The Large Aspect Ratio Air-blasted Liquid Sheet Revisited

A. Lozano*, F. Barreras J.A. García and E. Calvo
LITEC, CSIC-Univ. Zaragoza
María de Luna, 10
50018 Zaragoza, Spain

Abstract

Over the last few years, the large aspect ratio air-blasted liquid sheet has been extensively studied and has almost become a canonical flow. This is because, in spite of its simplicity, it is very suitable to study the complex mechanisms behind atomization, and in particular, the onset and growth of the instabilities that eventually lead to the liquid break up. By now, most characteristics of the atomization processes in this specific geometry have been experimentally observed and satisfactorily explained, and the theories utilized to this end are well established and commonly accepted. There are, however, some other aspects that are also generally accepted, but have not been supported by reliable experimental data, and their justifications are mere hypothesis. In some more extreme cases, some theories that have been proven to be incorrect are still in use and references to them can be seen in recent papers. In this work, some of these topics are debated, supporting our points of view with measurements, images and numerical results from our research team. Besides, new longitudinal oscillation frequency measurements simultaneously obtained both with a laser diffraction method and a microphone are presented to complete the discussion. In particular, some of the questions that are raised, and hopefully most of them answered, are related to the presence of dilatational waves, the accuracy of inviscid linear instability analysis, the transition between atomization modes, the influence of the air boundary layer, the equivalence of different measurement techniques and the factors fixing the transverse waves

Introduction

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Up to present day there are some facts that have been systematically confirmed and are generally accepted, but others are still controversial. A main reason for discrepancies 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, and the large aspect ratio air-blasted liquid sheet is still open to theoretical and experimental research.

Experimental facility

To discuss some aspects of the air-blasted liquid sheet, a set of experimental results will be used. They have been obtained in a facility that has been described in detail in previous papers [8, 11]. Only the most important characteristics, relevant to the results that will be shown, will be presented here. A photograph of the channel-contoured nozzle is displayed in Fig. 1. Water injected at the top of the nozzle head exits vertically forming a sheet with a span of 80 mm and a width of 0.5 mm. The sheet is confined by two air streams that flow in parallel to each side of the

*Corresponding author: Antonio Lozano, alozano@litec.csic.es

liquid curtain with an exit width of 3.45 mm. Water volumetric flow rate has extended up to 600 l/h, corresponding to a maximum liquid velocity U_w of 4.16 m/s. The maximum air flow velocity has been measured to be U_a = 80 m/s. The measurements obtained in the present experiments are in very good agreement with those previously acquired in the same facility [8, 11].

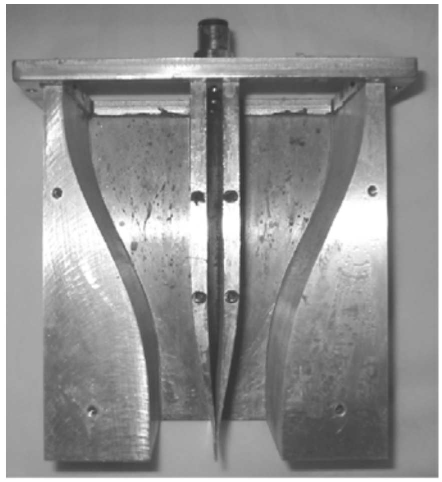

Figure 1: View of the nozzle head

Longitudinal oscillation modes

A characteristic and very studied feature of the gas co-flowing liquid sheet is the induced longitudinal oscillation. Quite early (see, for example [12]) it was theoretically established that a liquid sheet can oscillate with two wave modes: symmetric or dilatational and antisymmetric or sinusoidal. It was later determined [13] that under some flow conditions, the sinusoidal mode dominates and grows faster than the dilatational. However, and this is one of the facts that has to be remarked, we think that there is no experimental evidence of the presence of dilatational waves of measurable amplitude in an air-blasted situation, and only the sinusoidal ones have been characterized. Mansour and Chigier [4,6] define three zones A, B and C corresponding to different oscillation patterns dependent on the gas-liquid relative velocity. According to their description, zone B is characterized by a dominant sinusoidal mode, and the break up occurs after the appearance of streamwise ligaments. On the contrary, they claim that in zone C the presence of dilatational waves prevents the dominant growth of the sinusoidal ones. In zone A, for low water velocities, the sheet break up in longitudinal filaments occurs right at the nozzle lip and no intact sheet length is visible. After analyzing a large number of front, side and 45° images of different experiments, we believe that what might appear to be dilatational waves in zone C are in fact bag-like structures originated from transverse waves. Tentatively, we suggest that the transition between zones B and C corresponds to the point when the sheet edges begin to oscillate sinusoidally in phase with the rest of the liquid volume. As the edges are thickened due to surface tension, their inertia is higher and hence they require a higher air-to-liquid momentum ratio to start the oscillation compared to the thinner central part of the sheet. Figure 2 presents two images corresponding to a water velocity U_w of 2.08 m/s and an air velocity U_a = 20 m/s that show how the sheet central region starts oscillating while the edges are still not affected. The edges end up oscillating but de-phased with respect to the bulk of the liquid flow. If this hypothesis is definitely confirmed, the equivalence between planar and cylindrical air-coflowing liquid sheets might not be complete.

