

## **THE EFFECT OF AMBIENT AIR PRESSURE ON PLANAR LIQUID SHEET DISINTEGRATION AT GAS-TURBINE CONDITIONS**

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### **ABSTRACT**

Understanding the mechanisms of airblast atomisation is necessary to establish design guidelines for industrial air-blast injectors used in liquid-fuelled gas turbines. The motivation is ultimately to predict (and perhaps control) the atomisation performance and fuel placement of an airblast injector from the geometry and the operating conditions of the combustor. A second incentive is understanding the coupling between atomisation and combustion stability.

Experiments performed at ONERA and DLR in the frame of a cooperation analyse the disintegration of a planar liquid sheet on a prefilmer plate at isothermal conditions. The behaviour of the spray atomisation studied at ONERA at standard conditions is compared to the measurements taken at DLR, which were performed under elevated static pressure at room temperature. The similarity conditions are the Weber number, the dynamic pressure of the air flow, and the liquid inlet velocity.

The comparison between these experiments highlights the dramatic effect of an increase in air density on the atomisation. A clear distinction of subsequent break-up processes is no longer possible under high static pressure. Although the mass flow of injected kerosine still has an influence on the spatial distribution of the spray, the droplet size depends only on the air flow conditions.

### **INTRODUCTION**

Understanding the physics of liquid sheet disintegration is a major goal in research on gas turbines. The aim is to provide reliable tools for prediction and improvement of airblast atomiser performance (in terms of particle size, local spray density, and fuel placement) over the whole operating range of a liquid-fuelled system, such as an aeroengine. A second incentive is to analyse the coupling between fuel injection and combustion stability, especially for what concerns the development of lean-burn, low-Nox combustors. Understanding this relationship is a key to the design of robust combustion systems.

Air-blast atomisation is a complex process involving momentum transfer over a very small length scale between a low velocity kerosine liquid film and high velocity, high turbulence, and often swirled air flow, at elevated temperature and pressure. The different phenomena taking place in airblast atomisation have been decoupled and extensively studied for liquid round jet and flat sheet atomiser geometries at standard conditions (Lefebvre [1], Lozano et al [2], Marmottant and Villermaux [3]), with relative velocities up to 140 m/s, and well-defined turbulence levels for each of the two phases. Numerous models reproducing the successive break-up of the liquid from injection until achieving a steady droplet size distribution have been numerically validated.

In the frame of a cooperation, ONERA and DLR studied the liquid atomisation of a laboratory injector with similar prefilming geometries. Berthoumieu and Carentz [4] from ONERA performed measurements at standard conditions on the primary breakup of a wavy liquid sheet for water and ethanol yielding a specific oscillation frequency and corresponding particle size, primarily using visualisation methods. Following that, Kutzbach et al. [5] made a simulation using the Volume of Fluid (VoF) module of Fluent, which reproduced the sheet longitudinal flapping frequency and primary break-up length observed experimentally by Carentz [6]. The current project began when drops size and dispersion measurements previously performed at DLR (Brandt et al. [7]) with kerosine under elevated pressure were complemented with further measurements at intermediate pressure including visualisation techniques. The experiments were performed at isothermal conditions at room temperature. To compare the atmospheric and intermediate pressure measurements, the air flow dynamic pressure, liquid sheet injection velocity, and Weber number were kept constant. Ethanol was used at standard conditions because its surface tension is similar to kerosine's.

The laboratory model for airblast atomisation, the test rig and the measurement techniques are presented first. The analysis of the planar liquid sheet disintegration is as follows: the atomisation process for atmospheric and intermediate pressures is compared with visualisation techniques. Then the frequencies measured at the tip of the prefilmer are reported. After that, the measurements of the resulting spray with PDA and Malvern instruments establish trends of particle size and dispersion with increasing air velocity or pressure. Finally, the comparison between liquid sheet behaviour and resulting atomisation establishes the dramatic effect of the increase in air pressure on the liquid sheet disintegration.

## EXPERIMENTAL SETUP

### Principles of air blast atomisation, and modelling

The air-blast atomiser used in this study (figure 1, right) was designed to simulate the practical one commonly found in today's aeroengines (figure 1, left). Liquid enters the air-blast atomiser through a pressure swirl atomiser that generates a hollow cone spray, which impinges on the walls of a short converging canal known as the swirl cup or venturi (Becker and Hassa [8]). This impingement generates a liquid film that is transported by the inner air flow towards the atomiser lip. Two radial inflow swirlers induce a swirling motion on the air flows outside of the swirl cup. The atomisation of the liquid fuel film takes place mainly within the mixing layer developing downstream of the atomiser lip. The air swirl creates a central toroidal vortex stabilizing the flame along its outer limits, so that a physical flame-holder is not required.

