1. INTRODUCTION

Lean Premixed Pre-vaporized burners have been individuated by many industrial actors as the most promising technology in order to achieve low emission levels even if their degree of reliability is not completely satisfying.

As a consequence, since several years, numerous efforts have been made in order to comprehend more in depth the physical phenomena having place within such a kind of combustors. In particular, swirl stabilized burners have been investigated as the most suitable burner configuration. Attention has been focused mainly on two aspects: combustor flow field dynamic analysis and combustor overall performances (emissions, temperature distributions, efficiency, etc.).

With reference to the first mentioned topics, many authors have been highlighted the presence of a marked central recirculation zone often characterized by periodical velocity components fluctuations [1, 2, 3, 4]. This recirculation zone is deemed quite important in order to anchor the flame front, but, at the same time, can be put in relation with flame flash-back and auto-ignition phenomena within the premixing sections. Moreover, the periodical fluctuations detected within that zone can be considered responsible of triggering combustion instability phenomena [5, 6, 7].

The performances characterisation of this type of burners, in terms of emissions, temperature distributions, efficiency, etc., is the object of many studies [8, 9, 10].

These studies point out the capability to obtain a significant emissions reduction but also a worrying tendency to an unstable operational behaviour: lean blow-out and combustion instabilities (humming) phenomena.

The scope of the present research activity is to link the fluid-dynamic behaviour of a Lean Premixed Pre-vaporized (LPP) burner, designed by Avio S.p.A. for aeronautical applications. Main object of the present paper is that of achieving an in-depth interpretation of the interactions taking place between the unsteadiness of a complex air flow field and the dynamical behaviour of a liquid-fuel film break-up.

The experimental campaigns were focused upon the detailed characterisation of the unsteady air flow field as well as of the fuel spray dynamics in terms of velocities, diameters and spatial distribution of the fuel droplets. In order to perform the required measurements in a most accurate way, a 4.73-to-1 enlarged-scale model of an LPP burner has been realised. Measurements have been carried out by means of multiple laser-based instrumentations, namely: Laser Doppler Anemometry (LDA), Phase Doppler Anemometry (PDA) and Particle Image Velocimetry (PIV). Taking advantage of these measurements, taken in phase with the pulsating turbulent phenomena as induced by the precessing-vortex motion of the air flow field within the LPP injector, it has been possible to capture and clearly observe the unsteadiness of the fuel release from the premixing-duct exit lip. In particular, the fluctuations, in time and space, have been mapped of the number of droplets discharged from the liquid film break-up, together with their diameter distributions, both representative of the local fraction of the still un-evaporated liquid fuel mass-flow rate. Correlation and direct dependence of the fuel discharge fluctuations upon the pulsations within the air flow field have been clearly established by all measurements.


2. EXPERIMENTAL SET-UP

2.1 Test-rig

The test-rig (Fig. 1) consists of a centrifugal fan supplying the air flow, an electrical preheater to obtain the appropriate air temperature, and a settling chamber equipped with a honeycomb and screens to guarantee steady uniform flow. The LPP burner is installed between the settling chamber and a rectangular single sector duct simulating the combustion chamber with optical access from three sides.

The main parameters of the test-rig are:
- 15 kW variable speed centrifugal fan,
- 100 kW regulating air preheater,
- air flow rate up to 0.7 kg/s,
- maximum settling chamber pressure 115000 Pa,
- air temperature up to 700 K.

Fig. 1 Test–rig overview

The experimental measurements, here presented, have been carried out on a scaled model of a real prototype. The experimental operating point was determined imposing three conditions:

- conservation of the Reynolds number between the prototype and the tested model;
- conservation of the air/fuel mass ratio (AFR = 24);
- conservation of the ratio between the evaporation time and the residence time of the droplets in the premixing duct.

The ratio between the evaporation time \( t_e \) and the residence time \( t_r \) has been calculated as

\[
\frac{t_e}{t_r} = \frac{D_0^2}{KL} C_a
\]

where:
- \( D_0 \) is the initial droplet diameter,
- \( K \) is the evaporation rate constant, based on the single drop evaporation model [11],
- \( C_a \) is the mean axial velocity in the LPP burner,
- \( L \) is the axial length of the premixing duct.

From these similarity conditions hypotheses, the air and fuel flow rates, the air preheating temperature and the nominal diameter of the nozzle generated fuel droplets were evaluated. A mixture of ethanol (90%) and water (10%) has been chosen as fuel. The effectiveness of ethanol as fuel for spray and vaporization tests has been stated by previous studies, e.g. [12]. The operating conditions are summarized in Table 1. The burner pressure drop measured at these conditions is 2.2 per cent.

<table>
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<th>Air flow [kg/s]</th>
<th>Air temperature [K]</th>
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<td>100000</td>
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<tr>
<td>Fuel flow [kg/s]</td>
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2.2 LPP burner

The experiments were carried out on a large scale model (5:1) of a LPP burner for aero-engine application. The mixing tube exit diameter is 104 mm.