Longitudinal oscillation frequency

The longitudinal oscillation frequency has been extensively measured. Probably the most straightforward method to accomplish this task is applying the light diffraction method first described by Chigier in [6]. The best way to implement it consists in propagating a laser beam parallel to the liquid sheet pointing directly to a receiving detector, normally a photodiode. When the oscillating sheet crosses the light beam, it is partially blocked, and a difference in light intensity is detected in the photodiode, resulting in a periodic signal with a frequency related to that of the liquid sheet. Some authors [14] have argued that this technique might not be applicable for high air to liquid relative velocities, because the laser beam is spatially integrated through multiple waves in the spanwise direction. In order to confirm this assertion we have performed a set of frequency measurements simultaneously applying two different techniques: the laser diffraction one and detection of the acoustic signal using a Brüel & Kjaer pressure transducer. In both cases, the dominant frequency has been obtained calculating the FFT of the signal in a Tektronix TDS3012 oscilloscope equipped with a TDS3FFT module. The results of these measurements for a variety of water and air velocities are presented in Fig. 3.

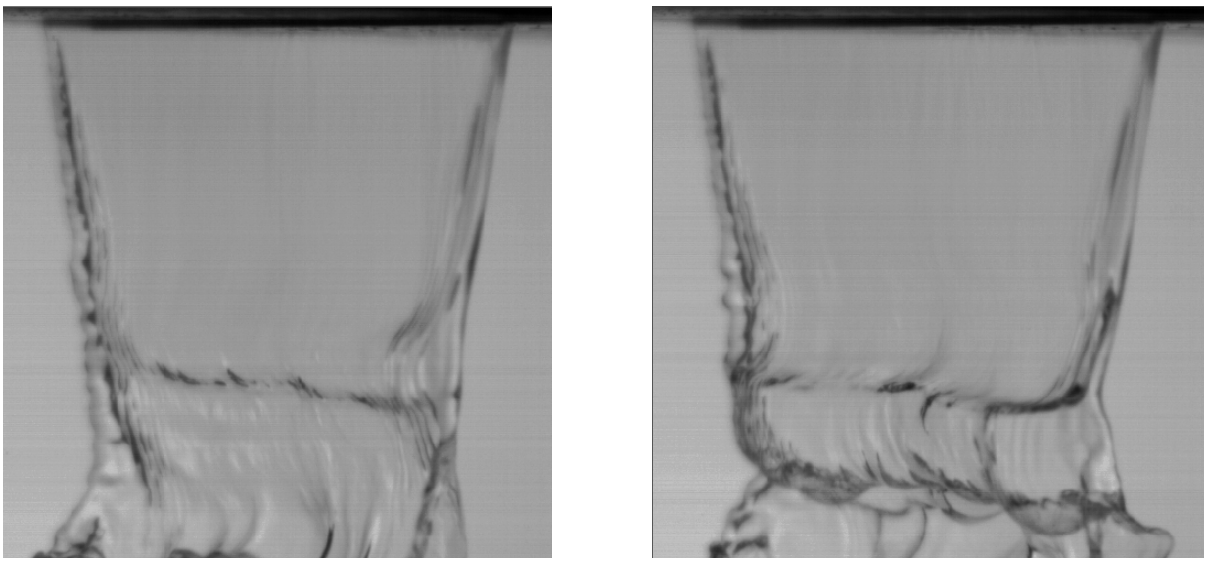

Figure 2: Views of the oscillating liquid sheet for water velocity U_w = 2.08 m/s and air velocity U_a = 20 m/s. In the first image the sheet central region starts oscillating while the edges are still not affected. In the second, the edges start oscillating but out-of-phase with respect to the bulk of the liquid flow.

