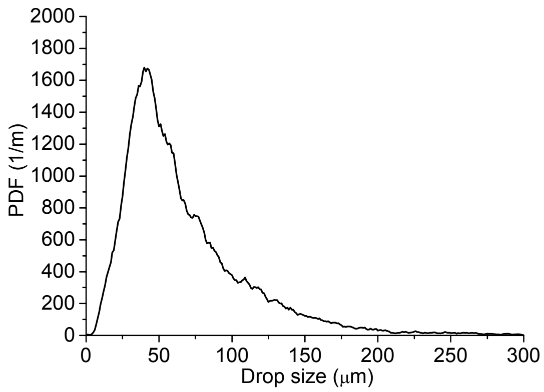


Fig. 5 Drop size PDF of a conical spray, flow rate 50l/h, sheet thickness at orifice 200μm.

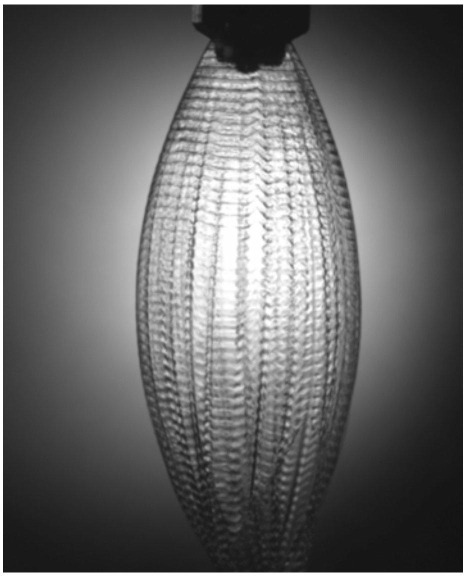


Fig. 6 Water bell under excitation with s_0<0.25µm, f=4.4kHz, sheet thickness at the orifice 100µm, U=2.9m/s.

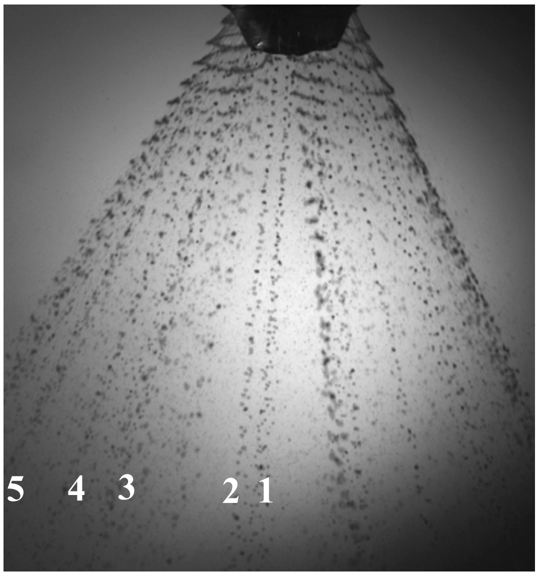


Fig. 7 Disintegration of the water bell under excitation with s_0>0.25µm, f=4.4kHz, sheet thickness at the orifice 100µm, U=2.9m/s.

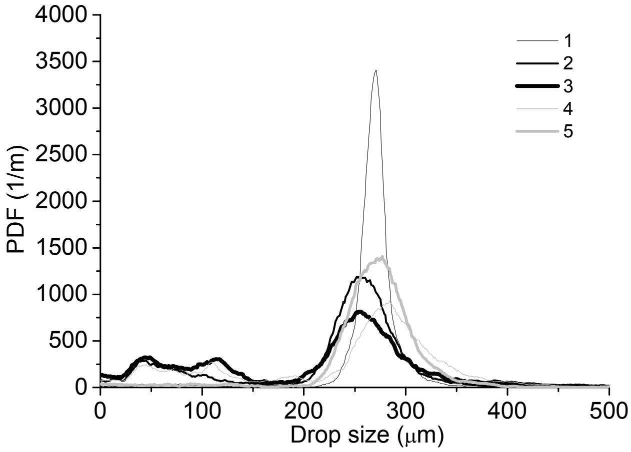


Fig. 8 Size distributions in drop streams from forced disintegration of the water bell in Fig. 7 (s_0>0.25µm, f=4.4kHz, sheet thickness at the orifice 100µm, sheet velocity U=2.9m/s).

