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Video Techniques Applied to the Characterization of Liquid Sheet Breakup

Berthoumieu, P.* and Lavergne, G.*

* ONERA – DMAE, 2 Avenue Edouard Belin, BP 4025 31055 Toulouse Cedex 4, France.
e-mail: pierre.berthoumieu@onecert.fr

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***Abstract*:** The understanding of the disintegration of a thin liquid film is the first step to obtain an accurate model of air-blast atomization. Various physical phenomena are involved in liquid sheet breaking. Planar sheets are often studied, assuming that the sheet behavior is representative of the behavior of real annular sheets, because their investigation is easier using optical techniques. Those kinds of measurements have been applied to determine and quantify the different steps of droplet generation. Global oscillation of the liquid sheet, ligaments formation and their breaking are approached. The evolution of ligament spacing according to oscillation frequency removes the sheet thickness influence. Correlations are now applicable to determine size of initial droplets. In this study the same investigation techniques have been applied on annular and planar configurations to find the eventual discrepancies.

***Keywords*:** liquid sheet, atomization, breakup.

1. Introduction

Aero-engines often use airblast atomization to introduce liquid fuel in combustion chamber. Air-blast atomization is a process in which a continuous liquid disintegrates into a cloud of droplets under aerodynamics effects. This process is, until now, not well modeled, because understanding of the fundamental physical processes implied in atomization has to be improved. The knowledge of these phenomena is of primary importance to optimize the design of new airblast injectors. Real injectors usually have an annular shape, nevertheless, an experimental planar geometry is often used (Mansour and Chigier, 1991; Lozano et al., 1996; Stapper and Samuelsen, 1990) because experimental investigations are easier to perform. One of the more appropriate investigation methods in planar liquid sheet disintegration is the observation with photographs, video or high-speed cinematography. The observation of images of liquid sheet primary breakup reveals the formation and rupture of ligaments in the air flow as was mentioned by Stapper and Samuelsen (1990) (Fig. 4). After that they are transported and secondary break induced by the surrounding airflow occurs. The aim of this study is to analyze primary liquid sheet breakup to try to predict the initial size of liquid packets. After that a secondary breakup model can be used to compute final droplet sizes (Berthoumieu et al., 1999).

The first work proposes analysis of a planar liquid sheet atomization, and then the analogy with an annular liquid sheet will be shown.

2. Experimental Setup

An experimental setup was designed to analyze the behavior of a liquid sheet submitted to adjacent airflow before and during its disintegration. The airflow is supplied by the expansion of compressed air which allows velocities up to 100 m/s. The air duct is one meter long to avoid perturbation in the flow, the inner section measures 46 × 46 mm. In order to perform optical investigations, the liquid injector is located in the middle of the exit section of the air duct (Fig. 1).

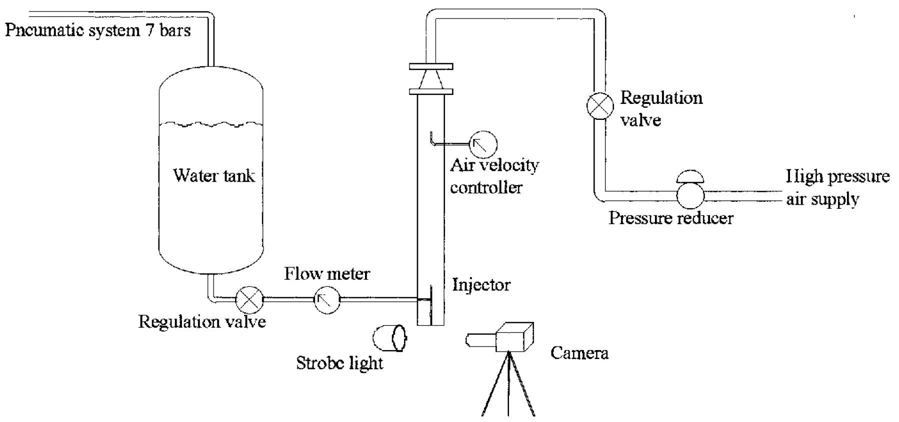


Fig. 1. Experimental setup.

