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## Experimental study on the influence of the liquid and air thicknesses on a planar air-blasted liquid sheet

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### Abstract

This experimental study is devoted to the analysis of an air-blasted atomizer behavior whose air and liquid thicknesses are changed. Variation of liquid thickness is realized by modifying the injector inside; when for air thickness, wedges are introduced in the air flow duct. Using different experimental methods: tomography and shadowgraphy visualizations, oscillation frequency and breakup length are measured and studied. Thickness of each fluid has not the same influence depending on each atomization process parameter. Breakup length is strongly correlated to liquid thickness; when frequency depend more on air thickness. But more than air thickness, for the frequency especially, the flow configuration plays the most significant role, through influence of boundary layer characteristics as wall shear stress. This study highlights the necessity of another non dimensional number than the momentum flux ratio (MFR). This new number could complete the physical description of the phenomenon by taking into consideration some geometrical aspects of the injector and some physical variables characterizing the air flow configuration.

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### Introduction

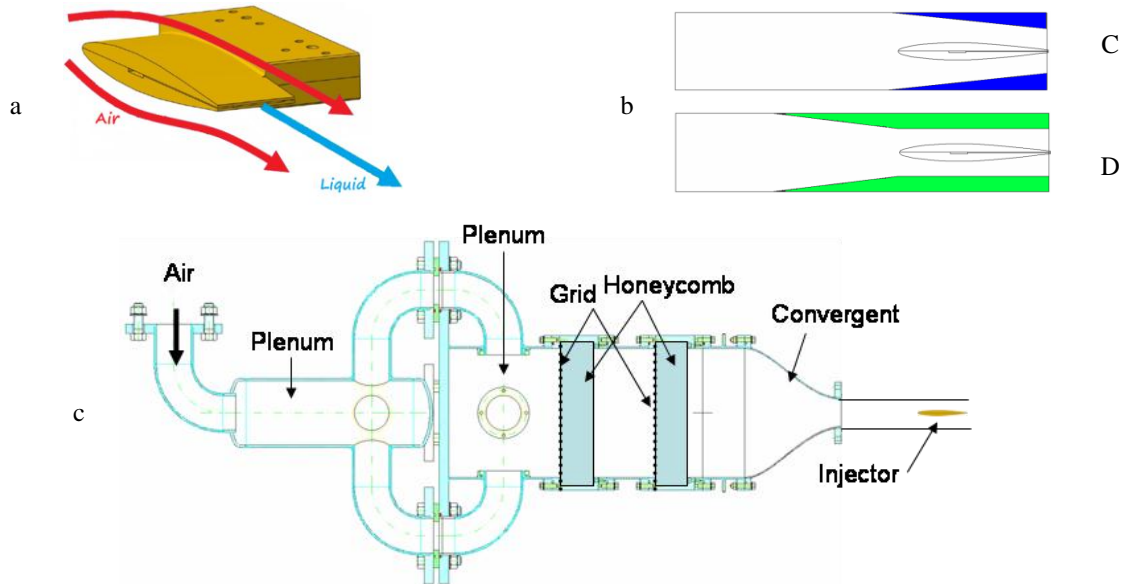
Reduction of pollutant emissions and improvement of the aircraft engine efficiency is currently the most important challenges of the aeronautical research. To reach these two goals, an optimization of the combustion processes based on simulations, is needed. Generally, for these simulations, the boundary condition for the liquid fuel is imposed through the numerical injection of droplets parcels. The characteristics of these droplets are deduced from size and velocity distributions measured a few millimeters from the injector. With this approach the great coupling between the gas and liquid phase during the first instants of the liquid injection is not taken into account. In particular, the influence of the flow unsteadiness resulting from this coupling, which directly impacts the flame behavior, is not reproduced in the simulations. In order to improve the quality of these calculations, it is therefore necessary to correctly model all the atomization steps and particularly the primary break-up, where the most part of difficulty reside.

For this purpose, experimental studies were led at Onera on liquid sheet pulverization by high speed air flow corresponding to an air-blast atomizer type (Carentz, 2000), (Larricq, 2006) and (Fernandez, 2010). Precedent studies revealed the influence of liquid thickness on the spray drop size (Lefebvre, 1992), the oscillation frequency (Siegler et al., 2003) and break-up length (Arai & Hashimoto, 1985). Few papers were focused on air thickness variation but the conclusions bring no answer about its influence, (Siegler et al., 2003) or (Lozano et al., 2005). In order to complete the data base and to have a better understanding of the influence of liquid and air thicknesses on the primary atomization process, new experiments were performed. The main results obtained are presented in this paper.

