SOME ASPECTS ON THE OSCILLATION OF AN AIR-BLASTED LIQUID SHEET

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ABSTRACT

Continuing with the analysis of the longitudinal oscillations of an air-blasted liquid sheet, some new results are presented trying to explain this phenomenon. Two aspects have been specifically addressed. Based on the ideas of Brenn et al. [1] a novel double beam diffraction technique has been implemented to measure the wavelength of the sheet oscillation, analyzing the correlation between the signals recorded for each beam. After designing and assembling the experimental set up, ranges of applicability have been studied, and measurements have been obtained. The results have been compared with those obtained by directly measuring on still images recorded with a CCD camera. Simultaneous measurements of wavelength and frequency enable the possibility of discussing some aspects about the wave propagation velocity. Simultaneously, the already ongoing study on the influence of the air channel thickness on the longitudinal oscillation frequency has been advanced, measuring this parameter for different configurations, and matching the results with numerical simulations of the air flow inside the channels.

1. INTRODUCTION

The liquid sheet configuration with or without coflowing air streams has become in the last years almost a canonical benchmark test flow to study basic atomization phenomena. However, despite its simplicity, apparent insignificant details can lead to erroneous conclusions, especially when universality is claimed. Limiting the references to air assisted or air blasted configurations, the first reported experimental investigations specifically centered on large aspect ratio liquid sheets date from 1980 [2, 3]. A large number of manuscripts were published in the next two decades, *e.g.* the well-known papers by Mansour and Chigier [4,5], or Stapper and Samuelsen [6] among many others. Up to date there are some facts that have been systematically confirmed and are generally accepted (linear dependence of the sheet longitudinal oscillation with air speed, decrease of the break up length as the air velocity increases, etc.). However, there are 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 (turbulence levels, nozzle profiles, sheet span etc.). The fact is that the problem is not yet completely understood, the large aspect ratio air-blasted liquid sheet is still open to experimental research and there are many researchers working on it [7,8].

2. DESCRIPTION OF THE EXPERIMENTS

This experimental investigation has been conducted in the large aspect ratio planar air-blast atomizer already described in detail in [9]. Water injected at the top of the nozzle head exits vertically forming a sheet with a span of 80 mm. The sheet is confined by air streams that flow in parallel to each side of the liquid sheet. In this study, sheets with two different widths have been considered, 0.5 and 1.9 mm. The water volumetric flow rate has been varied from 60 to 640 l/h, which corresponds to velocities ranging from $0.42 < V_l < 4.44$ m/s and $0.11 < V_l < 1.17$ m/s for each one of the sheets. Air channels have been tested with exit widths of δ_g = 3.45, 10, 17.25, 26 and 35mm and a maximum flow velocity of V_a = 65 m/s.

The wavelength of the liquid sheet oscillation has been measured applying a novel double beam laser diffraction method, inspired in the frequency measurement technique described in Mansour & Chigier [5] and the method described in Brenn et al. [1]. To perform the measurements, two beams are generated by a couple of 4,0 mW laser diodes that propagate horizontally parallel to the liquid sheet, one on each side of it, pointing directly to two receiving photodiodes. When the oscillating sheet crosses the light beams, they are partially blocked, and a difference in light intensity is detected in the photodiodes, resulting in a periodic signal that, in these experiments, has been analyzed in a Tektronix TDS3012 oscilloscope. One laser serves as reference (laser 1 in Fig. 1) and is placed in the appropriate position to detect the maximum displacement of the liquid sheet under the oscillating movement. The other laser (laser 2) is initially placed at the same height as laser 1 on the other side of the liquid sheet, so that the two signals are completely out of phase.

During the measurement process, laser 2 is displaced downwards and out of the liquid sheet in order to position it detecting the next amplitude maximum of the sheet oscillation. While the laser is displaced in this way, the phases of the two signals detected by the photodiodes start approaching so that in its final position both signals are totally in phase. The vertical displacement corresponds to one half of the wavelength. Furthermore, any of the two signals can be used to simultaneously calculate the sheet oscillation frequency. An FFT module (TDS3FFT) added to the oscilloscope has been used for this purpose.

