Influence of the air and liquid channel thickness on the oscillation behavior of an air-blasted liquid sheet

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In this paper an experimental study is presented which focuses on the influence of air and liquid channel widths on the oscillation of an air-blasted liquid sheet. Some preliminary results were already presented at the ILASS-Europe 2002 Conference. They confirmed the sheet oscillation dependence on liquid thickness and also revealed a dependence on air channel width. The study has been extended, including additional combinations of air and water configurations. A total of three liquid sheet widths and five air channels have been tested.
Measurements indicate, in agreement with previous results, that the oscillation frequency decreases with sheet thickness. However, it has been demonstrated that this decrease is not linear. It follows instead a square root dependence. It has also been shown that the measurements collapse if they are plotted as a function of a Momentum Ratio that includes the sheet width. The oscillation frequency also decreases as the air channel width is increased. Unfortunately, the characteristic length controlling the process does not seem to be the channel thickness, and has not been unambiguously determined.

1. Introduction

In spite of the fact that spray flows are common in a large variety of industrial and daily applications, the knowledge of the basic mechanisms that cause the primary break-up of the liquid flow into a cloud of droplets is still incomplete. Studies on atomization phenomena in liquid sheets are very extensive and were initiated in the XIX century. However, the first reported experimental investigations specifically centered on large aspect ratio liquid sheets surrounded by high-speed air co-flows to produce an air blast atomization date from 1980 [1, 2]. The analysis of these studies was mainly phenomenological, with a main interest in predicting the influence of the physical properties on the spray cloud characteristics. Recently, some other experimental works [3, 4] have been published, targeting the analysis in the region close to the nozzle exit. It has been demonstrated that it is in this region where the instabilities develop and grow, finally causing the liquid sheet break-up. However, there are still some aspects in which a definite consensus has still not been reached. A main reason is that in many cases, comparisons have been established among data obtained in different experimental set-ups, and consequently conditions were not identical (e.g. turbulence levels, nozzle profiles, sheet span etc.). In the present experiments, in the same facility measurements have been obtained varying water and air channel widths, to ascertain their influence on the sheet oscillation. A point that has been clarified is the convenience of introducing the momentum flux ratio (MFR) or the momentum rate (MR) as a controlling parameter [5].

2. Description of the Experimental Setup and Flow Conditions

This experimental investigation has been conducted in the large aspect ratio planar air-blast atomizer already described in detail in [4] and [6]. In short, water is injected at the top of the nozzle head and exits vertically forming a sheet with a span of 80 mm. Air flow is also introduced from the top following a settling chamber with two honeycombs and a wire mesh screen to smooth the flow. All the water and air nozzle profiles have been contoured fitting 6^{th} order polynomials to ensure uniform and parallel air and water velocity profiles at the exit. The air channels are located at both sides of the liquid nozzle in a “sandwich-type” configuration.

Air channels have been tested with exit widths of d_g = 3.45, 10, 17.25, 26 and 35mm, corresponding to contraction ratios of 15, 5.1, 3, 2 and 1.5, respectively. For the liquid sheets, three different widths have also been tested, d_l = 0.5, 0.7 and 0.9 mm, yielding contraction ratios of 16, 11.4 and 8.9, respectively. The experimental facility allowed a water volumetric flow rate ranging from 60 to 640 l/h. According to this, for each d_l the water velocity is limited from $0.42 < U_l < 4.44$ m/s, $0.29 < U_l < 3.17$ m/s and $0.23 < U_l < 2.47$ m/s, respectively. The resulting Reynold numbers, with d_l being the characteristic length, vary from $Re_l = 210$ up to $Re_l = 2250$. The air flow has been generated by a 5.5 kW fan controlled by a Danfoss frequency regulator, enabling air velocities as high as U_g = 75 m/s, except for the air channels of d_g = 35 mm, where the maximum velocity was only of 65 m/s.

In the experiments, the oscillation frequency has been measured using a laser diffraction method, as described in [7], as a function of both water and air velocities. The light emitted by a 5 mW laser diode has been pointed into a photo-diode, and a Tektronix TDS3012 oscilloscope has analyzed the voltage signal. The oscilloscope is equipped with an FFT module (TDS3FFT), which automatically calculates the frequency power spectrum of the signal.