### Experimental test-rig

This study is performed on a simplified 2D liquid sheet sheared on its two faces by a high velocity air stream (Figure 1 a). The liquid sheet generator was designed at ONERA in the framework of previous study on this topic (Larricq et al., 2005) and (Fernandez et al., 2009); it is an airfoil with an 89 mm chord and a NACA63-010 profile. A couple of perforations at each injector side allowed the entrance of the liquids. The liquid sheet is formed on the trailing edge of the injector through a 40 mm width slit. A wedge system inside of the airfoil permits to vary the slit thickness. Three values are considered in this study: 300, 450 or 600  $\mu\text{m}$ . A Masterflex pump is used to inject the liquid up to 90 g/s. This device permits to monitor the liquid flow rate that imposes the initial velocity of the liquid film.

The injector is placed on the SHAPE (SHeet Atomisation and Prefilming Experiments) set up shown in figure 1 c. The air flow is obtained from an 80 bars reservoir. Its mass flow rate is controlled by a valve coupled to a Coriolis flow meter. The main feature of this atmospheric injection line was designed in order to obtain uniform, stable and laminar flow from 20 to 100 m/s in a 46 mm square section. In order to modify the air flow thickness at the liquid injection outlet location, wedges with different shapes and width can be inserted in the square pipe. They can be convergent (named C) or divergent (D). These letters C or D are accompanied with a number corresponding to the air flow thickness in order to name each wedge configuration (Figure 1 b).



**Figure 1.** Experiment facilities. a: airblast generator, b: obstruction used to modify air flow, up: convergent (C); down: divergent (D), c: SHAPE bench sketch

## Measurement systems

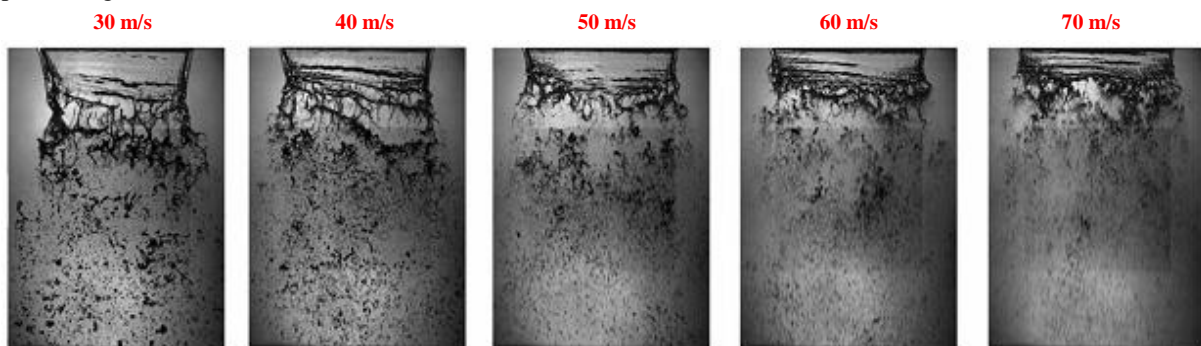
### *Boundary layer characterisation*

A hot wire probe of 1.25 mm length and 5  $\mu\text{m}$  diameter was used to characterize the air flow at the injector nozzle. Thanks to this device measures can be done at a few micrometres of the injector outlet with a great spatial resolution due to the small probe size. The frequency response of the CTA (Constant Temperature Anemometer) electronic device used permits to reach velocity fluctuations up to 100 kHz.

Before and after each measurement campaign a calibration is performed in comparison with a Pitot probe.

### *Visualizations and image processing*

The use of imaging techniques allows a better knowledge of the behaviour of the liquid sheet. These techniques, non-intrusive, can also give quantitative information on the breakdown of the sheet. Two main techniques are used: the shadowgraphy and laser tomography. In the two cases, a high speed video camera is preferred in order to follow the liquid sheet displacements. Shadowgraphy technique was used to obtain principally qualitative results (Figure 2) when tomography gives quantitative measures through images processing.