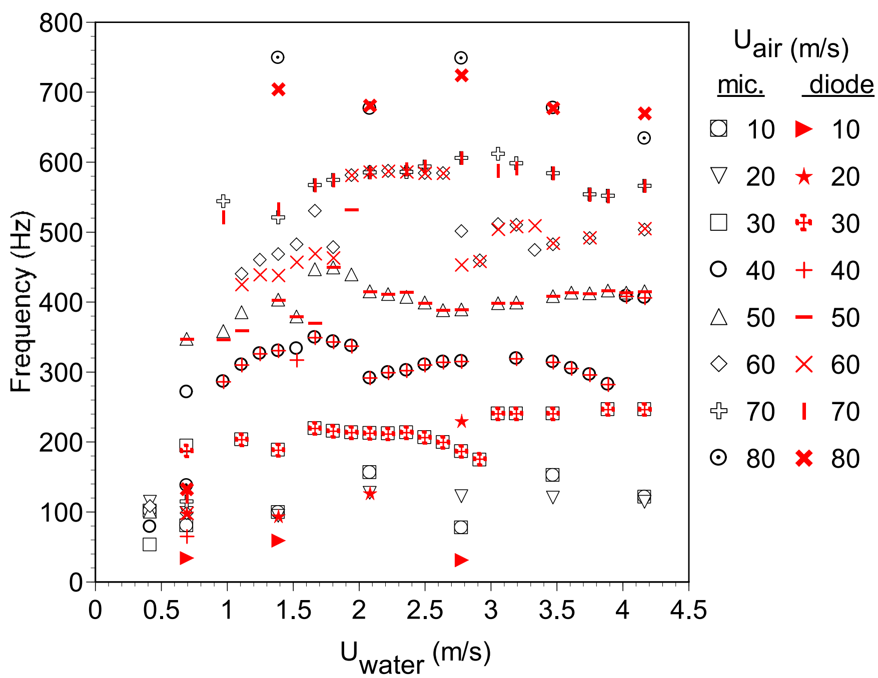

Figure 3: Sheet oscillation frequency measured with a pressure transducer (mic.) and detecting with a photodiode the passage of a laser beam

In general, it can be observed that for most air velocities, the frequency values measured with both techniques are almost identical. The most significant differences occur for the lowest air velocity, probably due to the low oscillation amplitude. In any case, both measurement methods appear to be valid for an ample range of air and water velocities.

Longitudinal filaments

For most operating conditions, prior to droplet formation, the sheet separates in a series of longitudinal filaments of variable length. They appear to be the consequence of the establishment of transversal sinusoidal waves. In some cases, these transversal perturbations combined with the longitudinal ones form a regular mesh in what is sometimes denoted as cellular break up mode [5]. The end filaments appear more or less stretched, depending on water and air velocities. An example of this situation is depicted in Fig. 4, corresponding to an air velocity U_a of 60 m/s and a water velocity U_w of 2.5 m/s. A clear view of the intuitive idea of the sheet breaking up in transverse strips that subsequently disintegrate into droplets, sometimes described in the Literature and depicted in Fig. 5, is extremely rare. As an immediate consequence, the application of 2D models to predict droplet diameters is highly questionable, unless some relationship is established between the longitudinal oscillations and the streamwise filaments. To our knowledge, such a relation has never been postulated.

A complete break up model needs to consider these filaments. Some papers have reported filament spacing measurements, but a question that remains open is to determine the mechanisms that impose a specific spatial frequency for their separation or their diameter. Some studies suggest that capillary waves reflecting in the sheet edges could influence or even fix the filament spacing.

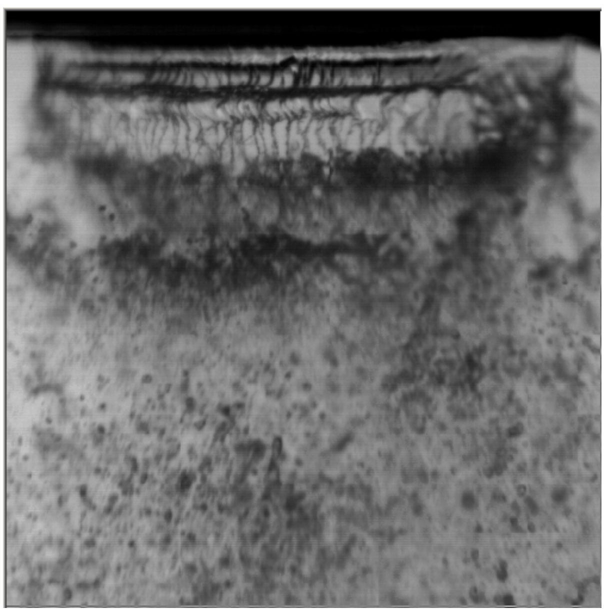

Figure 4: Front view of the oscillating liquid sheet for water velocity U_w = 2.5 m/s and air velocity U_a = 60 m/s.