This procedure is useful to provide information about the sheet oscillation behavior. The actual measurements are not very accurate because the wavelength grows with downstream distance, and especially because the wave amplitude growth soon becomes non linear, the wave profile is distorted, as described in [4], and it is difficult to unambiguously define a wavelength distance. This drawback is illustrated in Fig. 1.

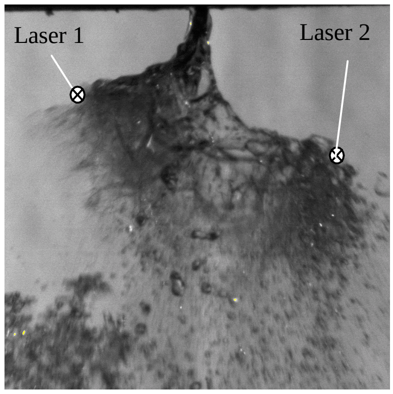

Fig. 1: oscillating sheet side view, with indication of the laser beam positions at the measuring point. The wave profile distortion compared to a sinusoidal shape is clearly visible.

The wavelength measurements obtained with the laser diffraction method have been compared with those obtained by direct measurement of still images acquired with a monochrome 12-bit Hamamatsu C4742-95-12ER CCD camera, with a resolution of 1024 x 1024 pixels and an exposure time of 139 μs. Values have been obtained for different combinations of air and water velocities, and for two different sheet thickness configurations, 0.5 and 1.9 mm, with a fixed air channel width of 26 mm.

3. RESULTS AND DISCUSSION

3.1. Wavelength results

Wavelength measurements have been obtained applying the two different techniques for the 0.5 and the 1.9 mm thick sheets. In general, it has been observed that the laser diffraction method seems to be superior to the direct image measurements for high water velocities, while the second method is more reliable for low water flows. For the thicker liquid sheet, a very good agreement has been achieved in the measurements obtained with both techniques, with an average relative difference between them of 3.5% and a maximum relative difference of 7.5%. For the 0.5 mm sheet, large discrepancies appeared for certain air/water combinations. In these cases, an average of measurements acquired with both methods has been considered in the analysis. In any case, it has to be indicated that the trends of the measurements for varying water and air velocities was the same in all the datasets.

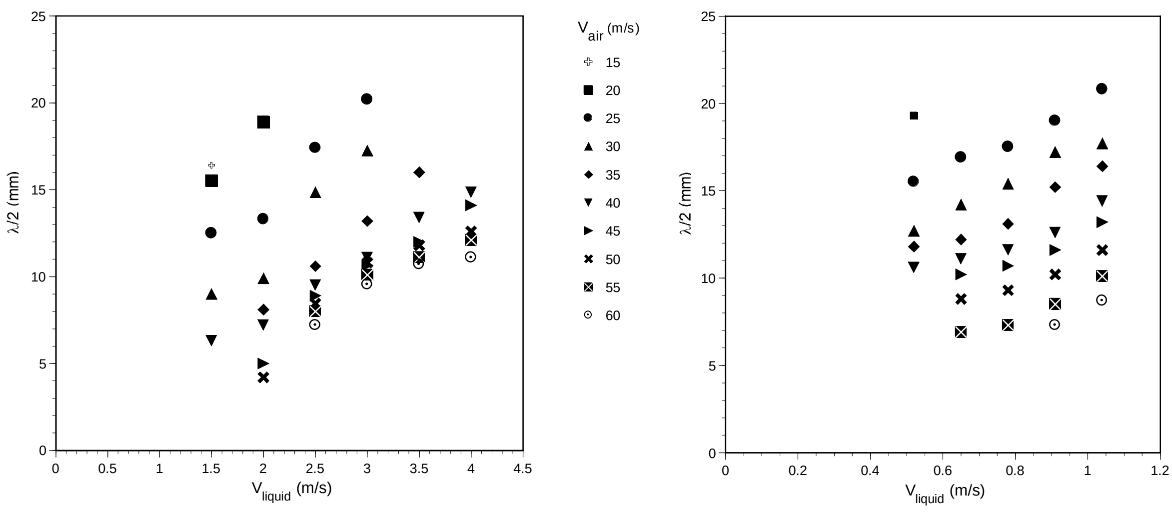

Fig. 2: Half wavelength of the sheet longitudinal oscillation as a function of the water velocity. Left: 0.5 mm thick liquid sheet. Right: 1.9 mm thick sheet.

