Mode Transitions in an Oscillating Liquid Sheet

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Abstract
Longitudinal oscillations in air-blasted or air-assisted liquid sheets have been the subject of a large number of papers in the last thirty years. Frequency and sometimes amplitude are the main parameters used to characterize these oscillations. Attending to them, and also in dependence on the surface topology (e.g. presence of perforations or ligaments) different oscillation modes have been described. In most works, two or at most three regimes are considered. Following these previous descriptions, this experimental work has found that some sub-modes can also be discerned. For some liquid and air flow rates up to 6 modes have been observed with defined transitions among them.

Introduction

Longitudinal oscillations in large aspect ratio air-blasted or air-assisted liquid sheets have been the subject of a large number of papers in the last thirty years. The topic has been covered both experimental and numerically. As usual, frequency, and occasionally, amplitude have been the main parameters analyzed to characterize these oscillations. In some studies, the frequency has been related to the sheet visual aspect to define different oscillation modes. For example, Rangel and Sirignano [1] describe a "cellular" break up mode opposed to a "streamwise ligament" one, depending on the presence of either a mesh of perforations, or longitudinal ligaments. Similarly, Mansour and Chigier [2, 3] define three zones A, B and C dependent on the gas-liquid relative velocity. According to their description, zone B is characterized by a single dominant sinusoidal mode, and the break up occurs after the appearance of streamwise ligaments, while in zone C the presence of dilatational waves are claimed to prevent 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, preventing its accurate experimental measurement.

In this work, the longitudinal oscillation of a gas coflowing liquid sheet has been examined, trying to identify different modes attending to sudden variations in frequency or spray angle. As will be seen, these changes can imply angle and frequency increases or reductions, or coexistence of more than a single dominant oscillation wave.

Materials and Methods

The facility in which the present measurements have been obtained has been described in detail in previous papers [4, 5]. For this reason, only the most important characteristics will be presented here. Water injected at the top of the nozzle head exits vertically forming a sheet with a span of 80 mm and a width of 0.4 mm. The sheet is surrounded by two air streams that flow in parallel to both sides of the liquid curtain with an exit width of 3.45 mm each. Water volumetric flow rate has extended up to 640 l/h, corresponding to a maximum liquid velocity U_w of 5.37 m/s. The maximum air flow velocity has been measured to be U_a = 70 m/s.

To determine the oscillation frequency, the acoustic signal has been detected using a type 2669 Brüel & Kjaer pressure transducer. The FFT of the periodic signal has been obtained in a Tektronix TDS3012 oscilloscope equipped with a TDS3FFT module. Image sequences have also been recorded with a 512x512 CMOS RedLake HS-4 high-speed camera.

Results and Discussion

While measuring the oscillation frequency for different air and water velocities, several oscillation modes have been detected, with some particular characteristics. In general, the procedure to locate them has consisted in fixing the air velocity, and then sweeping over the full range of water velocities. It is to be noted that hysteresis has been observed in these cycles, so that the transition points between modes have been found to be slightly different when water velocity was being either increased or decreased.

Although sometimes it has been difficult to clearly separate between different modes, the following classification is proposed to explain the present measurements and observations, corresponding to increasing water flow rates:

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- Mode 0: similar to Mansour and Chigier zone A. Includes the situation where the low water flow rate is not enough to form a continuous sheet and exits from the nozzle as discrete filaments, and the initial stage of an incipient sheet. These two situations could be considered as sub-modes
- Mode 1: the sheet oscillates with two coupled frequencies.
- Mode 2: single dominant frequency of sinusoidal oscillation
- Mode 3: single dominant sinusoidal oscillation after a sudden reduction in frequency and spray angle.
- Mode 4: further reduction of the angle, with dephasing in the sheet edges oscillation. The edges tend to approximate each other at the sheet far end.
- Mode 5: No oscillation frequency can be measured any longer. For large air velocities this mode cannot be reached even for the maximum water flow rates.

Water velocities for which transitions between consecutive modes occur, for different air velocities, are summarized in Table1. Figure 1 displays the evolution of the transition points between modes 0-1 (T0), 1-2 (T1) and 2-3 (T2).

References

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Table 1. Water velocities (in m/s) for which transitions between consecutive modes occur

Ua (m/s)	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**
T0	0.35	0.53	0.56	0.69	0.69	0.78	0.87	0.87	0.95	1.13
T1	1.13	1.56	1.82	2.13	2.39	2.86	3.21	3.56	3.91	4.08
T2	1.40	2.99	3.82	4.56	5.23					
T3	2.24	4.56								
T4	3.21	4.86								

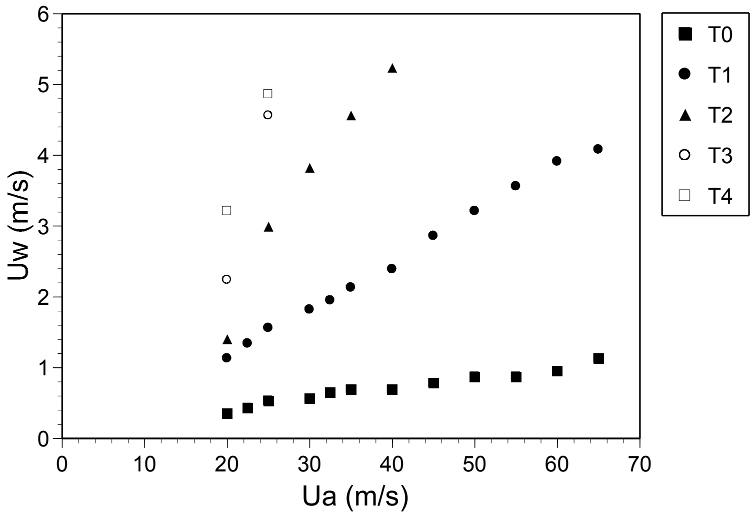

Figure 1. Transitions as a function of air velocity U_a