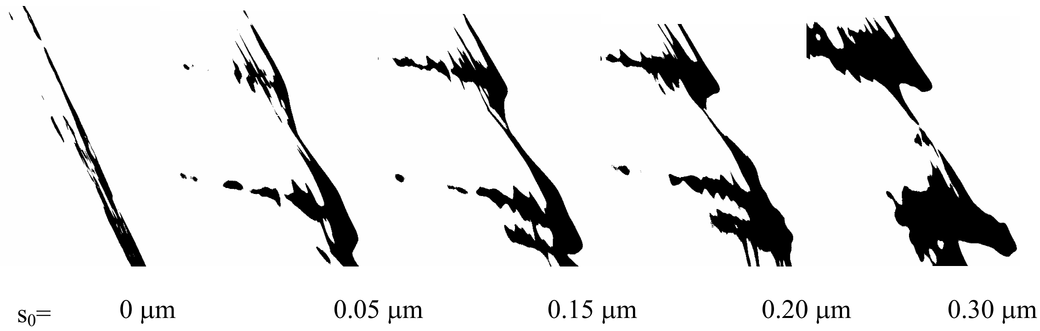


Fig. 9 Surface wave formation on a conical sheet, 20mm downstream from the nozzle, varying excitation amplitudes s_0. Magnification factor 10. Flow rate 60l/h, f=4.5kHz, slit width 100µm.

The influence of the excitation amplitude on the formation of surface waves is shown in Fig. 9. The microscopic images of the sheet surface shapes were taken by means of the high-speed camera. Figure 10 shows the mechanism of drop formation. The vibrational excitation of the sheet causes the formation of rims on the sheet surface. These rims behave similar to free ligaments and, through the growth of waves, break down into ensembles of droplets of nearly the same size. Figure 11 shows that a capillary mechanism is one of the steps in the formation of the drops. The uniformity of the drop sizes produced from conical sheets by this process is comparable to what was observed in the forced breakup of flat-fan sheets. However, a contribution to the drop size spectra comes from the breakup of the portions of the sheet which are not accumulated in the rim before its breakup.

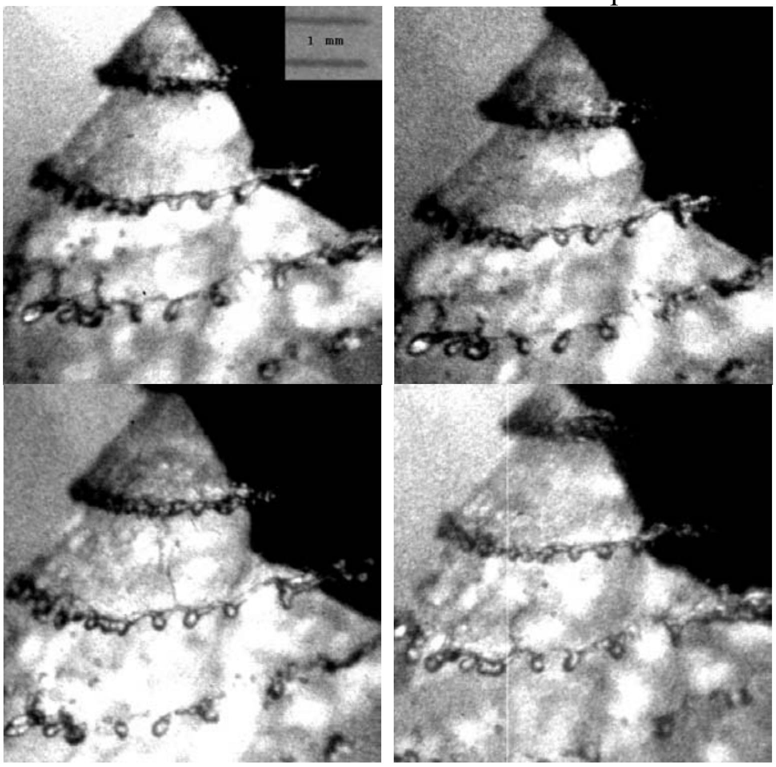


Fig. 10 Microscopic images of the conical sheet close to the orifice.
Flow rate 60l/h, f=4kHz, time step between the images 60μs.