Analyzing the results, some tendencies are clear. Wavelength increases with water velocity, as could be expected considering that the wave travels with the water flow (Fig. 2). At the same time, it decreases when the air velocity is increased (Fig. 3). This fact can be understood by considering that more energy is delivered to the system, which leads the oscillation to respond with shorter wavelengths.

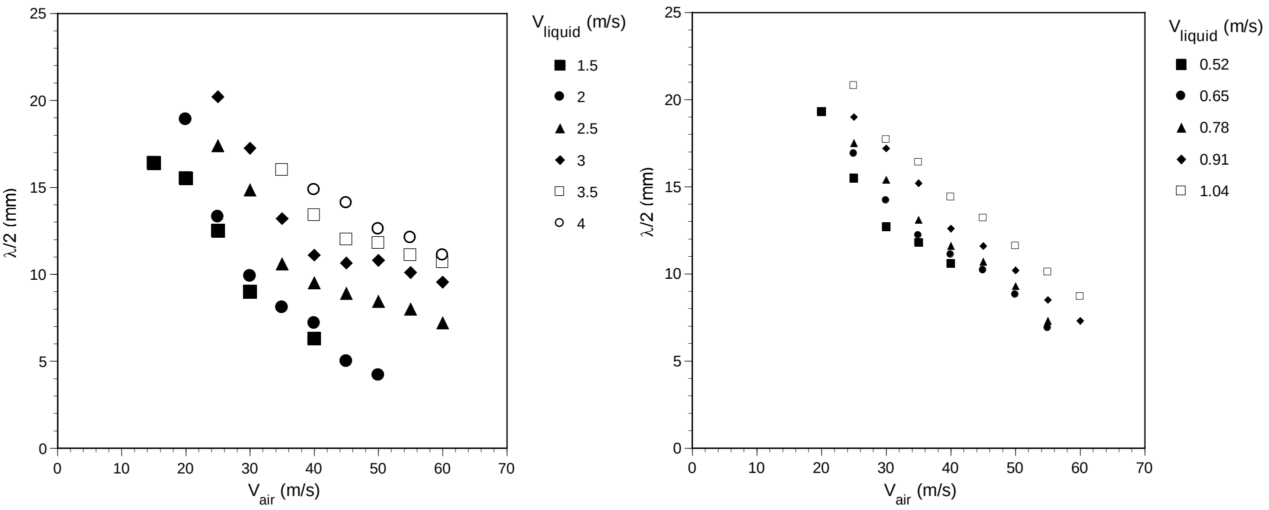

Fig. 3: Half wavelength of the sheet longitudinal oscillation as a function of the air velocity. Left: 0.5 mm thick liquid sheet. Right: 1.9 mm thick sheet.

Based on previous analysis to relate oscillation parameters with air and water velocities and sheet thickness [10], it is proposed to relate a non-dimensional group including the wavelength with the momentum ratio *MR* defined as $(\rho_a V_a^2 \delta_a)/(\rho_l V_l^2 \delta_l)$. Again, in accordance to Siegler et al. [10], an inverse square root dependence on sheet thickness is tested. To form a non-dimensional group another length is still required. Since the same air channels were used in both experiments, the square root of their thickness is selected, so that the resulting group is $\lambda/\sqrt{\delta_l \delta_a}$. When plotting the measurements as a function of the so defined non-dimensional groups, the graphic in Fig. 4 is obtained. Note that the values of λ therein are referring to the full wavelength, taken as the double of the measured half wavelength. Black symbols correspond to the 0.5 mm sheet, while the homologous grey symbols refer to the 1.9 mm thick one. The line fits all the values to a –1/2 power dependence, so that the following approximate relation has been obtained

$$\frac{\lambda}{(\delta_l \delta_a)^{1/2}} = \frac{k}{MR^{1/2}}$$

where *k* is a constant that, for the best fit results to be 22.07.