**Figure 2.** Shadowgraph of the liquid sheet

Laser tomography is used to determine breakup length and oscillation frequency of the liquid sheet. A planar laser sheet perpendicular to the liquid plane is used to illuminate a liquid slice in the middle of the liquid layer. In this case, fluorescein is added in the water. This dye absorbs the photon emitted by the laser at 495 nm (blue) and re-emits light at 521 nm (green) (Figure 3). The use of a matched filter on the camera lens eliminates the direct reflection from the incident laser sheet on the surface of the liquid film.

### Breakup length measurements

For these measures, both visualisation techniques are used simultaneously in order to obtain an image where both laser continuity and liquid sheet are visible simultaneously. By this way the threshold used during the image processing is adjusted to reveal the real breakup length (Figure 4). 500 images are taken and for each experiment configuration and the threshold is adapted on the about 50 first images thanks to the shadowgraphy.

### Frequency measurements

From tomography images acquired with high speed camera, the instantaneous transversal location of the liquid sheet is determined at different longitudinal positions. FFT of these displacement signals permit to determine the flapping frequency of the liquid sheet. To have frequency results high speed camera was coupled with a laser sheet to obtain a longitudinal section in the liquid sheet (Figure 5). The purpose was to measure the liquid sheet displacement over time and after apply an FFT analysis on this signal to finally have a measurement of the flapping frequency. This technique allows to check visually the result obtained and also to have a frequency spectrum all along the liquid sheet, from injection point to breakup. For this acquisition 2048 images are taken at a rate of 3400 im/s, for the frequency measurements the resolution becomes 1.7 Hz.

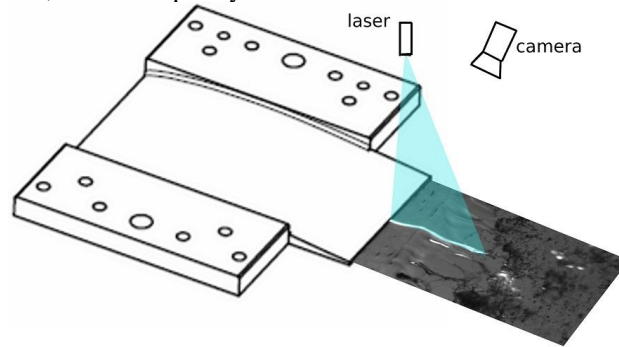


Figure 3. Laser tomography

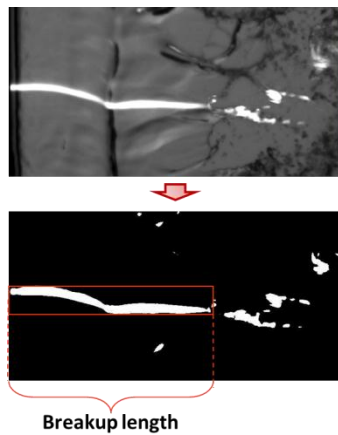


Figure 4. Breakup length measurement

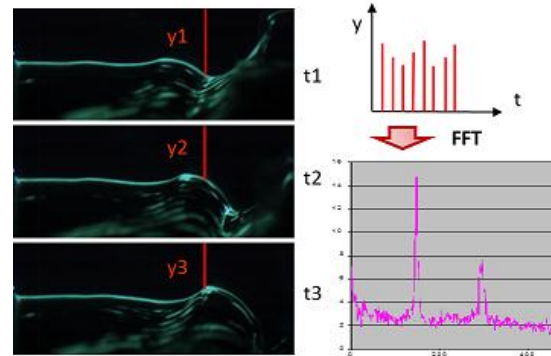
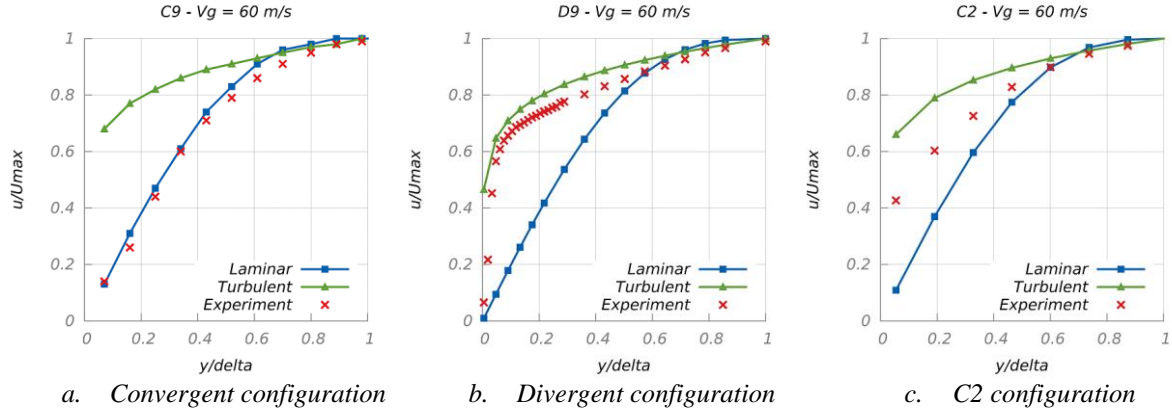