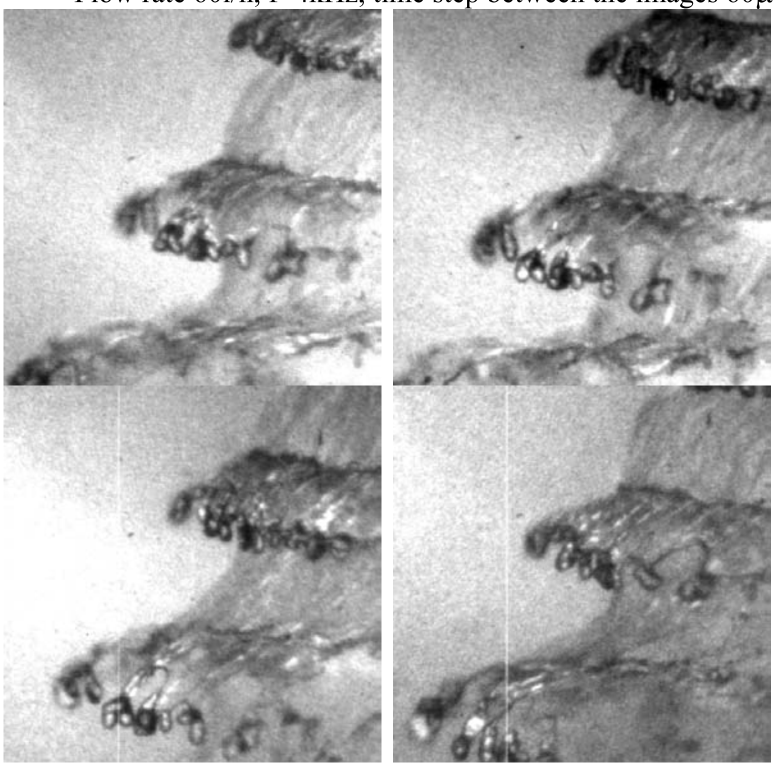


Fig. 11 Microscopic images of the conical sheet farther downstream from the orifice.
Flow rate 60 l/h, f=4kHz, time step between the images 60μs.

The operation window of our technique of forced sheet breakup was investigated with water as the test liquid. We found that it is applicable in a range of frequencies between 3 and 5kHz and flow rates from 40 to 80l/h for the case that the slit width at the orifice is 100µm. The results are shown in Fig. 12.

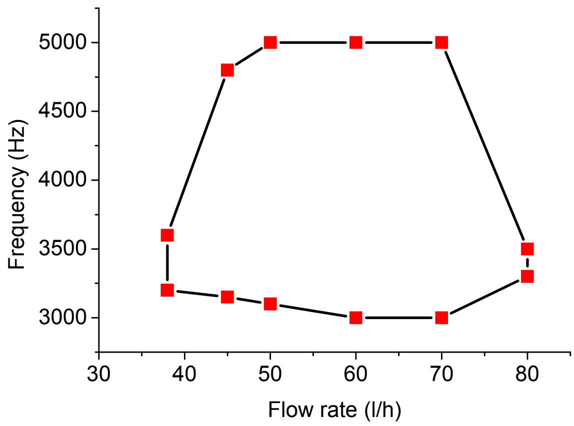


Fig. 12 Operation window for the conical nozzle.

5. Theoretical considerations

The sketch in Fig. 13 shows the simplified geometry of the disintegrating conical sheet. The sheet is characterized by its full opening angle 2α and its breakup length l^*. On the surface of the sheet, waves are produced due to the pulsating liquid flow through the orifice caused by the excitation of the sheet generator. These are not shown in the sketch.