Water is used as simulation liquid; it is stored in pressurised tank. The maximum supplied velocity is 4 m/s, which is greater than the fuel velocities in real airblast injectors. Two kinds of liquid sheet generators have been used in the same air supply device (Fig. 2). The first injector is dedicated to the study of a planar liquid sheet. The liquid sheet is generated by a slit with a thickness ranging between 200 μm and 500 μm and a width of 18 mm. In the second step, two annular sheet generators were designed to be closer to the real airblast atomisers. The slit generating the liquid sheet is, for the first one of variable thickness (between 200 and 400 μm) for a radius of 7 mm while the second one has a radius of 5 mm and is 300 μm thick.

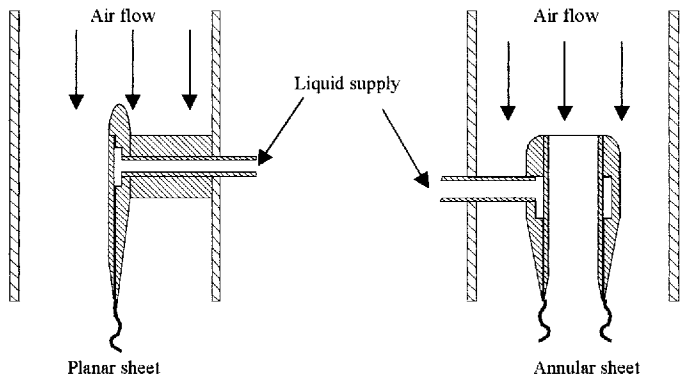


Fig. 2. Cross section of test injectors.

In all cases injectors are designed with a buffer zone upstream of the long liquid duct to provide a well known velocity profile at the injector exit. Due to the sheet thickness, liquid velocity profiles cannot be measured. For all the comparison and parametric studies liquid velocity is the mean liquid velocity calculated with the injected liquid flow rate. A Pitot tube is used to measure air velocity.

3. Measurements

As in many studies in this domain, optical systems are used to investigate the liquid sheet behavior. Direct observation of the liquid sheet behavior is done by the use of a progressive scan CCD camera (JAI CVM10). Images are taken with a back light technique. The camera synchronizes the light emission of a stroboscope which gives short duration flashes (3 *m*sec). This system allows to take instantaneous images of the sheet. Those images will be used to obtain dimensional measurement of waves that appears on the sheet. This camera is coupled with an image acquisition system on a PC. It consists of a Matrox frame grabber "Genesis" which is able to take images at video cadence and permits to perform some operations in real time during image acquisition. This system permits to grab simultaneously up to four cameras, so to improve understanding of liquid sheet behavior, some sequences are taken by using two cameras synchronized and placed on both sides of the sheet, one face to it and the other on the side. In this case the light emitted by the strobe is split in two by the use of a prism (Fig. 3).

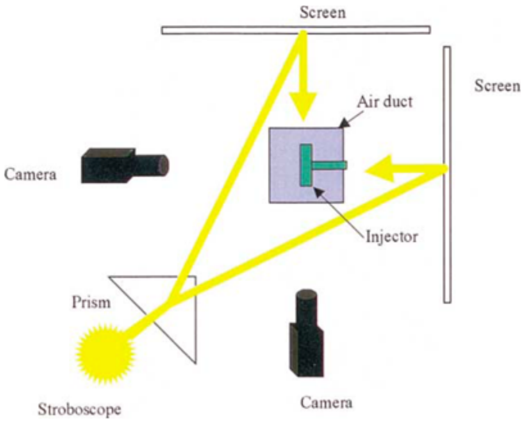


Fig. 3. Upside view of stereoscopic vision setting.

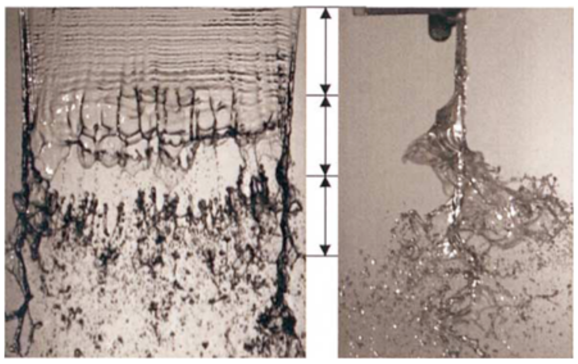


Fig. 4. Liquid film disintegration (front and side views, 50 mm × 58 mm).