Figure 5. Frequency from high speed video.

## Results and discussion

### Boundary layer characterisation

Test campaign with a hot wire probe is made at the trailing edge of the injector without water injection. The measurements are done for all the wedges and for air velocity ranging from 30 m/s to 90 m/s. Velocity profiles in Figure 6 are representative of the different boundary layer shapes obtained. To estimate the flow regime, the boundary layer profiles are compared with a 1/7 law corresponding to a turbulent boundary layer and a Pohlhausen law approximating of the exact Blasius theory obtained for a laminar boundary layer (Gosse, 1995). This approximation is valid for a uniform flow parallel to flat plate with no incidence and is considered acceptable for this study.



**Figure 6.** Velocity profile close to the injector lips

With the convergent wedges, the shape of the curve is close to the laminar profile. On the opposite the velocity profile obtained for the divergent configuration is close to a turbulent flow condition. For the C2 configuration a particular behaviour is observed and can be described as a transitory profile due to the low air flow thickness. As a first conclusion on the boundary layer profiles, a configuration difference (convergent / divergent) will lead to a different flow regime (laminar / turbulent) which could explain some behaviour differences between the two configurations. The first element extracted from these measurements is the boundary layer thickness which is defined as the distance from the wall where the velocity is 99% of the maximal air velocity. As expected there are large differences between the laminar and turbulent regimes (Table 1).

Boundary layer thickness	Wedges (air thickness)							
	Divergent configuration			Convergent configuration				
Air velocity	D22 22 mm	D14 14 mm	D9 9 mm	C14 14 mm	C9 9 mm	C6 6 mm	C4 4 mm	C2 2 mm
30 m/s	2,67 mm	3,69 mm	4,11 mm	0,73 mm	0,65 mm		0,64 mm	0,53 mm
40 m/s	2,29 mm	3,66 mm	3,98 mm	0,66 mm	0,63 mm	0,61 mm	0,55 mm	0,45 mm
50 m/s	2,10 mm	2,98 mm	3,63 mm	0,64 mm	0,62 mm	0,55 mm	0,52 mm	0,42 mm
60 m/s	2,21 mm	2,56 mm	3,52 mm	0,57 mm	0,55 mm	0,50 mm	0,47 mm	0,37 mm
70 m/s	1,69 mm	2,59 mm	3,31 mm	0,52 mm	0,51 mm	0,47 mm	0,46 mm	0,35 mm
80 m/s	1,67 mm	2,37 mm	3,09 mm	0,48 mm	0,47 mm	0,44 mm	0,42 mm	0,31 mm
90 m/s			2,95 mm	0,45 mm	0,41 mm	0,45 mm	0,39 mm	

**Table 1.** Boundary layer thickness evolution for the different wedges

In the divergent configuration the boundary layer thickness increases as the air thickness decreases due to a change of the expansion ratio, it varies from 1.24, for D22, to 1.9 for the D9 configuration. This larger expansion promotes an earlier detachment. On the other hand, in the convergent case, boundary layer thickness decreases with the air thickness. For the largest air configuration, C14 to C4, boundary layer profiles correspond perfectly to the laminar profile except for the C2 configuration giving a profile between the two used laws (laminar and turbulent Figure 6 c). The wall shear stress can be extracted from these measurements by the classical formula (1) by considering the closest position where velocity values are valid in this case 0.2 mm from the wall and assuming that this point was in the viscous sub layer. Values are available in Table 2.