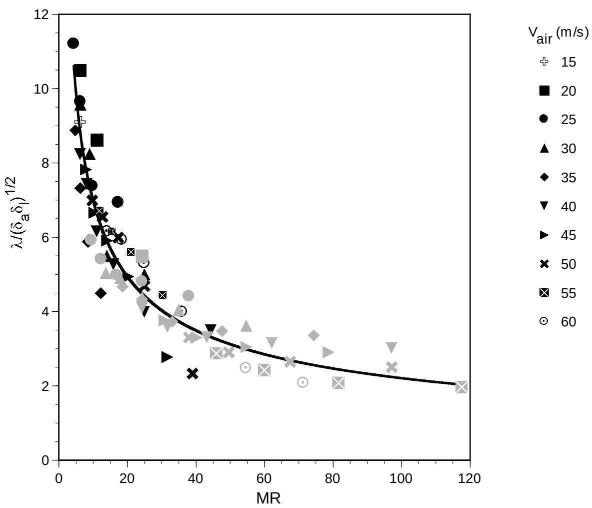

Fig. 4: Non-dimensional wavelength $\lambda/\sqrt{\delta_l \delta_a}$ as a function of the Momentum Ratio *MR*. Black symbols correspond to the 0.5 mm sheet. Grey symbols correspond to the 1.9 mm one.

Some comments are pertinent with respect to this dependence. An inviscid linear instability analysis will predict a quadratic dependence of the oscillation frequency on air speed (or relative velocity), a fact that is not confirmed experimentally. Lozano et al. [9] demonstrated that this erroneous prediction is due to neglecting the gas viscosity. In a similar way, the inviscid analysis prescribes a quadratic decrease of the wavelength when the relative gas-liquid velocity (that corresponds to the liquid velocity for sheets exiting into quiescent ambient air) is increased (see [8]). If viscosity is included in the air stream, and the linear dependence of the oscillation on air speed is recovered, the wavelength dependence on air or relative velocity is no longer calculated to be $1/V^2$ but $1/V$ as confirmed by the present experiments.

3.2. Propagation velocity

As frequency and wavelength measurements have been obtained, it is possible to calculate the wave propagation speed *c*. Again, it has to be noted that, as the wavelength grows with downstream distance while the frequency remains constant, so does the propagation velocity, that has hence to be considered local for the points where the wavelengths have been measured. The calculated values are presented in Fig. 5, where again the black symbols are for the 0.5 mm sheet and the grey ones for the thicker 1.9 water channel.

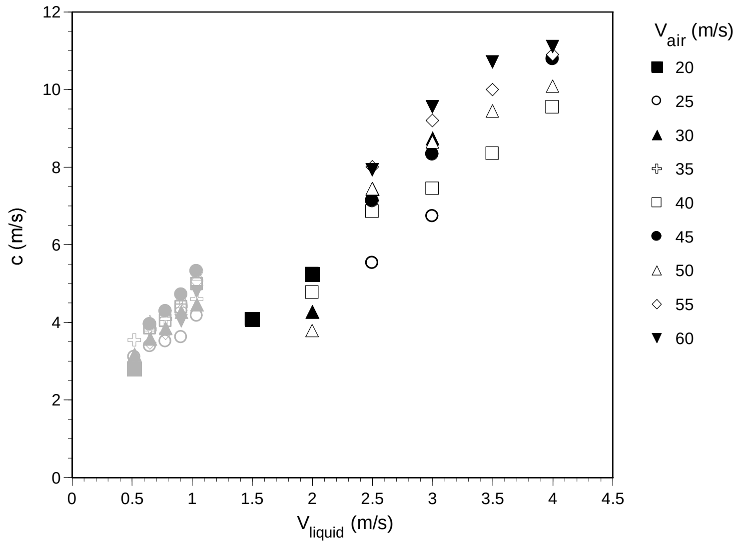

Fig. 5: Wave propagation speed as a function of liquid velocity. Black symbols correspond to the 0.5 mm sheet. Grey symbols correspond to the 1.9 mm one.