The airblast atomiser efficiently produces small particles and good mixing at full-load (take-off and cruising) thus preventing excessive soot formation. The drawback, however, is a rather coarse spray at part-load (idle mode).

In order to analyse the physics of the air-blast atomisation in this device, the focus is first put on the interaction between the liquid sheet moving along the last millimetres of the swirl cup and two co-flowing streams of air, and then on the resulting atomisation. In the prefilming atomiser (figure 1, right) the closed tube-shaped original film is modelled as a flat film for both optical access and ease of manipulation. Due to the high curvature to film-thickness ratio of the swirl cup, the flat film represents a discrete sector of the original film, and measurements performed in the centre of the liquid sheet do not suffer from edge effects. Due to the high aspect ratio (film width / film thickness = 60) the flow of the sheet can be assumed to be two-dimensional.

Hence, parameters such as the film curvature effect or shear strain due to the presence of swirling flows are not analysed in this phase of the work. Nevertheless, this configuration represents a useful intermediate step towards reality.

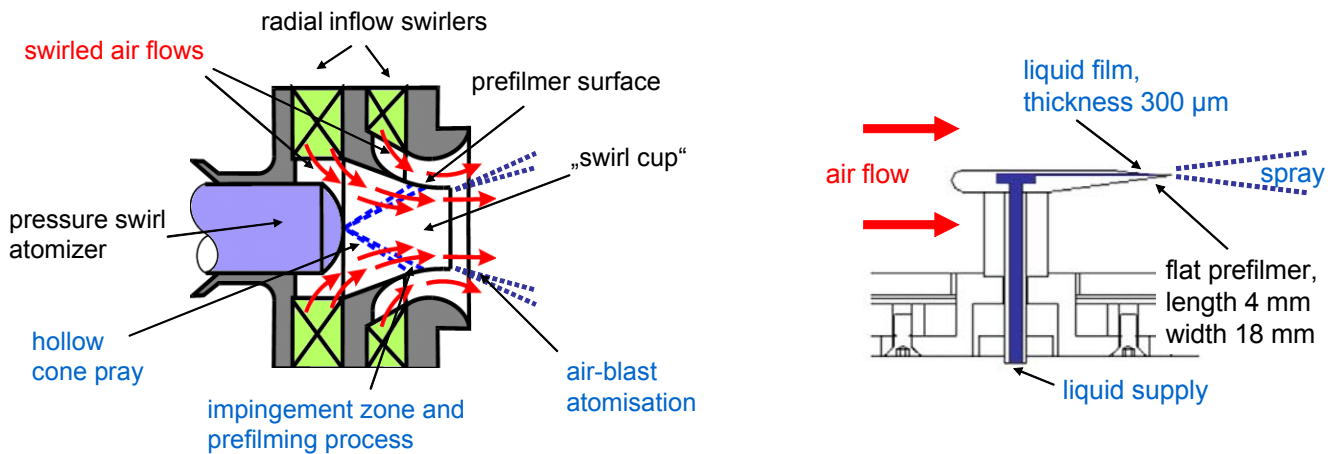


Figure 1 : Real air-blast injection principles (left), and laboratory model (right).