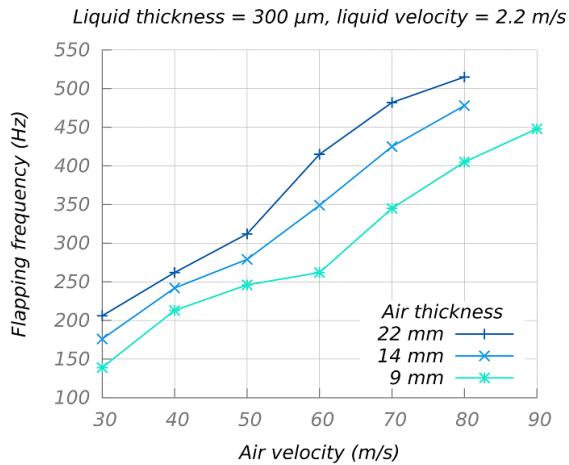
Wall shear stress	Restriction (air thickness)							
	Divergent configuration			Convergent configuration				
Air velocity	D22 22 mm	D14 14 mm	D9 9 mm	C14 14 mm	C9 9 mm	C6 6 mm	C4 4 mm	C2 2 mm
30 m/s	1,83	1,68	1,21	1,27	1,39		1,43	1,61
40 m/s	2,53	2,31	1,80	1,78	1,78	2,11	2,34	2,55
50 m/s	3,26	2,92	2,52	2,12	2,36	2,74	2,69	3,60
60 m/s	4,02	3,57	2,85	3,00	3,29	3,45	3,71	4,94
70 m/s	4,79	4,29	3,53	3,94	4,12	4,29	4,27	6,27
80 m/s	5,62	4,87	3,97	4,86	5,07	4,97	5,13	6,81
90 m/s			4,39	5,84	6,24	5,31	6,08	

**Table 2.** Wall shear stress evolution for the different wedges

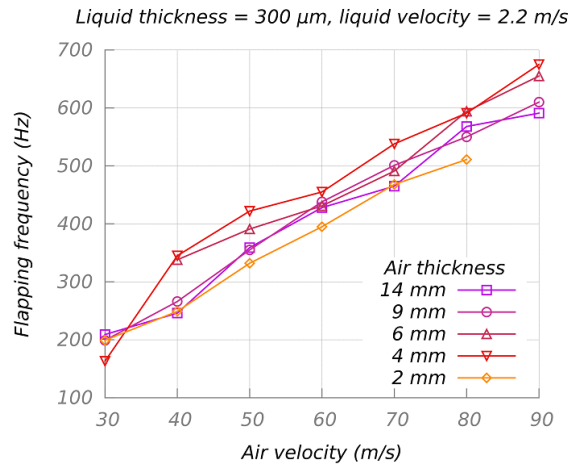
$$\tau_p = \mu \frac{\partial U}{\partial y_0} \quad (1)$$

**Frequency**

Thanks to the high speed camera records, frequency measurement is done by image processing all along the liquid flow and confirmed by image visualization. This technique corroborates that the flapping phenomena is associated with a continuous frequency increase with air flow velocity for both configurations (convergent and divergent). Nevertheless, a different behaviour can be observed between the two flow configurations. For the divergent case, an increase of the air flow thickness leads to a significant frequency rise (Figure 7). Otherwise, in the convergent case, the air flow thickness seems have a lower influence (Figure 8).



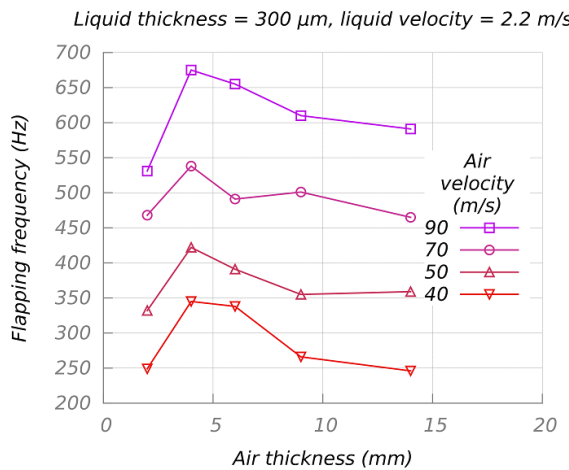
**Figure 7.** Flapping frequency evolution with air velocity – Divergent wedges