3. Effects of the water channel width

To analyze the effects of a variation in the sheet thickness, three different nozzles have been tested combined with the 3.45 mm and the 35 mm air channel configurations. For each combination frequency measurements have been obtained for a complete panel of air and water velocities. The whole set of measurements for the 3.45 mm air channel is presented in Fig. 1. In this graphic, a different symbol represents each one of the air exit velocities. Each sheet thickness corresponds to a different color: 0.5 mm black filled symbols, 0,7 mm grey symbols and 0.9 mm hollow symbols. This nomenclature is kept in all the figures in this section.

Analyzing the curves in Fig. 1 it is clear that for a given air velocity, the oscillation frequency decreases with sheet thickness. However, a very interesting fact, that to our knowledge had never been reported previously, is that the dependence is not linear, but scales with the square root of the sheet thickness. Another clear feature is that the frequency maxima in the curves for a fixed air velocity correspond to water velocity values that increase as the sheet thickness decreases. This phenomenon responds to the fact that it is more difficult to induce sinusoidal oscillations in thicker sheets with more inertia, that tend to enter in what Mansour and Chigier [7] denote as zone C for lower velocity values. From these observations, a procedure can be devised to collapse the oscillation curves for the three water sheets for each air velocity. Effectively, this can be accomplished normalizing the oscillation frequencies multiplying them by the square root of the sheet thickness, and rescaling the water velocities in the horizontal axis in the same way. Results of these operations are displayed in Fig. 2.