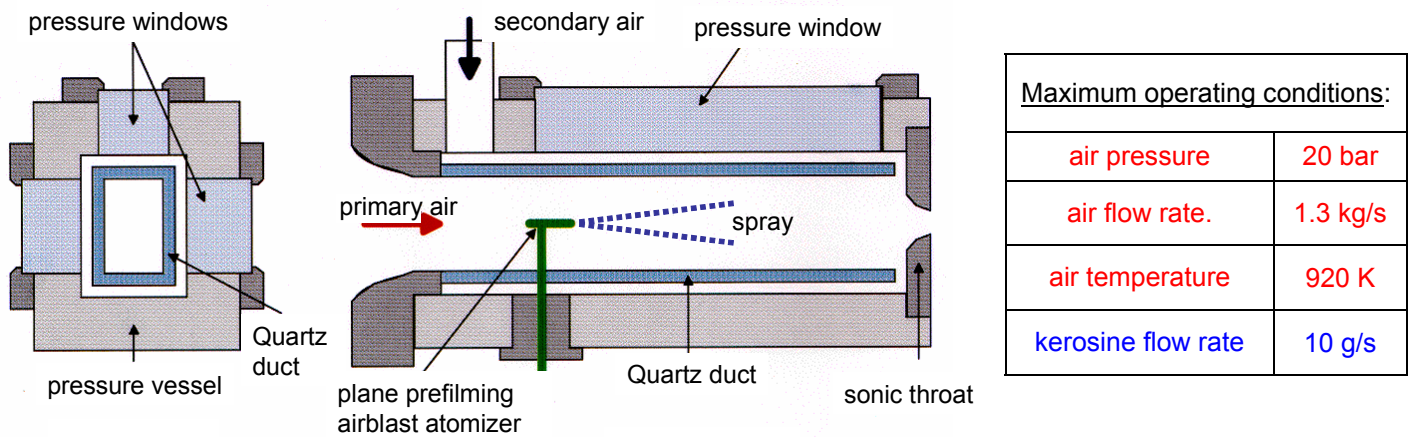
### Experimental test section

The LPP test rig allows both the atomisation and vaporisation process to be reproduced under realistic conditions of pressure and temperature, in non-reactive conditions. This facility (Brandt et al. [7]) was originally conceived for a lean premixing and prevaporisation (LPP) burner study.

The test section is depicted in figure 2: it consists of an inner glass channel made of Herasil for high temperature measurements, surrounded by a peripheral cooling duct. A set of 3 high-pressure windows provide optical access. The volume of investigation is 40\*40\*200 mm. The maximum operating conditions of the test rig are reported in figure 2 (right). For environmental reasons, the kerosene mass flow is limited by the operating range of an afterburner placed downstream of the installation.

The combination of air pressure and velocity ( $P, V$ ) depends on the temperature of the flow and on the diameter of the sonic throat placed at the end of the test section. The available set of diameters, from 23 mm to 41 mm, make the axial air velocity vary from 40 m/s to 120 m/s at room temperature. A flame detector turns off the fuel supply in case of auto-ignition, though this risk is negligible at room temperature.

The installation at ONERA for atmospheric pressure measurements included an open windtunnel, similar to the inner glass channel (no secondary air and no sonic throat), for the analysis of the confined case, and a free-jet configuration, where the outer limit of the primary air duct is aligned with the tip of the injector for the visualisations.



**Figure 2 : Experimental test section. Front and side sections of the test rig.**

### Instrumentation and data processing

A CCD camera was used for the visualisations performed at both ONERA and DLR. Pictures were taken at 25 Hz in non-interlaced mode, with background lighting (experiments at standard condition) or forward lighting with a reflective background surface (experiments at elevated pressure) in order to visualise the prefilmer surface and the resulting atomisation simultaneously. Some results are shown in figure 3. The image processing (structure and ligament sizing, spray dispersion angle, spray envelope...) was done with a software developed by Berthoumieu [4].

Concerning the measurement of the liquid film flapping frequency at the tip of the injector, the line-of-sight He-Ne laser light intensity (633 nm, 5 mW) intermittently obstructed by the passage of liquid was measured by a photodetector (Si diode) connected to a B&K spectral analyser (see figure 4, left).

For the quantitative analysis performed on the resulting spray, PDA measurements were conducted focusing on the spatial distribution of liquid fuel flux and SMD. A Dantec 2-D PDA system was used to measure the axial and the vertical droplet velocities and the droplet diameters. A spectral analysis routine was developed in order to observe cyclic passage of particles, based on the time of appearance of events measured by the PDA. This method consists in the analysis of a time-resolved sampling of event packets, and is discussed in more detail by Ramond [9].

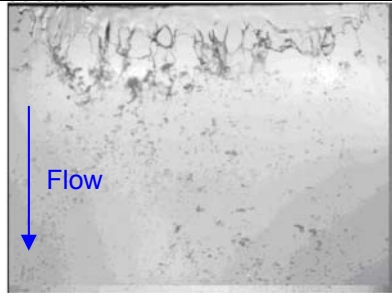

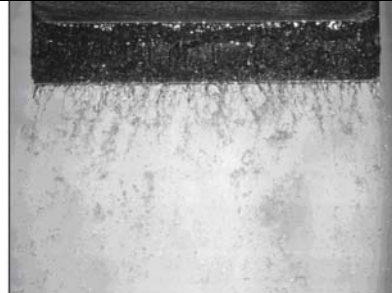
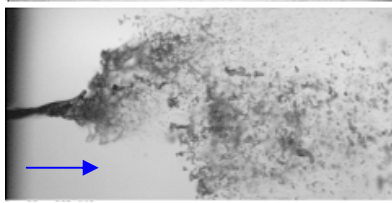