The LPP burner (Fig. 2) is equipped with two co-rotating centrifugal swirlers with different exit angles (Fig. 3), in order to create a zone with high shear stresses that enhances the fuel droplets evaporation rate and the air-fuel mixing.

Fig.2 LPP burner

Fig.3 Inner and outer swirler

The design swirl number is 0.5. The fuel injection and atomization is performed by means of a DELAVAN WM556 hollow cone nozzle located on the LPP burner axis and fed at 5 MPa, that produces droplets with a 40 µm nominal SMD and a spray cone angle of 60°.

In order to verify the nominal spray characteristics, an experimental characterization of the fuel nozzle has been carried out by means of PDA measurements at cold condition and in absence of air flow. The results obtained on a radial traverse located 10 mm downstream the nozzle confirmed that the actual droplets SMD varied between 30 and 50 µm.

2.3 LDV/PDA system characteristics

Time resolved velocity measurements at the exit of the LPP burner have been performed by means of a four-beam two-colour fibre optic LDV/PDA system with forward-scatter collection optics. The light source is a 300 mW argon ion laser, operating at 514.5 nm (green) and 488 nm (blue). The transmitting probe has a front lens of 300 mm focal length and a beam separation of 38 mm, resulting in a geometrical control volume of 90 µm diameter and 1.9 mm length. The LDV/PDA receiving probe is a fibre 112 mm PDA probe DANTEC 57X90, with a front lens focal length of 300 mm and a spatial filter maintained to its maximum aperture of 200 µm.

The probes are stiffly mounted on a three-axis computer-controlled traversing mechanism. The motion is transmitted to the carriages by stepping motors through a preloaded ball-screw assembly with a minimum linear translation step of 8 µm. A Bragg cell is used to apply a frequency shift (40 MHz) to one of each pair of beams and
allows to solve directional ambiguity and to reduce angle bias.

For the air velocity field characterization the flow is seeded with a 0.5-2.5 µm atomized spray of silicon oil injected in the settling chamber, whereas for the liquid phase analysis the fuel droplets themselves act as scattering particles.

Drop sizes were measured in the first order refraction mode. Light was polarized parallel to the scattering plane and to minimize reflection effects a scattering angle of 70° was utilized.

The Doppler signals are transmitted by optical fibres to the receiving unit (Dantec Dual PDA 58N81 detector unit) where they are filtered to minimize the background noise. The signal transduced by the photomultipliers is collected by a Burst Spectrum Analyzer (Dantec BSA P70 processor). The frequency range extends from 122 Hz up to 120 MHz, with accuracy better than 0.1% of the bandwidth. Dedicated software is used for the data post-processing and the results visualization.

A comprehensive analysis of experimental uncertainty associated with LDV measurements is given by Boutier [13]. A specific evaluation of error for frequency domain processors is given by Modarress et al. [14]. Based on the above references and on authors’ experience in LDV measurements, the uncertainty on the single velocity LDV realization has been estimated to be lower than 2 per cent.

Uncertainty of drop size measurements has been extensively analyzed in literature, e.g. [15, 16]. The flow was surveyed on a traverse located 30 mm downstream of the premixing duct (Fig. 4), made of 28 equally spaced measuring points, with the initial point on the axis of the premixing duct.

2.4 PIV/Mie-scattering system characteristics

Two synchronized Nd:YAG lasers are employed to generate two light sheets with a narrow time delay depending on flow velocity, a CCD camera collects the couple of flow field images that are analyzed by means of spatial cross-correlations by the Dantec FlowMap 2100 processor.

For the PIV campaigns two different set-ups were utilized (Fig. 5): the first one allowed to obtain the velocity distribution in the meridional plane of the duct simulating the flame tube (plane containing the LPP burner axis); the second one allowed to perform measurements in the frontal plane located 30 mm downstream of the premixing duct, where also the LDV/PDA data have been collected.

Systematic uncertainties for PIV velocity measurements have been extensively analyzed in literature, e.g. [17]. Based on the above references systematic error of 4% has been evaluated for the present experiment and instrumentation.

2.5 Data processing

LDV/PDA data were processed by means of an ensemble averaged technique. An air-cooled miniaturized pressure transducer, located at the wall downstream of the LPP burner, provides a reference signal in phase with the relevant periodic phenomenon. To obtain statistically accurate ensemble averages, a total of 100000 validated data for each velocity component have been collected for each measuring position. Instantaneous velocities and drop diameters are sorted into 8 phase bins, each representing a particular phase of the cycle. In regions where the data rate fell down from the typical value of 1 kHz to about 100 Hz a minimum number of 10000 samples were collected.

The time-varying mean velocity component \( \bar{v} \) is obtained by ensemble averaging the samples

\[
\bar{v}(i) = \frac{1}{K_i} \sum_{k=1}^{K_i} v(i,k)
\]

where \( i = 1 \ldots I \) is the index of the phases into which a perturbation period is subdivided and \( k = 1 \ldots K_i \) is the index of the samples for each window associated with a particular phase \( i \).