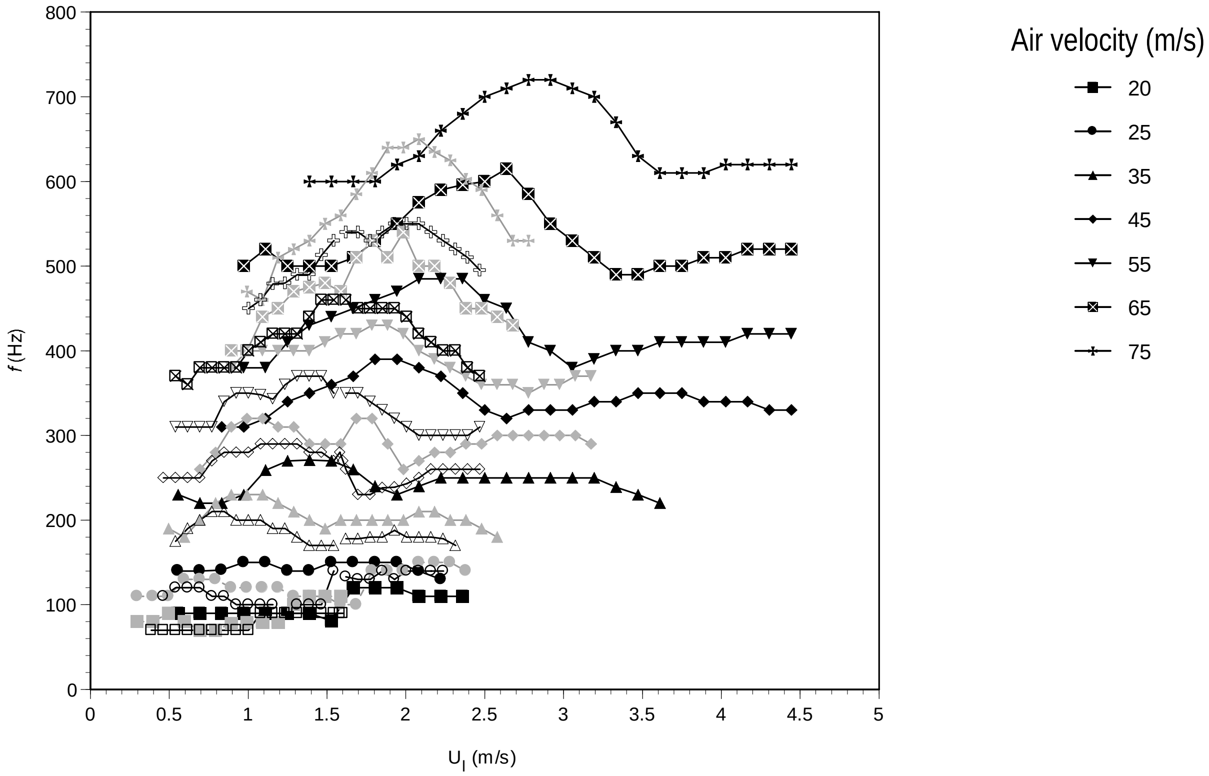


Fig. 1. Frequency measurements for an air channel of 3.45 mm and three liquid channel widths (0.9 mm, 0.7 mm and 0.5 mm). See nomenclature in text.

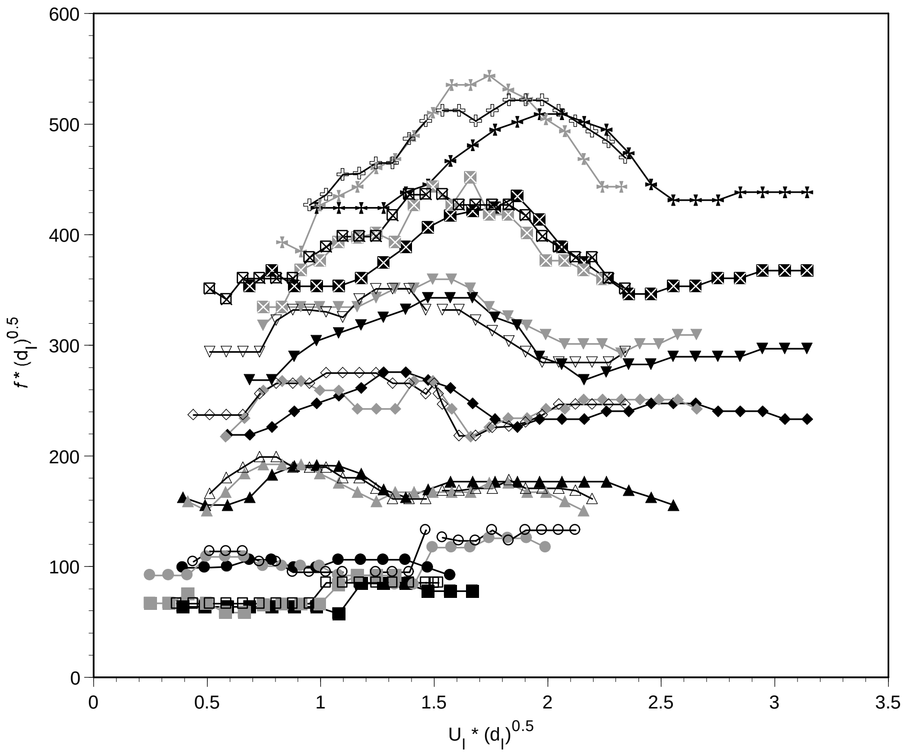


Fig. 2. Normalization of the frequency measurements in Fig. 1 using the square root of the liquid sheet thickness.