Figure 5: Sketch of a liquid sheet breaking up in transverse strips. This process has not been observed experimentally

Linear instability analysis

2D temporal linear instability analysis has been customarily applied to explain the liquid sheet oscillations. With all the shortcomings already expressed when applying 2D models to certain aspects of this particular problem, temporal linear instability analysis has been mainly used to calculate the unstable oscillation frequencies and the wave growth rates. Some comments are also pertinent regarding these results. The linearized equations can only be solved analytically for the fully inviscid problem. If liquid viscosity is considered, an algebraic dispersion relation can be found, but it has to be solved numerically. If gas viscosity is also taken into account, both in the stationary solution and in the perturbations, then a numerical solution has to be found for the complete system of Orr-

Sommerfeld equations [8]. For simplicity reasons, many studies assume an inviscid gas profile, i.e., ignoring the gas boundary layer, arguing that the inclusion of the air viscosity does not substantially change the results. We want to emphasize that the solution is actually dependent on this parameter, as can be seen in Figs 6 and 7, where δ represents the boundary layer thickness and *h* is one half of the sheet thickness.

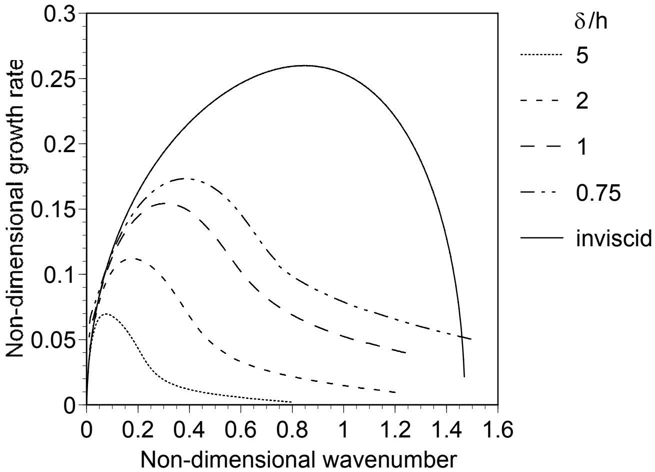

Figure 6: Non-dimensional growth rate vs. non-dimensional wavenumber for fixed Re_w = 340 (U_w = 2 m/s) and Re_a = 535 (U_a = 25 m/s), and varying boundary layer thickness δ, divided by the sheet half-thickness *h*.

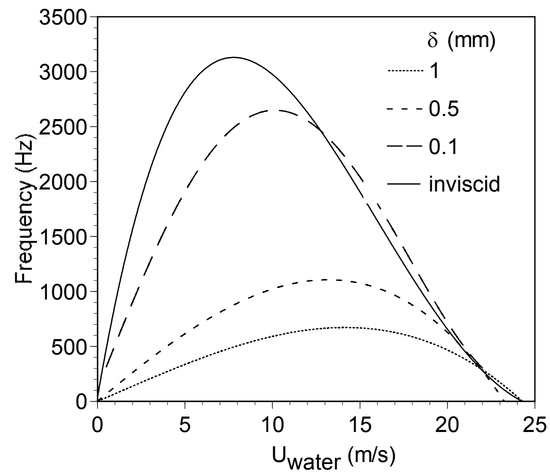

Figure 7: Maximum oscillation frequencies for fixed air velocity U_a = 25 m/s, and varying water velocities, for different air boundary layer thicknesses δ.

Variations in the boundary layer thickness affect the region of unstable frequencies, the growth rate and the frequency of maximum growth. After observing these graphics, it is fair to affirm that inviscid analysis might be acceptable for sheets exiting into a quiescent atmosphere, but in the air-assisted configuration it can only be acceptable to infer trends or qualitative behaviors. Correct predictions of quantitative values will be coincidental, if not completely wrong. A comparison between experimental measurements and numerical calculations can be found in [8].

Conclusions

Some aspects of the air-coflowing planar liquid sheet have been revised and analyzed. Emphasis has been placed on points appearing in the Literature where a general consensus has not been reached. From our experimental results, we believe that dominant dilatational waves have never been observed or characterized in the air-coflowing oscillating sheet. Some structures that might appear as dilatational waves can be the effect of transverse sinusoidal waves when viewed from the side. We have also postulated that transition between zones B and C, as defined by Mansour and Chigier, can be strongly influenced by edge effects, specifically by the point when the edges start oscillating. Another point that has been discussed is the appearance of transversal filaments instead of streamwise ones. Some characteristics of these filaments, among others, the physical mechanisms that establish their spacing, have not yet been satisfactorily explained. A consequence of their presence is the inadequacy of using 2 D models to predict droplet sizes. Finally the influence of the air boundary layer thickness in the results obtained by linear instability analysis has been discussed. Neglecting air viscosity when attempting quantitative predictions can lead to erroneous results.

Nomenclature

U velocity
h sheet half-thickness
δ boundary layer thickness

Subscripts
a air
w water

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