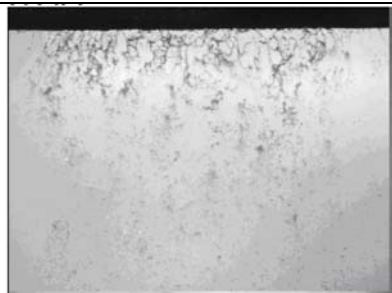


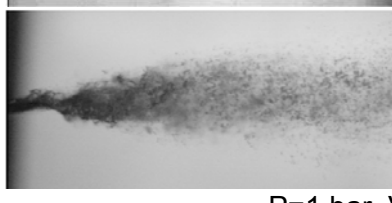

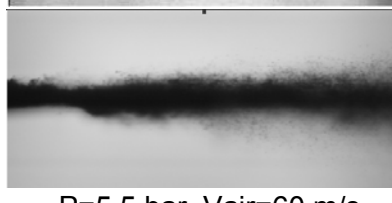
Additionally, a Malvern ECPS unit was used for the operating range investigated by the PDA. It simultaneously measures the droplet size distribution and the relative spray density based on an analysis of forward scattering and line-of-sight extinction of laser light. A post-processing correction was required due to multiple parasitic laser reflections between the window surfaces (Giuliani and Hassa., 2003 [10]).

## THE EFFECT OF AMBIENT AIR PRESSURE ON PLANAR LIQUID SHEET DISINTEGRATION

### Regimes of disintegration at atmospheric pressure

At atmospheric pressure, the thin film disintegration process is defined as a function of the air and liquid inlet conditions and the geometry of the injector. Until medium-range relative velocities are reached, the liquid sheet behaves as is visible in the top left view of figure 3.

- The liquid film exists at the tip of the prefilmer. Longitudinal and then transverse waves appear on the liquid surface. These instabilities are responsible for the rupture of the film, leading to the generation of liquid ligaments. This is known as primary disintegration.
- The ligaments also encounter an instability, resulting in their break-up and the generation of spherical droplets. After that the liquid exists in a droplet state. This is secondary disintegration. As more clearly shown by Pilch and Erdman [11], the secondary atomisation includes multiple breakup mechanisms according to the particle sizes and local flow conditions. Anyhow, the droplet size distribution is steady a few millimetres downstream of the secondary disintegration zone, which was confirmed with the help of PDA measurements.

			Atmospheric pressure		Elevated pressure
			Water	Ethanol	Kerosine
Similarity condition	$\rho V_{air}^2/2=3564 \text{ Pa}$	Top view			
		Side view			
			P=1 bar, Vair=77 m/s		P=1.6 bar, Vair=60 m/s
	$\rho V_{air}^2/2=11880 \text{ Pa}$	Top view			
		Side view			
			P=1 bar, Vair=141m/s		P=5.5 bar, Vair=60 m/s

**Figure 3: Thin liquid film disintegration snapshots with background lighting (top and side views) for water, ethanol and kerosine. Liquid injection velocity: 1 m/s. Film inlet height: 300  $\mu\text{m}$ . Width of each view: 20mm.**

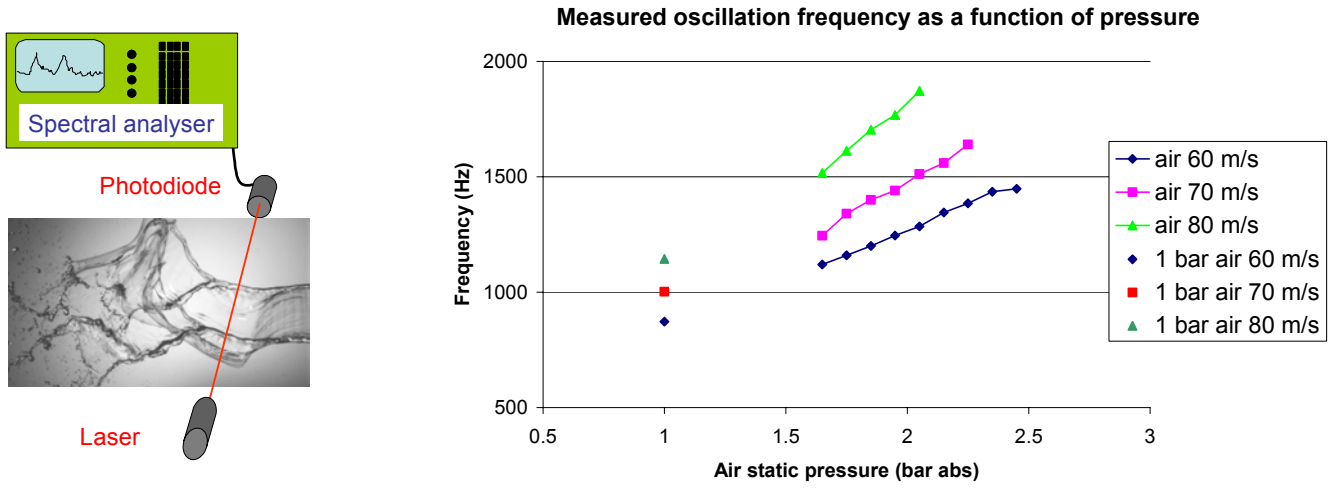
### Atomisation behaviour at elevated pressure

The comparison in figure 3 highlights the dramatic effect of an increase in air density. The top view shows that the size of the visible liquid structures is reduced under pressure, making a clear distinction of subsequent break-up processes no longer possible. An organised wavy sheet motion is clearly visible on the measurements at atmospheric pressure (see the side view) as predicted by Lefebvre [1].