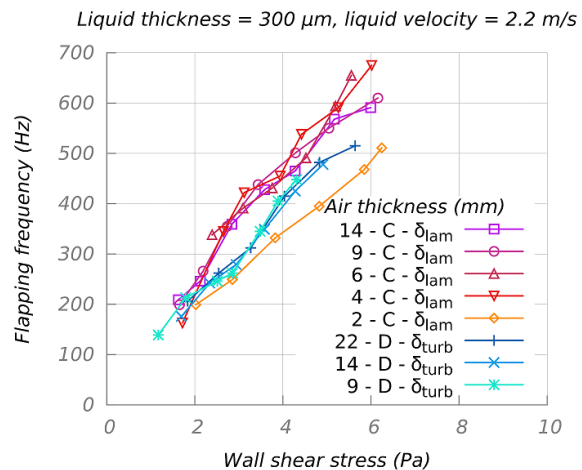
**Figure 8.** Flapping frequency evolution with air velocity – Convergent wedges

For these configurations the flapping frequency is plotted against the air thickness at a given air velocity (Figure 9). Except for the thinner air flow configuration (C2), the flapping frequency decreases when the air thickness increases. This difference obtained with the C2 wedge can be explained by the transitory boundary layer condition revealed from the velocity measurements.

These first results show some differences depending on air flow conditions. Nevertheless they are not directly related to the air thickness or to the boundary layer thickness. So it is important to find parameters which can explain the differences between the configurations. For this purpose, the frequency evolution against the wall shear stress was plotted for all the flow conditions (Figure 10). It can be seen that quite linear curves are obtained. Nevertheless two distinct slopes can be discerned depending on the wedge configuration. Furthermore it can be seen that the smaller convergent configuration (C2) have a behaviour closer to the divergent case than to the other convergent cases. Thus, it seems that the slope depends not only on the shear stress but also on the boundary layer type (laminar or turbulent) so another parameter, not identified yet, has to be considered.



**Figure 9.** Flapping frequency evolution with air thickness – Convergent wedges



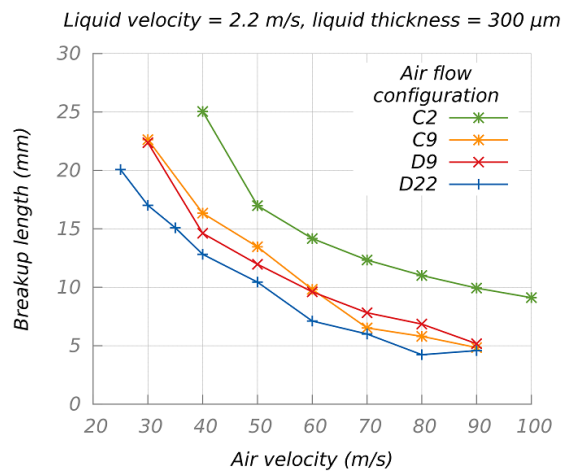
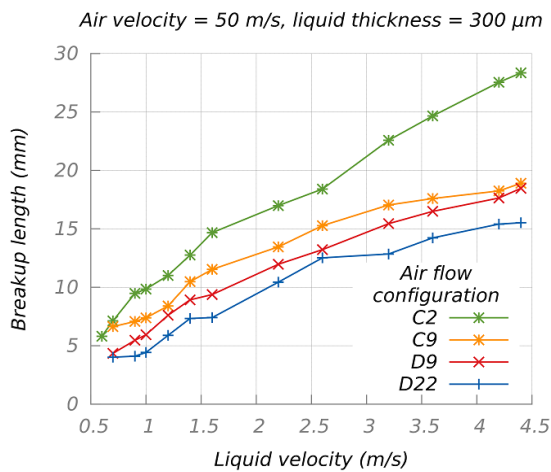
**Figure 10.** Oscillation frequency evolution against wall shear stress for convergent (C) with laminar boundary layer ( $\delta_{lam}$ ) and divergent (D) with turbulent boundary layer ( $\delta_{turb}$ )