The front view (Fig. 4), in the upper part of the liquid sheet, presents wavelets mainly due to vibrational effects of the main part of the injector, which is excited by surrounding air (Carentz et al., 1998). After that, the tearing of the liquid sheet starts with the formation of ligaments. Those filaments are then broken into big droplets that are convected and break again, while interacting with the surrounding airflow. The side view images present a waving of the liquid sheet. Both images are taken simultaneously to insure that the location of ligament formation corresponds to the location of the sheet curvature. The drops are produced by the ligaments break, so to predict the drops characteristics, the ligaments formation must be understood and calculated with the aerodynamic and geometric conditions. It is interesting to notice that ligaments break occurs when the amplitude of liquid sheet oscillation is maximum. As is shown in Fig. 5, air velocity has an influence on the emergence of ligaments. The length of the continuous part of the liquid sheet decreases with an increase of air velocity, as well as the number of filaments. The liquid sheet disintegration is the result of three different phenomena. The first is small amplitude waves that appear at the injector outlet.

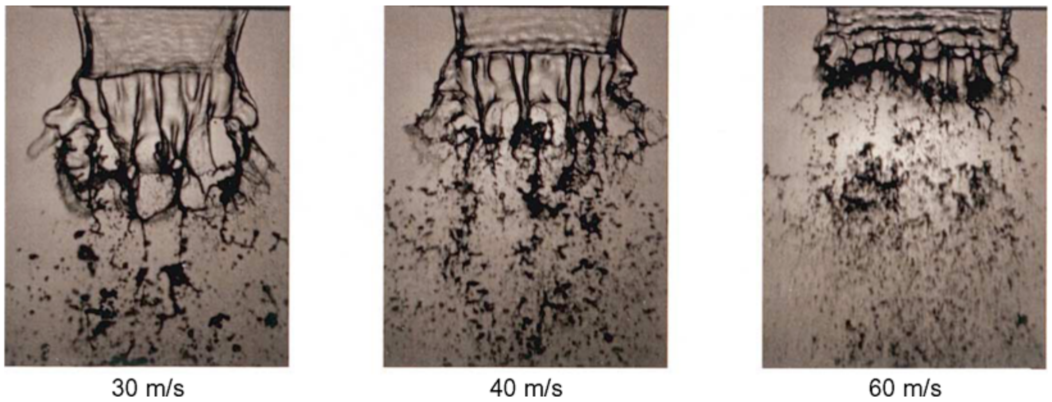


Fig. 5. Planar liquid sheet: ligament spacing according to air velocity (30 mm × 38 mm).

In annular injection, globally the same behaviour of the liquid film is observed. As in the planar case without air, surface tension effects tend to close the cylinder of the liquid created by the injector in a single jet of water (Fig. 6 (a),(b)). In the planar case the air flow gives back the planar form at the liquid sheet. In the annular case at very low air velocities, large liquid bubbles can be observed at the injector exit (Jeandel and Ledoux, 1999), because air inflates the closed cylinder and generates bubbles (Fig. 6 (c)).