Concerning the atomisation of kerosine at intermediate pressure, frequency measurements performed with the laser-obstruction technique (see figure 4, left) on the structured flapping motion of the liquid sheet at the atomiser lip are discussed (figure 4, right). The general trend is a linear rise of frequency with pressure, the slope of this rise being a function of the air velocity. The linear correlation between standard condition measurements and the same conditions at elevated pressure is satisfactory for low velocities (see the 60 m/s curve), the deviation is greatest at high velocities. The dramatic loss in terms of amplitude of motion with pressure and the uncertainty of the exact spectrum peak position is a significant source of error. The flapping motion is a part of the primary disintegration process, and these experiments show that this motion, while conserved, decreases in terms of amplitude with rising pressure and velocity, until it is no longer detectable.

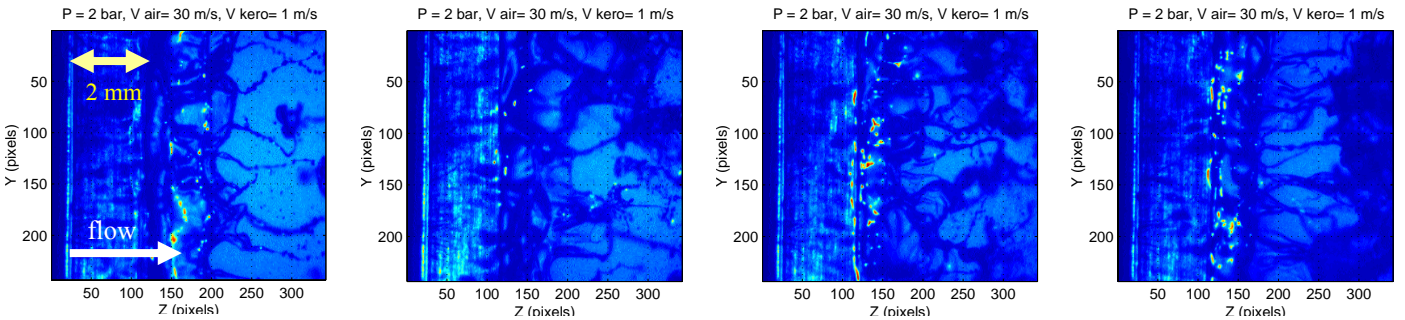
At higher air dynamic pressure (lower row in figure 3), the water and ethanol sprays also both lose an organized wavy motion. This is the “prompt atomisation regime” described by Lefebvre, where some “sheet stripping” (or atomisation over the surface of the film, a notion discussed by Sridhara and Raghunandan [12]) is already visible at the surface of the prefilmer. However, even for the ethanol spray with a Weber number similar to the one of kerosine, a difference due to the effect of air density remains. The liquid film itself no longer continuously develops on the prefilmer plate under elevated pressure, and the notion of liquid film disintegration after the atomizer lip as it is usually observed at atmospheric pressure needs to be revised for engine conditions.





**Figure 4: Variation of the liquid film oscillation frequency with pressure for ethanol (1 bar) and kerosine (intermediate pressure). Left: principle of the laser obstruction measurement technique (the beam is placed in the plane of the liquid sheet a few millimetres down the prefilmer tip). Right: film flapping oscillation frequency measurements. Liquid injection velocity is 1m/s.**

A close-up on kerosine atomisation (figure 5) shows the complexity of the process. Even though air velocity and pressure are quite low, we observe that a sheet hardly exists at the tip of the prefilmer. No repetitive patterns (film length, ligament size and disposition) are seen from one picture to the next, the primary atomisation seems extremely chaotic. It is not clear if the measured frequency reported in figure 4 consists in a flapping motion (the surface looks like it endures a 3D motion) or a cyclic detachment of liquid situated directly at the tip of the prefilm where the second liquid surface meets the air, such as the last picture of the samples suggests.