**Breakup length**

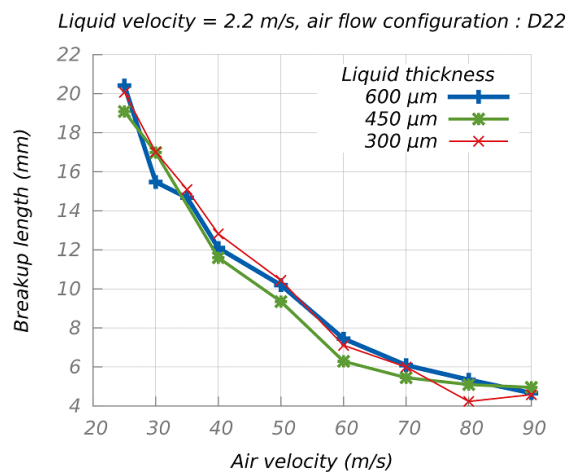
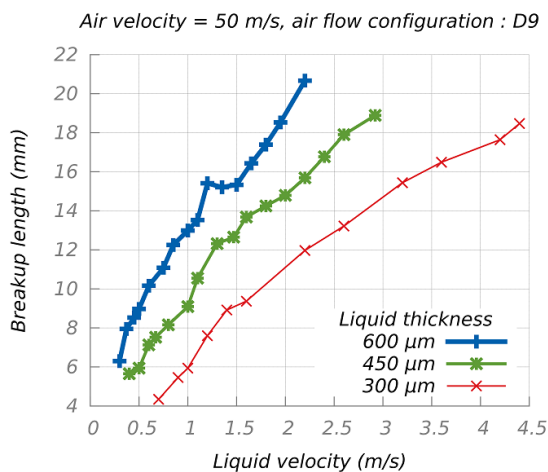
In a second step the influence of the air thickness on the breakup length of the liquid sheet is studied. The experimental determination of this quantity is difficult because the instantaneous breakup position is not fixed; it changes with the flapping of the sheet. To perform these measurements an automatic image analysis was developed in order to process 500 images and obtain a good statistical representation.

This analysis shows expected tendencies as a decrease of the breakup length with the air velocity increase or a liquid velocity decrease. The breakup length is linearly dependent on the liquid velocity (Figure 11). Otherwise, the breakup length decreases with the air speed value following a  $v_{air}^{-1}$  law (Figure 12). Those tendencies are well-known results and this study was made to bring out the air flow configuration influence. As shown on Figure 11 or Figure 12, an air flow thickness augmentation leads to a decrease of the breakup length whatever the convergent or divergent configuration. This decrease is nearly proportional  $t_{air}^{-0.25}$  where  $t_{air}$  is the air flow thickness. At a given air velocity and for a same air thickness, a divergent and a convergent air flow will give approximately the same breakup length. This result indicates that the breakup length depends not only on the air velocity but also on the air momentum flux.

By comparing the results obtained with different liquid thicknesses, it can be seen that this parameter influences the break-up length when the liquid and the gas velocity are kept constant (Figure 13). Nevertheless, if the liquid flow rate is fixed no influence is observed (Figure 14).



**Figure 11.** Breakup length according to liquid velocity **Figure 12:** Breakup length according to air velocity



**Figure 13:** Breakup length according to liquid velocity for different liquid sheet thickness for a constant air velocity (50m/s)

**Figure 14:** Breakup length according to air velocity for different liquid sheet thickness for the same liquid flow rate

## Conclusion

This study on liquid sheet atomization highlights the influences of liquid and air thicknesses of the different characteristics of atomization process (oscillation frequency, breakup lengths, mean droplet sizes...). Different influences have been shown depending on each fluid flow and break-up characteristics. A direct correlation between liquid flow rate and break-up length is clearly identified. For this parameter, air flow thickness plays a less influential role and configurations none. As for flapping frequency, it is the opposite. Liquid flow thickness influence could not be shown when effect of air flow thickness is obviously highlighted. For this parameter, its evolution depends on the air flow configuration and more especially through the wall shear stress and the air flow boundary layer. The regime of this near wall flow gives different results depending on its laminar, turbulent or transitory behavior. Flapping frequency evolution against wall shear stress gives then a good agreement for each flow regime. These results, on the liquid sheet atomization by an air flow shear, show the importance of fluids thicknesses on different parameters of primary break-up. These influences highlight the need of others parameters as only density and air flow through the momentum flux ratio (MFR) used actually to describe atomization regimes. This goes in the same way as the conclusions of Lozano who has introduced fluids thicknesses in this ratio (Lozano et al., 2005). But as shown on frequency results, flows thicknesses are not enough to determine primary breakup characteristics and other parameters of boundary layer as wall shear stress or vorticity thickness have to be taken into consideration.

## Acknowledgments

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