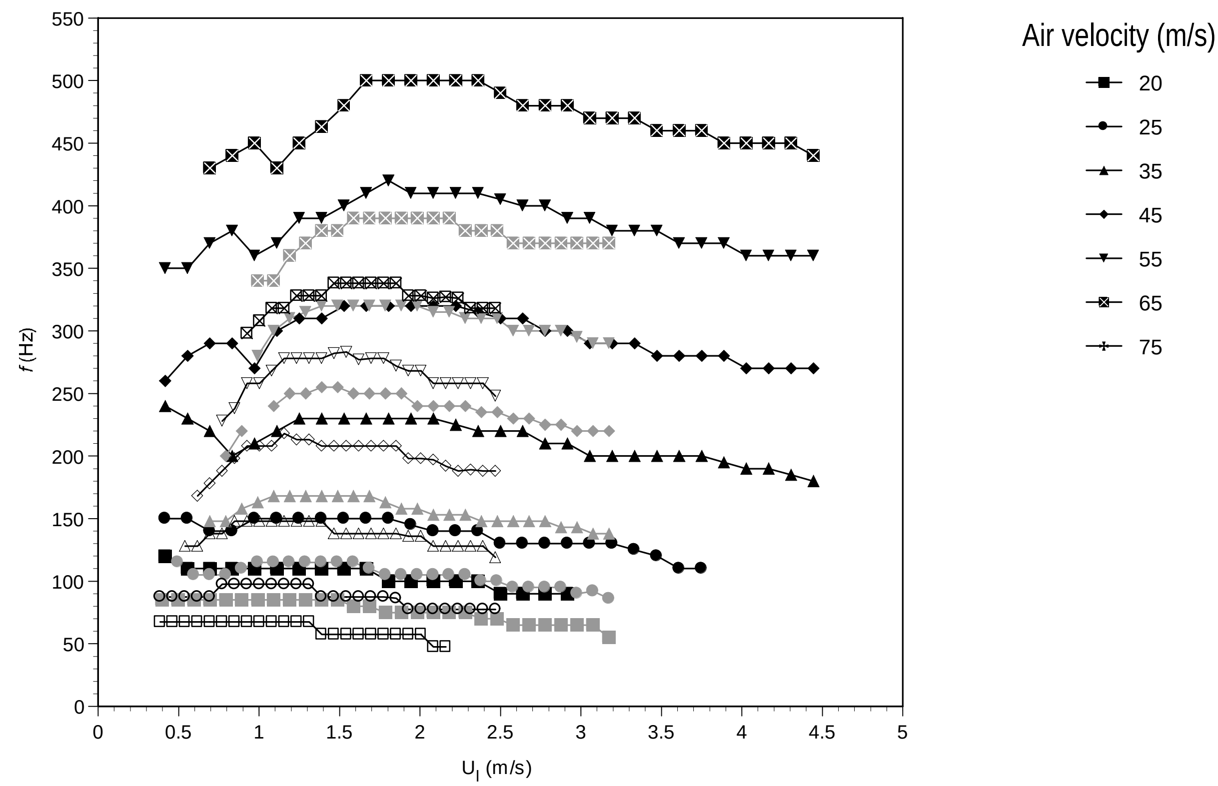


Fig. 3. Frequency measurements for an air channel of 3.45 mm and three liquid channel widths (0.9 mm, 0.7 mm and 0.5 mm). See nomenclature in text.