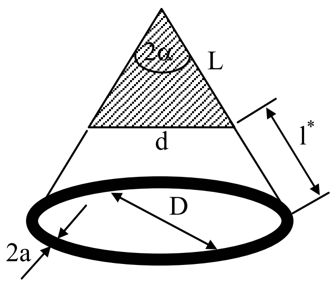


Fig. 13 Geometry of the brass cone (shaded), the conical sheet of length l^*, and the rim.

At the end of the sheet, a free rim is formed, which is clearly seen in Fig. 10. This rim is formed within the time $t=1/f$, and its breakup is the mechanism of formation of the larger droplets dominating the spectra in Fig. 8. The finer size fractions are produced by the – undesired – breakup of the remaining parts of the sheet which are not accumulated in the rim. The aim of our simple computations is now to predict the size of the larger drops. We first calculate the thickness of the sheet at its end, close to the breakup zone. The thickness of the conical sheet moving at constant velocity is given by the equation

$$h(l) = \frac{d \cdot h_s}{2 l_p \sin\alpha} \quad , \tag{1}$$

where l_p is the distance of a point on the sheet from the pole of the flow, h_s the slit width at the orifice of the sheet generator, which marks the sheet thickness at $l_p=L$, and d the diameter of the brass cone at the orifice. Formulating l_p for a point at the end of the sheet with the sheet breakup length via $l_p^*=L+l^*$, we obtain the sheet thickness in the breakup zone as

$$h(l^*) = \frac{h_s}{1 + 2\left(l^*/d\right)\sin\alpha} \quad . \tag{2}$$

In Eq. (2), the ratio of breakup length to brass cone diameter l^*/d is unknown. It is obtained from visualization experiments. From Fig. 7, e.g., we see that $l^*/d \approx 1$. The rim at the end of the sheet grows during its lifetime by retraction of the edge of the sheet, which follows the equation

$$x_M(t) = \sqrt{x_0^2 + \frac{2\sigma}{\rho h} t^2} \quad . \tag{3}$$

In this equation, x_M denotes the location of the center of gravity of the rim [4]. Assuming that this location is initially $x_0=h/2$, and the rim accumulates the liquid volume $x_M \cdot h \cdot C$, where C is the circumference of the rim, we can formulate the liquid volume V_r contained in the rim after a time $T=1/f$ as

$$V_r = h \cdot \sqrt{\frac{h^2}{4} + \frac{2\sigma}{\rho h}\frac{1}{f^2}} \cdot C \quad , \tag{4}$$

where h is given by Eq. (2). Equating this volume with $\pi a^2 C$, where a is the radius of the rim, and assuming that the rim disintegrates into droplets according to the Rayleigh mechanism, we find the equation for the drop size as

$$d_d = 1.89 \cdot h \cdot \sqrt{\frac{2}{\pi}} \cdot \left(1 + \frac{8\sigma}{\rho h^3}\frac{1}{f^2}\right)^{1/4} \quad . \tag{5}$$

Calculating the drop diameter by Eq. (5) and comparing the result with results from measurements on photographs, we obtain the data in Fig. 14. In view of the simplifications made, the agreement is acceptable.