**Figure 5: Snapshots (non consecutive) of thin kerosine sheet atomisation. The 2-mm long prefilmer plate is visible on the left part of each picture. Static pressure: 2 bars, air velocity: 30 m/s, liquid injection velocity: 1m/s. 1  $\mu$ s exposure duration.**

### Particle size analysis

The PDA investigation was realised as shown in figure 6. Due to problems of optical access and spray density, the data validation rate becomes acceptable 15 mm away from the tip of the prefilmer. At this distance, the atomisation process is believed to be complete (see the 20 mm long side views for kerosine in figure 3). The average velocity of the particles will increase until about Z=50 mm before it achieves the air velocity (figure 6, upper right).

The liquid flux is measured for each X-traverse (figure 6, bottom left). The space distribution of the liquid flux along X is close to a normal distribution. The selected boundaries, in order to investigate the spray dispersion, are placed at 2 times the standard deviation  $\sigma$  on each side of the median of the liquid flux distribution through the spray.

The chosen parameter for the atomisation effectiveness is the Sauter Mean Diameter SMD [m or  $\mu$ m] defined as:

$$SMD = \frac{\sum_{i=1}^k n_i d_i^3}{\sum_{i=1}^k n_i d_i^2}$$

where  $d_i$  is the diameter of a particle belonging to a size interval ranked  $i$

and  $n_i$  is the number of particles belonging to the interval ranked  $i$

The interest in the SMD for atomisation related to combustion is that it models the spray as a monosized atomisation where the liquid flux and overall surface exchange are similar to the real spray's.