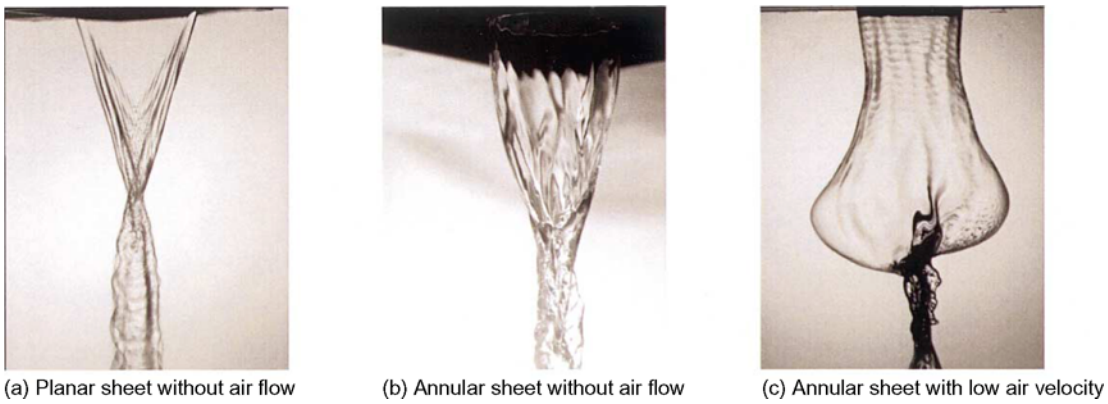

(a) Planar sheet without air flow (b) Annular sheet without air flow (c) Annular sheet with low air velocity

Fig. 6. Annular and planar liquid sheet behaviour without air flow.

When air velocity increases, the kinetic energy of the air is high enough to counteract the influence of the surface tension in the liquid film, while the liquid cylinder continues to oscillate. The formation of ligaments is also visible when the sheet bends. The influence of air velocity on ligament spacing and break-up length is the same as for the planar case (Fig. 7). In the case of an annular sheet a single image represents the equivalence of the front and side views of the planar case.

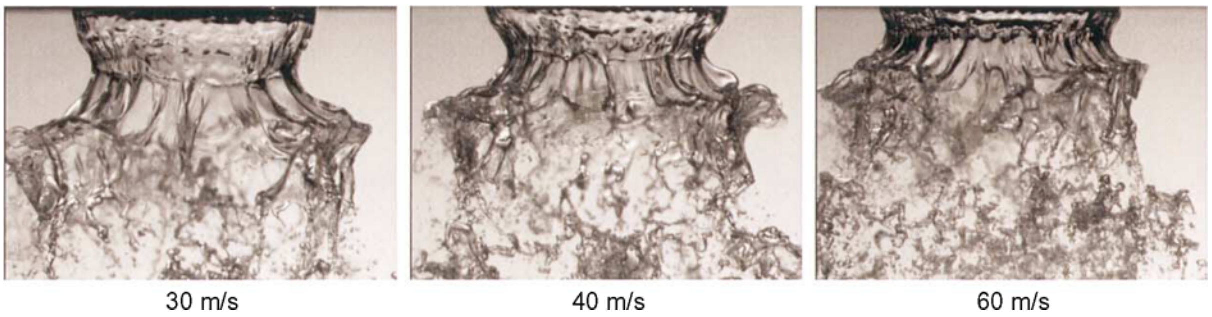


Fig. 7. Annular liquid sheet behaviour according to air velocity (22 mm × 16 mm).

A characterization of oscillation frequencies has been carried out in various flow conditions. To measure sheet oscillation frequency, two systems have been used. In the first case when the oscillation amplitude is high the measure of light attenuation during the cross of the liquid sheet is done with a photodiode. The operating system was similar to the one used by Mansour and Chigier (1991). A Xenon lamp with a collimating lens is placed on one side of the liquid sheet and a photodiode with a small aperture is placed facing it. The signal given by the photodiode is linked to the attenuation of the light by the liquid sheet. This signal is introduced in a Bruel & Kjaer spectrum analyzer to obtain the corresponding oscillation frequency. In the other case as it is difficult to locate correctly the measurement volume on the liquid sheet border, the photodiode is replaced by an high speed video camera. The images are taken with a rate of 4000 images per second. In those conditions the light source is a continuous Xenon lamp, and the camera has an internal shutter which allows an exposure time of 10 μsec. Those images are then analyzed to follow the liquid sheet position on a complete sequence. The position signal on each image is then analyzed and a FFT is applied to obtain the oscillation frequency.

For a given liquid flow rate, measured frequencies increase with air velocity for both cases (Fig. 8). The main difference is on the growth level. In the planar case, the evolution is quasi-linear in the studied air velocity range. In the annular case the evolution is slower, with a logarithmic variation.

At first sight the frequency evolutions, with liquid velocity, are inverted (Fig. 9). The frequency grows in the annular case and decreases in the planar case. We could, therefore, assume that these variations have the same behaviour but in different zones. For low liquid velocities the oscillation frequency of the planar sheet begins to grow to a maximum and then decreases but this maximum is rapidly reached. In the annular case this maximum also exists but is reached for higher liquid velocities.