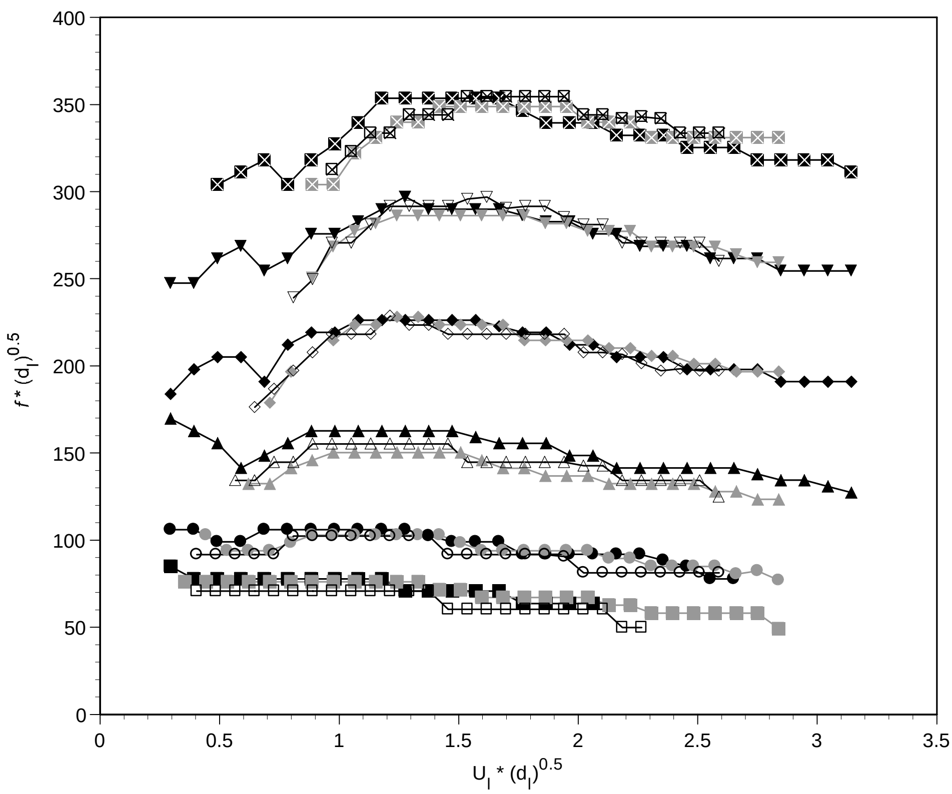


Fig. 4. Normalization of the frequency measurements in Fig. 3 using the square root of the liquid sheet thickness.

It can be verified that for each air velocity, the curves for all the different sheet thickness become very close to each other.
It has to be realized that the water velocity rescaling is indeed indicating that the oscillation is dependent on the total water momentum defined by $\rho_l U_l^2 d_l$. Consequently, a relevant dimensionless group to characterize the oscillation including sheet thickness effects will be the Momentum Ratio MR.
The same steps have been followed for the measurements obtained with the 35 mm air channels. The "raw" oscillation frequency values are presented in Fig. 3. The plots rescaled with the square root of the sheet thickness are depicted in Fig. 4. Again, it is evident that for each air velocity, the frequency curves for the three sheets collapse into a single one very satisfactorily.
Once known the oscillation dependence on sheet thickness, dimensionless groups can be formed to compact the plots. Pending to ascertain the dependence on the air channels, two groups are tentatively proposed: MR for the ordinate axis, defined by $(\rho_g U_g^2 d_g)/(\rho_l U_l^2 d_l)$ and a Strouhal number for the abscissa axis, defined by

$$St = \frac{f\sqrt{d_l\, d_g}}{U_g - U_{\min}}$$

The occurrence and meaning of U_{min} is explained in [4]. Forming these parameters and replotting Fig. 2 and Fig. 4, the resulting Fig. 5 and Fig. 6 are obtained. All the curves therein have been nicely collapsed into a single one. However the St values in both figures are not the same, indicating that the air channel width is not the appropriate parameter to account for the air dependence.