It can be observed that *c* increases with water velocity. This should be expected from the dependence found between λ and *MR* together with the relation between *MR* and the Strouhal number *St*, presented in [10]. For low water velocities (large *MR*), *St* can be assumed to be constant and in this case, *c* will depend linearly on the product $V_l\delta_l$. It is interesting to note that for both water sheets the calculated propagation velocity is higher than that of water at the nozzle exit. This might be caused by the acceleration undergone by the liquid sheet due to the interaction with the high-speed air coflow. In fact it would be necessary to measure the local liquid velocity to determine if the wave propagates with it or if the propagation is faster than that of the water sheet.

3.3. Effects of channel geometry

In previous experiments [10], the effect of the liquid sheet thickness on the longitudinal oscillation for similar nozzle geometry was ascertained. The role of the air channel shape and width was not so clearly determined, and some more efforts have been devoted to this issue. To decide the possibility of characterizing the air flow effect by just giving the channel exit width, tests were performed where oscillation frequency 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 already presented in [10] are displayed here again in Figure 6. Black symbols correspond to the divergent contour, while their gray 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. Therefore the channel exit width can not be the adecuate parameter charecerizing the influence of the co-flowing air.

After analyzing these results, the measurements for both geometries can be approximately brought to common values normalizing them by the square root of the channel contraction ratio defined as the ratio between the exit width and the width at the throat (minimum distance between the channel walls). For the studied cases, these ratios are 1.4 for the diffuser geometry and 1.03 for the non-diffuser one. However, if measurements are obtained mounting in the atomizer head air channels pieces for different exit widths, this ratio is not adequate to normalize the frequency measurements. This is indicates that there are two separate (although possibly related) effects, one dependent on the channel inner geometry and another likely tied to the flow conditions at the exit. A possible hypothesis is to relate the oscillation with the air boundary layer thickness. The main objection is that this is a parameter that depends itself on the air exit velocity, and if it is introduced to normalize the oscillation frequencies, the linear relation between frequency and air velocity is lost.