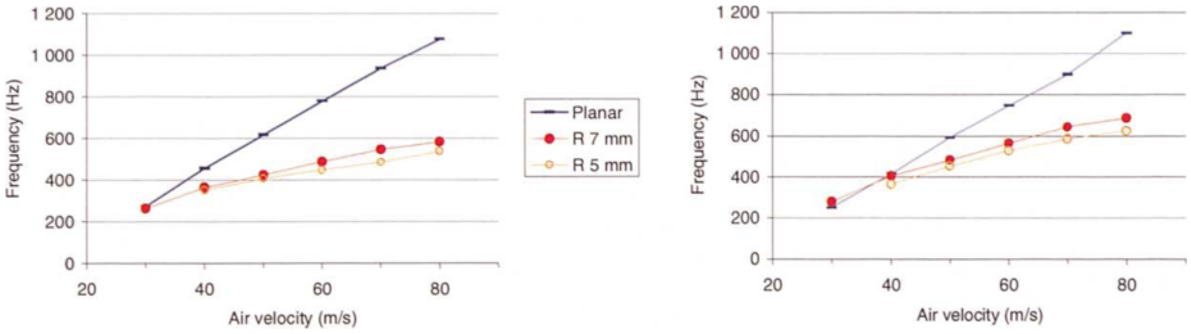


Fig. 8. Frequency evolution against air velocity for two liquid velocities (1.75 m/s and 2.5 m/s).

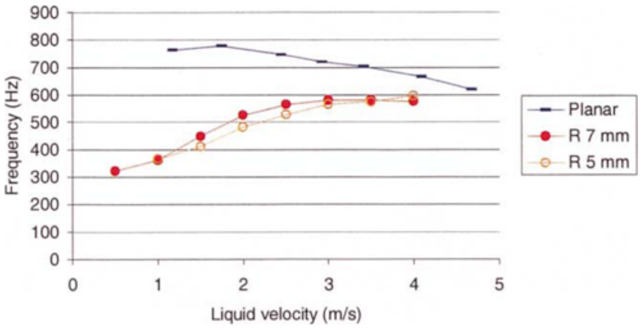
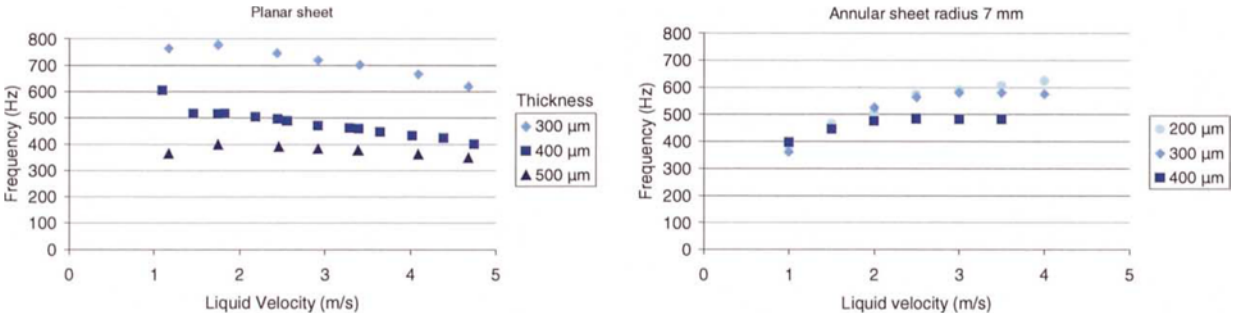


Fig. 9. Frequency evolution against liquid velocity for an air velocity of 50 m/s.

The influence of the liquid film thickness has been tested for the planar and the 7 mm radius annular injector. Sheet behaviour is equivalent in both cases. Due to its higher momentum thicker sheets have a lower oscillation frequency (Fig. 10).