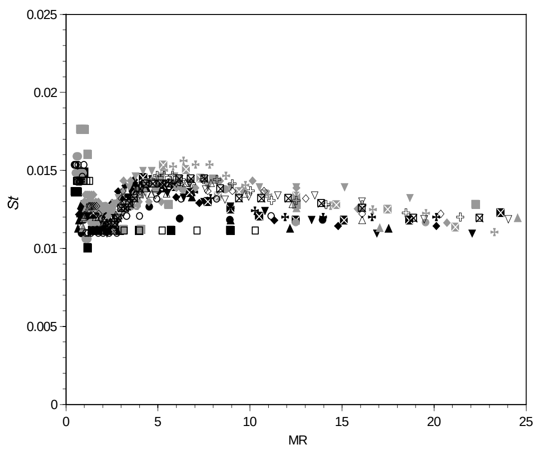


Fig. 5

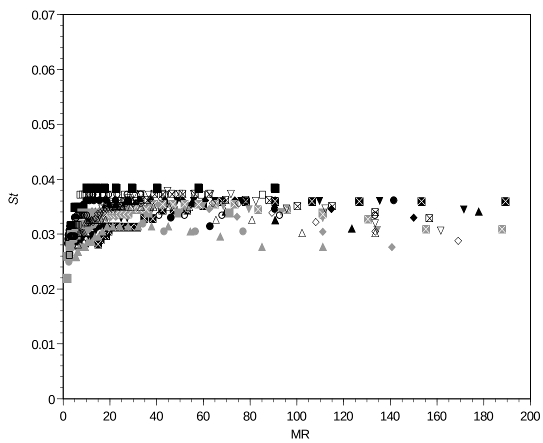
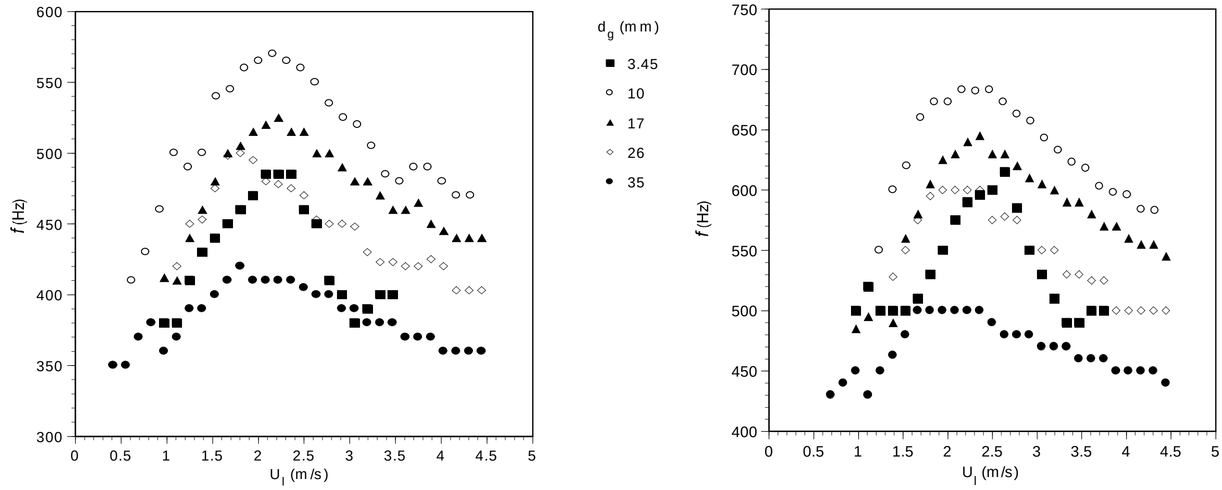


Fig. 6

Figs. 5 and **6.** Collapse of the frequency measurements using the Strouhal number and the momentum ratio. Fig. 5 corresponds to an air channel thickness of 3.45 mm and Fig. 6 to 35 mm

4. Effects of the air channel width

To determine the influence of the air channel width, different contoured side pieces have been mounted in the atomizer head, resulting in exit widths of 3.45 mm, 10 mm, 17 mm, 26 mm and 35 mm. Frequency measurements have been obtained with this configurations, for the whole range of air and water velocities. Results, however, do not show a single and clear



a **b**

Fig. 7: Frequency measurements for different air channel widths and an air exit velocity of **a)** 55 m/s; **b)** 65 m/s.

trend to fully explain the role of the air in the break up process. Measurements are presented in Fig. 7a for an air velocity of 55 m/s and Fig. 7b for 65 m/s. Although it is not shown in this paper, for all the geometries a linear dependence of oscillation frequency on air velocity has been verified, in agreement with many previous experiments (see *e.g.* [4], [6])

In any case, some conclusions can be drawn from Fig. 7. For all velocities, and with exception of the 3.45 mm channels, oscillation frequencies decrease as the channel width increases, with lowest values corresponding to the 35 mm channels, *i.e.*, to the widest case. Only the 3.45 mm case appears to behave anomalously with frequency values lower than expected. However, a satisfactory collapse of the different curves cannot be achieved by normalizing either with the channel width or with its square root.