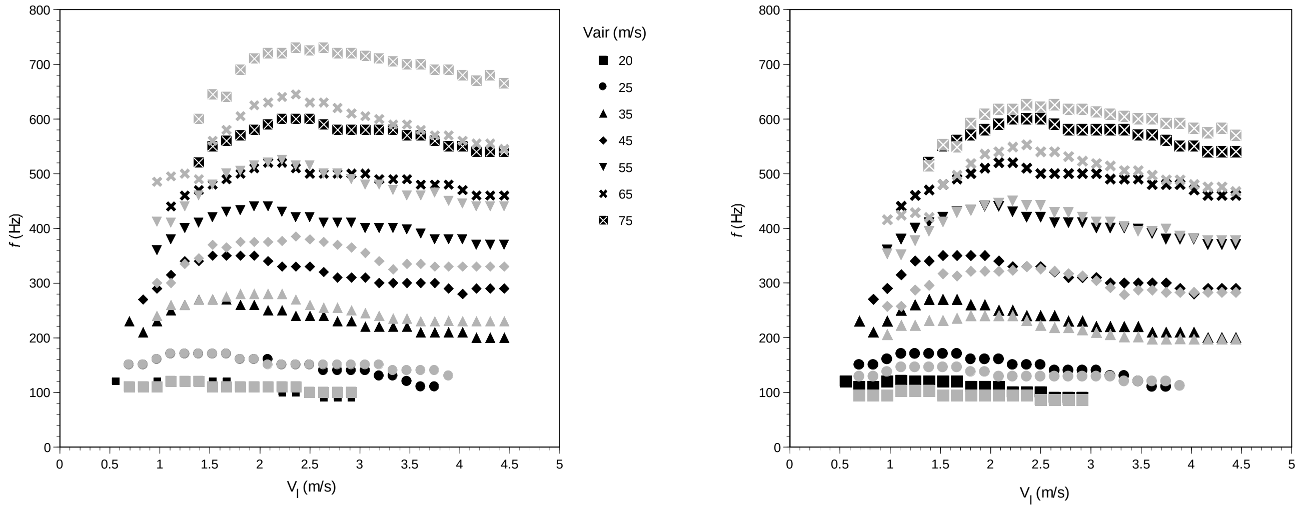

Fig. 6: Frequency values with a 17 mm air channel with contoured profile (gray symbols) and divergent profile (black symbols). Left: raw measurements; right: frequcy values corrected by the channel contraction ratio in each one of the configurations.

To further explore this issue, computational simulations have been performed to calculate the boundary layer thickness for different channel widths and air velocities. The predictions have been compared to Pitot probe measurements, yielding very good agreements. The square root of the boundary layer thickness has been used to attempt a frequency normalization for the different channels. Results, however, have not been satisfactory. It can arguably said that the collapse is better than the one obtained dividing by the square root of the channel exit width, but it is not consistent for all the channels and all the air velocities. As a consequence, at this point no normalization factor can be satisfactorily proposed to achieve a collapse of the oscillation frequency plots for the different air channels.

4. CONCLUSIONS

An experimental work has been presented centered on the longitudinal oscillations of an air-blasted liquid sheet. The oscillation wavelength has been measured directly from still images of the flow, and with a novel dual beam laser diffraction method. From the results it is concluded that the wavelength increases with water velocity and decreases for increasing air speed. It has been observed, for the first time to our knowledge, that the wavelength is inversely proportional to the square root of the Momentum Ratio *MR*. If definitively confirmed, this is a quite interesting result, because it is in discrepancy to the inviscid linear instability analysis, that predicts a dependence on velocity squared. It has also been deduced that for a constant *MR* value, the wavelength increases with the liquid sheet thickness. Simultaneous measurements of the oscillation frequency have enabled the possibility of some discussion about the wave propagation speed. It increases with water velocity, and in all cases is higher than the water velocity at the nozzle exit. However, it might be coincident with the local water speed, as the water sheet accelerates with downstream distance. Unfortunately, no measurements of this local velocity were available.

Attempts have also been made to clarify the role of the air channel geometry and width on the oscillation frequency. Tests performed with two air channels with the same exit width and different internal shape, have proved that the contraction ratio is influential in the oscillation. The present measurements could be brought to common values multiplying by the square root of the contraction ratio defined as the exit width divided by the width in the channel throat. However, the effect of the channel width on the oscillation has yet not been quantified. Oscillation frequency measurements obtained for different air channels and varying air and water velocities cannot be collapsed satisfactorily with any of the normalizations attempted. The exit width was already discarded as the parameter determining the oscillation frequency [10]. Here, tests have been made considering the air boundary layer thickness. Multiplying the frequencies by the square root of this thickness can bring the measurements obtained for some of the channels to a common ground, but the collapse is incomplete. Furthermore, introduction of this parameter conditions the linear dependence observed in most experiments between oscillation frequency and air velocity. To find a definitive solution to this issue, new experiments will have to be performed.

Acknowledgements

This work has been partially supported by the Spanish Research and Technology Ministry under the project DPI2002-04550-C07-07.

5. NOMENCLATURE

Latin alphabet

c wave propagation velocity [m/s]

f sheet oscillation frequency [Hz]

MR Momentum Ratio
V velocity [m/s]
St Strouhal number

Greek symbol

δ channel width [mm]
λ sheet oscillation wavelength [mm]
ρ density [kg/m^3]

Subscripts

a air
l liquid

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