Planar sheet

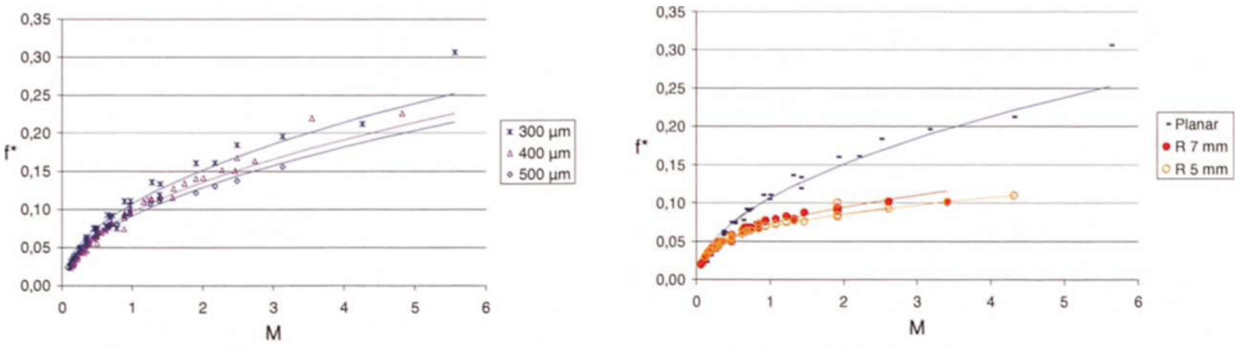
Annular sheet radius 7 mm

Fig. 10. Frequency evolution against thickness for an air velocity of 60 m/s.

In order to interpret the different results, a non dimensional representation is commonly used (Mansour and Chigier, 1991; Lozano et al., 1999). A non dimensional number f^* representing the reduced frequency $f^* = \frac{fe}{U_l}$, (f is the frequency, e the sheet thickness and U_l the liquid velocity), is plotted as a function of the momentum flux ratio $M = \frac{r_g U_g^2}{r_l U_l^2}$, (suffix g representing gas phase and suffix l the liquid phase).

The interpolation curves can be written as the form $f^* = A\sqrt{M}$, with A varying with the injector thickness. This formulation is efficient for low values of M, as experimental data fits well with the interpolation curves. When M becomes high, for low liquid velocities and high air velocities the gap between measurements and interpolation becomes more important.

In Fig. 11, the experimental values are plotted as dots, solid lines represent an interpolation of those measurements. For the planar geometry the evolution of f^* could be approached by a $f^* = aM^{0.5}$, in annular geometry the interpolation is done with respectively $f^* = aM^{0.37}$ for the radius of 7 mm and $f^* = aM^{0.32}$ for the radius of 5 mm. As shown in Fig. 11, lower radii result in lower global oscillation frequencies. More experiments with higher radii are needed in order to be able to conclude that a planar sheet behaves as an annular sheet with high radius.



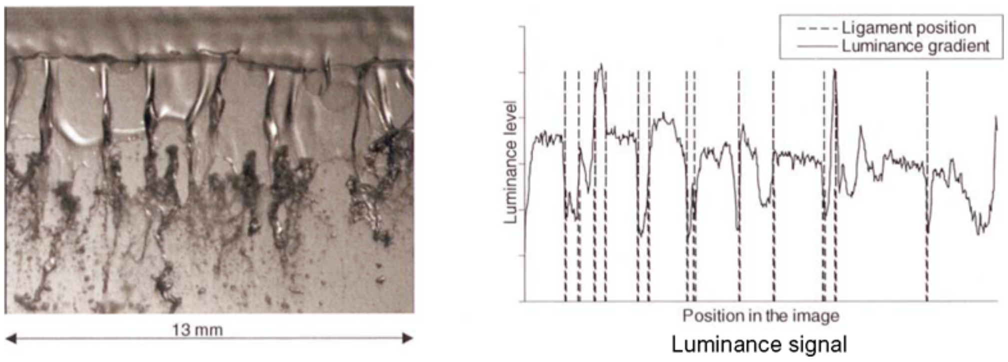
(a) Thickness influence on the planar sheet

(b) Radius influence

Fig. 11. Reduced frequency evolution with momentum flux ratio.

In a second step an analysis of front view images was carried out to measure the variation of ligament spacing. The influence of liquid and air velocity conditions have been tested. To increase the accuracy of the measurements, the images have been magnified.