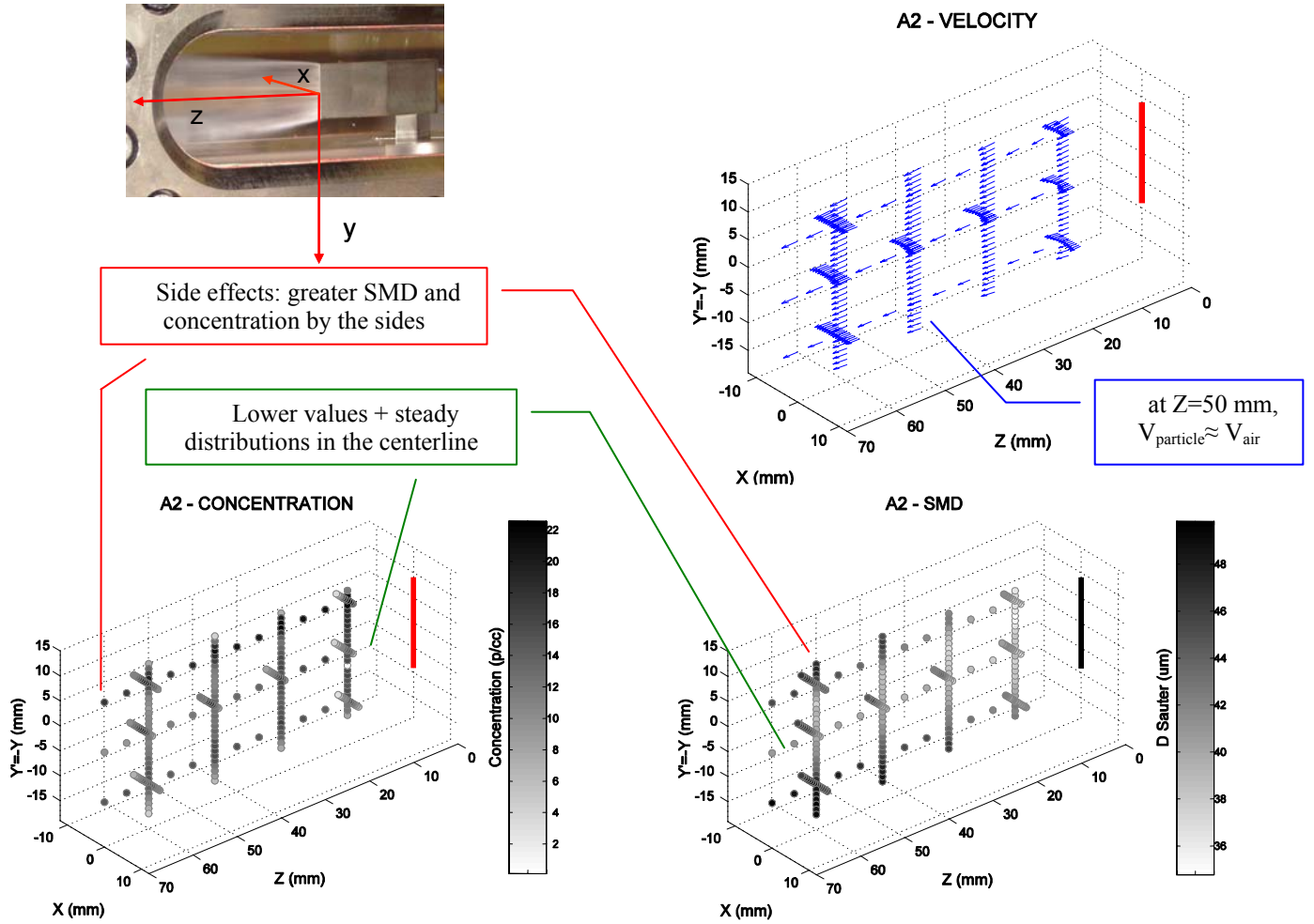


Figure 6: PDA measurements performed on the spray. Top left: picture of the atomiser mounted in flag configuration, with corresponding system of coordinates. Top right: 3D measurement grid with corresponding axial velocities. Bottom left: qualitative spray concentration. Bottom right: SMD. Air injection conditions: 60 m/s at 3.3 bar, kerosine injected at 2 m/s.

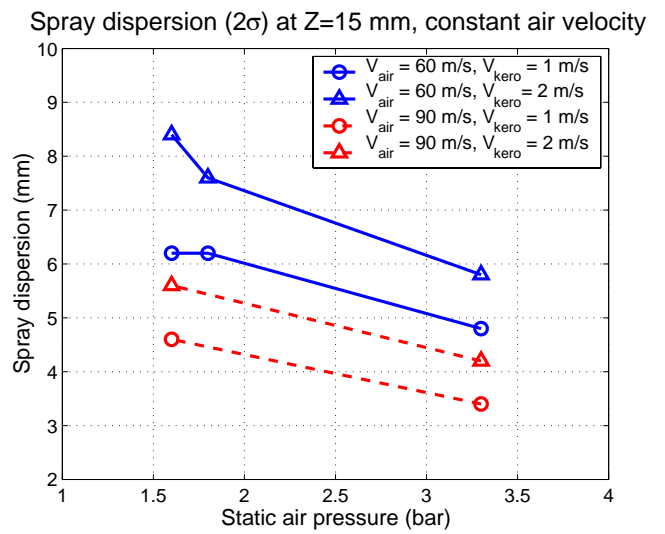
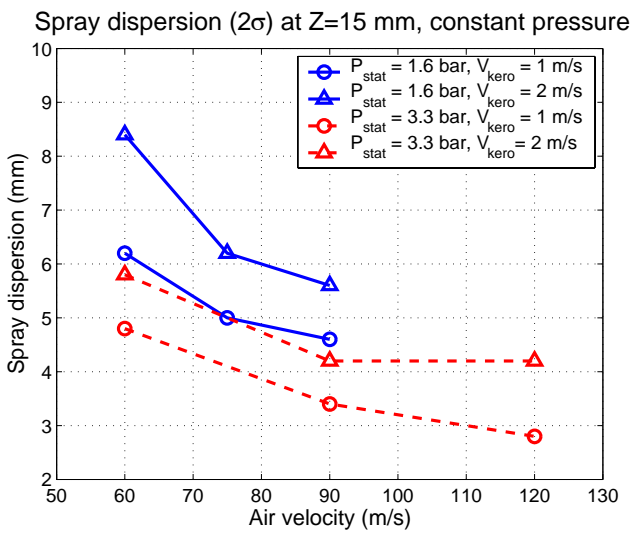
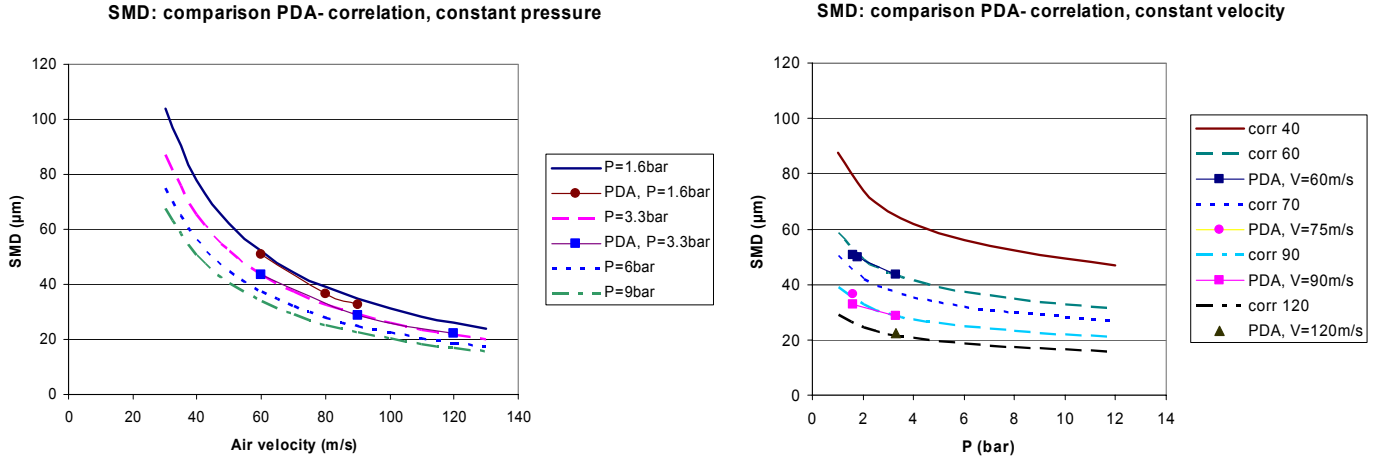