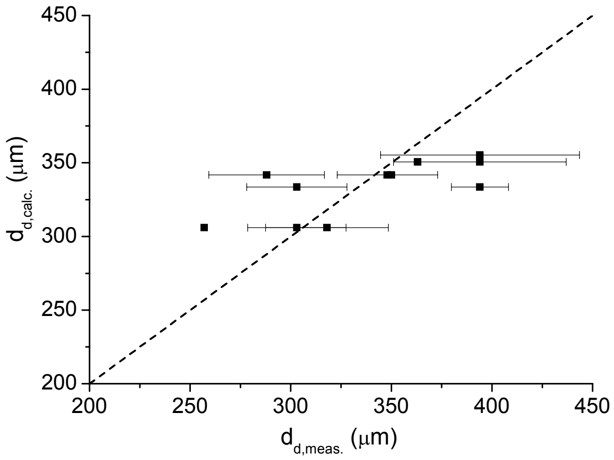
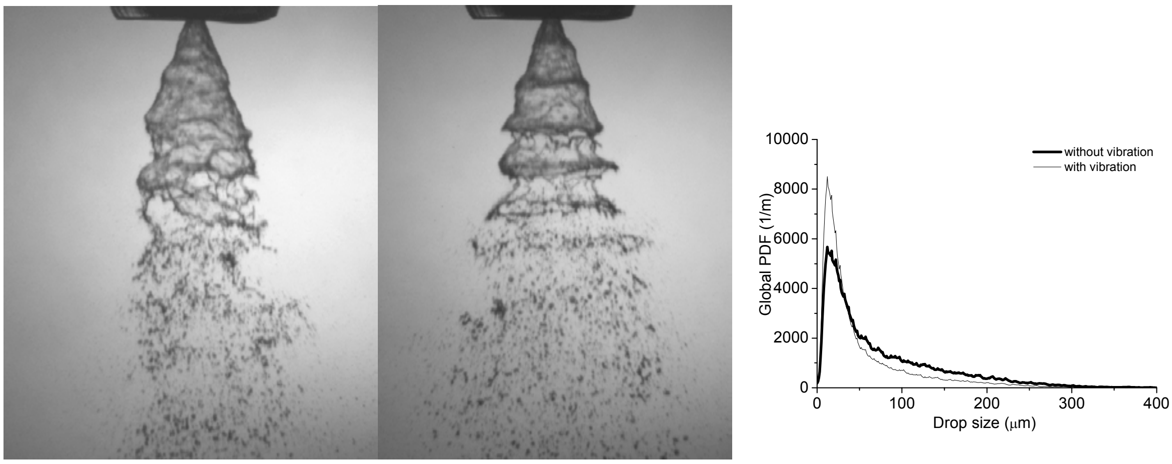


Fig. 14 Comparison of drop sizes as calculated with Eq. (5) and measured on images from the high-speed camera used for the visualization of the sheet breakup.

6. Behavior of a commercial pressure-swirl atomizer

Figure 15 shows the influence of vibrational excitation of a commercial pressure-swirl atomizer on the conical spray produced. Waves on the surface of the sheet are visible. The measured global drop size distributions shown in Fig. 15c reveal that the nozzle vibrations cause changes of the drop size spectra, enhancing the formation of small droplets. A similar result was found in the earlier work Brenn et al. (2001) also [2]. We can conclude from this result that, in principle, commercial pressure-swirl atomizers are suitable for use with our technique. In the experiments it was found, however, that the frequency bands suitable for use with these atomizers are very narrow, so that virtually single frequencies at certain flow rates can be used only. With commercial pressure-swirl atomizers we found the same behavior as with other types of atomizer and with our conical sheet generator in the sense that small Weber numbers of the liquid flow through the nozzle are required in order that the technique can work properly.



(a) (b) (c)

Fig. 15 Sprays produced with the pressure-swirl atomizer Lechler 216.324, slit width 1mm, flow rate of water 25l/h, (a) – without excitation, (b) – with excitation at f=4kHz and s_0<0.25μm, (c) – global drop size spectra without and with excitation.

7. Conclusions

Experiments with a conical sheet generator excited by axial vibrations of controlled frequency and amplitude showed that nearly monodisperse sprays may be formed under the influence of the vibrations. Similar success was achieved earlier with the forced disintegration of flat-fan sheets. The drop size distributions obtained in the conical sprays may be even more uniform than obtained with flat-fan nozzles. The drops are predominantly formed by breakup of free rims at the end of the excited conical sheets. The drop formation mechanism may be considered as similar to the Rayleigh mechanism. Investigations carried out with commercial pressure-swirl atomizers showed that vibrations of the atomizer lead to a wavy shape of the sheet and shift the drop size distribution towards smaller droplets.

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