A large number of images has been analyzed to obtain a statistically good database. The images have been processed semi-automatically by selecting one or several lines in the ligaments formation zone and by analyzing the luminance signal. Figure 12 shows the evolution of the luminance signal on one line in the ligaments formation zone of the image on the right. The application of a threshold on the gradient evolution of the luminance signal permit to detect the ligament boundaries. This process determines the spacing of ligaments with a good accuracy but sometimes some light reflections or bubbles in the liquid give wrong transition, so the operator must validate the position of each ligament. This procedure gives a large number of ligament spacings in a relatively short time. The spacing evolution is given for each velocity condition on more than one hundred ligaments.



Luminance signal

Fig. 12. Image of ligaments, U_{air} = 60 m/s and U_{liq} = 1.7 m/s.

Figure 13 shows the evolution of ligament spacing for a 300 and 400 μm thickness liquid sheet. Plotted data represents the mean value of measurements on 30 images. Results agree with measurement done by Lozano et al. (1999), the spacing decreases with an increase of air velocity or a decrease of liquid velocity.

Thickness has an important influence on ligament formation. In fact ligaments are wider spaced when the sheet is thicker. Nevertheless it is difficult to show a particular behavior (Fig. 13) because the variation of liquid velocity is inverted with the change of liquid film thickness.

As noticed in the description of disintegration mechanisms, the ligaments appear simultaneously with the beginning of the sheet oscillation and break when the oscillation reaches a maximum amplitude. So it seems interesting to represent the ligament spacing according to frequency (Fig. 14). This representation is possible when we simultaneously measure the frequency and ligament spacing for a chosen couple of velocities. Each mark on the following graphic represents an experimental value.

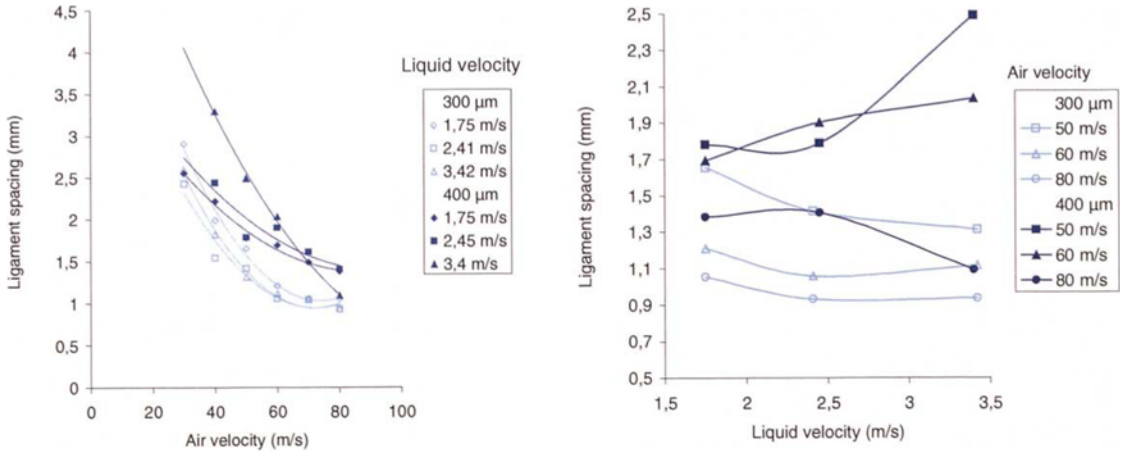


Fig. 13. Ligament spacing evolution with air and liquid velocity for 300 and 400 μm sheet thickness (Planar case).

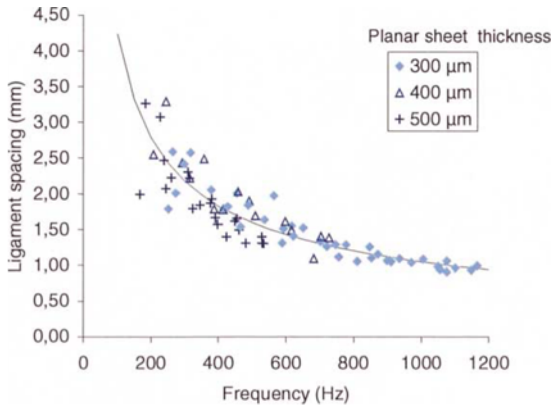


Fig. 14. Measurements of ligament spacing according to oscillation frequency for different liquid sheet thickness.