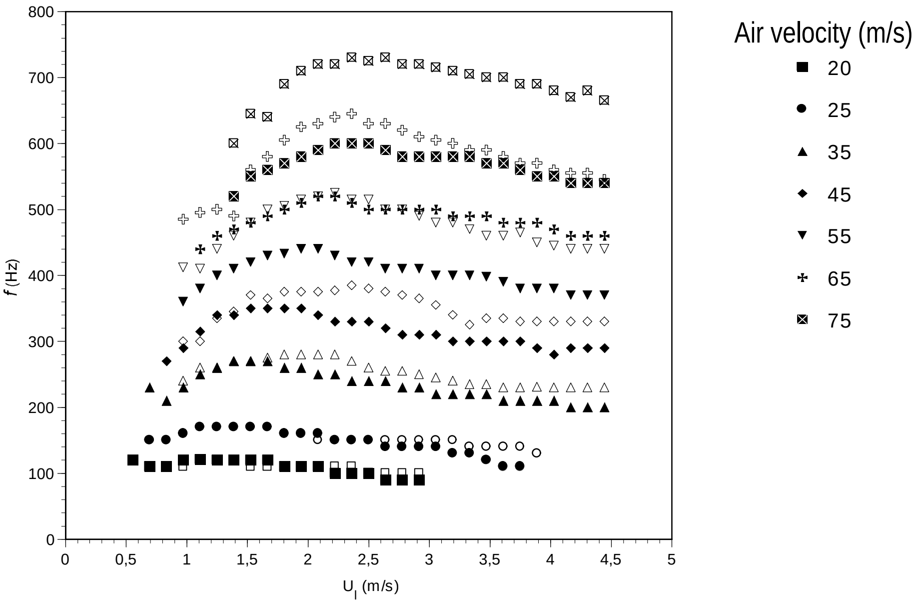


Fig. 8: Frequency values with a 17 mm air channel with contoured profile and divergent profile

Normalization with the square root of the channel width does indeed overlap the 26 mm and the 35 mm measurements, but not the frequencies obtained for the rest of the widths.

Results in the previous section already pointed out that the air channel width did not seem to be the relevant parameter. Indeed, the difficulties in collapsing the graphs in Fig. 7 seem to confirm this hypothesis. An immediate alternative would be to analyze the air boundary layer thickness. Unfortunately, although measurements of this parameter were taken, their precision was not high enough to provide reliable conclusions.

A tentative argument to explain the unexpected behavior of the 3.45 mm air channels could be that in this case the air streams are thinner than the oscillation amplitude of the liquid sheet before the break up.

Some final tests are indicative of the importance of the nozzle geometry irrespective of the actual exit width. Measurements were obtained for an air channel thickness of 17 mm but with two different nozzle contours that configure a contraction and a slightly divergent outlet.The measured frequencies are depicted in Fig. 8. Filled symbols correspond to the divergent contour, while their hollow counterparts correspond to the contoured nozzle exit. Although for low air velocities the impact on the oscillation frequency is negligible, as velocity increases the difference between the two geometries becomes increasingly accentuated, with higher frequency values corresponding to the convergent case. This effect should be attributed to a thinner boundary layer, resulting in a stronger air/water interaction, and evidences again the importance of this parameter as opposed to the channel width.

5. **Conclusions**

An experimental study has been performed to analyze the effect of water and air channel widths on the oscillation of an air-blasted liquid sheet. Oscillation frequency measurements obtained for different liquid sheet thickness have served to clarify the influence of the sheet width in the process. The oscillation frequency decreases with sheet thickness. However, it does not scale linearly, but with a square root dependence. Besides, the oscillation depends on the liquid total momentum, so that an appropriate non-dimensional parameter to define the problem results to be a momentum ratio of the form $(\rho_g U_g^2 l)/(\rho_l U_l^2 d_l)$ where l is a characteristic length related to the air streams. In the calculations here presented, the air channel width d_g has been used. Regarding the influence of the air channels, it has been observed that, as a general rule, the oscillation frequency also decreases with their width. However, in this case, neither a linear nor a square root dependence on thickness can be derived from the measurements. The evidences indicate that the magnitude that controls the process is not the channel width. It is likely that the influent parameter has to be the air boundary layer thickness. To complete the study, measurements of this parameter have been obtained. Unfortunately, they have not been acquired with the required accuracy to yield reliable results. It is expected that soon improved measurements will both help to understand the prominent role of the air breaking up the liquid sheet and enable the completion of this research.

6. **Aknowledgments**

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7. References

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