Figure 7: Evolution of the spray dispersion at constant pressure (left) and constant velocity (right). The measurement is based on a X-traverse placed at  $Z = 15$  mm ( $Y=0$ ).

The spray dispersion as a function of air velocity and pressure is reported in figure 7. The general trend is a dramatic decrease at low pressures or velocities, followed by an asymptotic behaviour towards higher values. We note also that the liquid flow rate has a significant affect on the spray boundaries. Assuming that a flapping motion exists at low (P,V) conditions, it could be related to the high dispersion values observed in these regions (the alternate sweeping motion of the liquid film distributes the liquid over a wider range). The “wavy-sheet” motion no longer exists above P=2.5 bar and V=80 m/s. For higher (P,V) conditions, the spray dispersion seems to become a function of the air mixing layer width downwards from the prefilmer, and of the quantity of injected kerosine.



**Figure 8: Evolution of the SMD at constant pressure (left) and constant velocity (right). The established correlation is compared with the PDA measurements.**

Concerning the effectiveness of the atomisation, it was found that the quantity of injected kerosine has a negligible affect on the resulting droplet size distribution. The spray SMD was systematically only a function of the (P,V) air conditions. The coupled PDA-MALVERN investigation led to the establishment of the following correlation:

$$\|SMD\| = \left\| \frac{6.237 \cdot 10^{-2}}{V \sqrt[4]{P}} \right\|$$

where the SMD is expressed in [m] provided the axial air velocities  $V$  is given in [m/s] and the air static pressure is given in [Pa].

The trends of the SMD evolution as a function of the air velocity or pressure are shown in figure 8. We note in both cases no sudden change in behaviour that could be related to a change of liquid regime.

The spectral analysis performed on the PDA data does not show a peak in the frequency domain related to the flapping motion of the liquid sheet at intermediate (P,V) air conditions. If a cyclic detachment related to the primary disintegration exists, as suggested by the results from figure 5, this periodicity does not survive the secondary atomisation process. So that, the clear deterministic relationship between the film behaviour at the atomiser lip and the resulting atomisation observed at atmospheric pressure could not be extended to the disintegration at elevated pressure.

## CONCLUSION

The phenomenology of liquid sheet disintegration varies in a dramatic way when augmenting the static pressure, so that the atomisation sequence can no longer be compared with atmospheric experiments realised at similar conditions of dynamic pressure, liquid injection velocity, and Weber number. At intermediate conditions of air pressure and velocity, the primary atomisation takes place directly at the tip of the prefilmer. Augmenting the pressure or air moves the atomisation process back along the prefilming surface, where primary and secondary atomisation are hard to differentiate. So that it seems to be the sheet stripping process, obtained at relatively high air velocities under atmospheric conditions, that drives the atomisation under elevated pressure. Augmenting the temperature would reduce the liquid surface tension, and would further enhance this immediate sheet stripping atomisation at the liquid outlet.

The primary disintegration at atmospheric pressure is responsible for both periodic liquid release and liquid spatial distribution through a structured sweeping motion. This no longer occurs at elevated pressure, where the presence of the wavy sheet motion does not result in a periodic spray, so that this periodicity is smoothed by the secondary disintegration process. Here, the droplet size distribution seems to be driven only by the air flow conditions. The liquid flow conditions affect only the spray spatial distribution, even though augmenting air velocity or pressure tend to provide a more compact spray.

Concerning the understanding of the disintegration at elevated pressure, the effort should be put on the interaction of air and liquid within the air boundary layer at the surface of the prefilm, which is a technical challenge given the complexity of the 2-phase flow there. The intermediate pressure and velocity ranges, where the liquid prefilm still exists are currently under investigation at DLR. A transparent prefilmer that will be used to visualise the zone of contact between the liquid film and the prefilmer plate without disturbance from flying particles will provide further information on the actual atomisation process at realistic operating conditions.

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