With this representation, the ligament spacing evolution is simplified. The influence of thickness and velocity conditions are taken into account in a singular relation with the use of the frequency. A single interpolation curve is available for the three thicknesses. This fact is very important because it means that the ligaments formation is highly correlated to sheet oscillation.

In the case of annular sheet, it is not possible to measure directly a distance between ligaments due to the curvature of the liquid sheet. An angle between ligaments is measured. Figure 15 shows the principle of the method. After the designation of the ligaments location a diameter is found by applying a threshold on the image, the ligaments positions are validated by the user and equivalent angle is obtained.

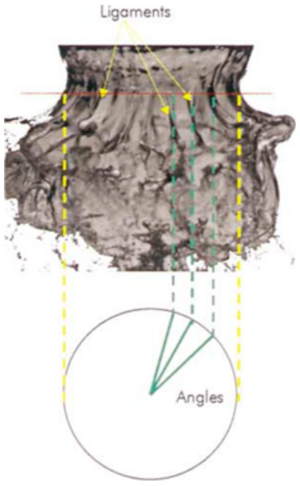


Fig. 15. Ligament spacing measurement on annular liquid sheet.

Ligament spacing can be correlated with frequency (Fig. 16). A dimensional relation between spacing and frequency is obtained by, $s = af^{-0.72}$. For a given frequency, ligament spacing is smaller for the annular case. A probable explanation is that the curvature radius of the sheet downstream is higher in the annular design, which was observed but is not yet measured. In fact this curvature radius is difficult to obtain. Some attempts have been performed for the planar case by laser tomography but this is not applicable for the annular design (Berthoumieu and Carentz, 2000).

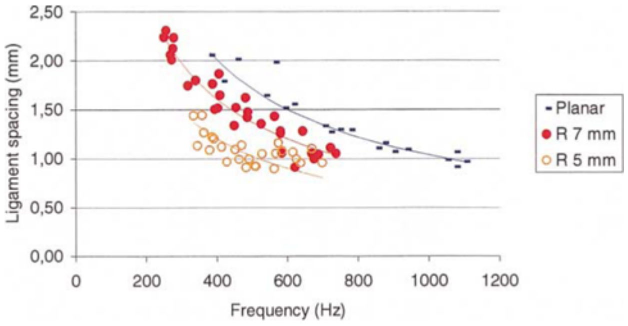


Fig. 16. Ligament spacing evolution with frequency.

4. Conclusion

At this point of our liquid film disintegration study, some correlations have been found and allow to determine empirical models to estimate the oscillation frequencies of the liquid sheet before its disintegration. A bilinear evolution of frequency oscillation with the two fluids velocities has been found. This evolution depends on the liquid film thickness. A relation gives the ligament spacing a function of frequency oscillation. The thickness and velocities are both taken into account in this formulation. These correlations are available as well in planar case as in annular configuration. With these relations the quantity of liquid collected in these ligaments can be estimated and then used to calculate initial drop sizes. Two phase flow computational codes are able to transport those droplets and by the use of secondary break up correlations, to determine the final drop size and droplet repartition. Understanding of some processes remains to be improved. It is now difficult to describe how ligaments breaking occurs.

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Authors Profile

Pierre Berthoumieu: He received his doctor's degree in Mechanics from University Paul Sabatier of Toulouse in 1983. Since 1985 he is working at ONERA in the DMAE (Aerodynamics and Energetics Models Department) in the multiphase flow unit. He has been in charge of the development of visualization techniques and image processing in the study of sprays.

Gérard Lavergne: He received his doctor's degree in Mechanics from University Paul Sabatier of Toulouse in 1978. Since 1979 he is involved in propulsion and mainly in two phase flow studies at ONERA-DMAE (Aerodynamics and Energetics Models Department). Since 1997 he has been the head of Multiphase Flow Research Unit. He is also teaching in Supaero School.