Ensemble averaged RMS are calculated as

\[
\sqrt{\overline{v'^2}}(i) = \sqrt{\frac{1}{(K_i - 1)\sum_{k=1}^{K_i} [v(i,k) - \bar{v}(i)]^2}}
\]

The statistical uncertainty of the ensemble averaged velocity is estimated 0.7 % considering a turbulence intensity of 20 % and a mean number of samples for each phase bin equal to 4000. A further 0.3 % of uncertainty may be attributed to the effect of time window extension (T/24), which results in an apparent turbulence intensity increase. In the case of 400 samples for phase bin the statistical uncertainties increase respectively to 2.2% and 1%.

For PIV measurements the reference signal from the miniaturized pressure transducer was used as trigger for the laser emission and image capture. The signal was time
delayed in order to cover the entire perturbation period by means of 8 distinct phases. The ensemble average technique has been applied to 50 instantaneous PIV couples of pictures at the same phase. A statistical uncertainty of 6% for the PIV measurements is evaluated. However, for present experiments this technique has been chosen to obtain immediate and reliable flow field overviews, rather than to measure velocity magnitude with accuracy.

3. AIR FLOW FIELD

In order to better understand the phenomena affecting the fuel break-up and distribution into the combustion chamber, a description of the unsteady flow field characterizing the LPP injector is here given.

To obtain the simultaneous flow fields of the gas as well as of the liquid fuel, the PDA data were post-processed according to a discriminating procedure based on scattering particle size [18].

Figure 6 reveals the axial velocity profile on a radial traverse located in the combustion chamber 30 mm downstream the LPP injector, pointing out a significant accordance between fuel droplets velocities and air velocities.

The flow is dominated by a vortex breakdown phenomenon. An external annular jet and an extended low velocity inner region oscillate because of the interaction with a precessing spiral vortex developing at the interface between jet and separated bubble (see fig 7). The spiral vortex originates at the centreline within the mixing tube and propagates downstream in axial and radial directions with a spiral winding in a sense concordant to the mean swirling flow.

A recirculation zone, characterized by near zero mean axial velocity, is clearly visible near the axis. This recirculation zone is due to the large axial gradient of the angular momentum of the flow and the sudden section enlargement experienced by the flow at the mixing tube exit. The recirculating flow presents null mean radial velocity and a counter clockwise tangential velocity profile that follows the Rankine vortex behaviour with solid body rotation near the axis [3, 4].

To describe the time evolution of the flow, the ensemble average technique has been applied. The ensemble averaged axial velocity components at $r=0$ mm and $r=56$ mm, reported in figure 8, indicate the presence of large periodic fluctuations in a relevant jet portion. The ensemble averaged RMS distributions show that the amplitude of the random fluctuations has the same order of magnitude of the mean velocity. Spectral analysis reveals that the periodic velocity fluctuations have a characteristic frequency of 290 Hz.

4. LIQUID FUEL FILM BREAK-UP

Figure 9 represents the liquid fuel release into the combustion chamber immediately downstream the LPP injector. This visualization has been obtained projecting a laser sheet on the combustor meridional plane and capturing the light reflected by the fuel droplets by means of a CCD camera.

A relevant lack of homogeneity is highlighted in the spatial distribution of the fuel release; is quite evident that the fuel is mainly discharged into the combustion chamber from the premixing duct exit lip, determining a region located in correspondence of the symmetry axis devoid of liquid fuel.

Further evidence is that, considering a single instant (i.e. the instant of the laser shot), the intensity of the fuel release is different between two diametrically opposite sides of the exit lip.
The PDA technique provides number, size and velocity of the fuel droplets which transit at each measurement point during the acquisition time. Data obtained on a radial traverse located 30 mm downstream of the premixing duct exit plane have been used to evaluate a parameter strictly related to the local flow rate of the not yet evaporated fuel.

$$FFI_s(i) = \frac{n_d(i) D_{30i}^3}{\sum_{i=1}^{n_d} n_d(i) D_{30i}^3 \times 100}$$

where $D_{30}$ is the droplet volume diameter

$$D_{30} = \left( \frac{1}{n_d} \sum_{i=1}^{n_d} D_{3i}^3 \right)^{1/3}$$

This parameter, named by the authors Spatial Fuel Flow Index (FFI$_s$), has been defined as the ratio between a quantity proportional to the flow rate of the liquid fraction in each single measuring point ($i$) of the traverse and the total amount of the same quantity along the whole traverse, in percentage. Figure 10 shows the spatial distribution of the FFI$_s$ along the investigated radial traverse, highlighting again the presence of liquid fuel mainly in correspondence of the premixing duct lip, located at $r = 52$ mm.

Concerning the difference in the fuel discharge from the upper and lower side of the premixing duct lip (see fig 9), since the PDA measurements are phase-locked, it is possible to define also a Time dependent Fuel Flow Index (FFI$_t$), parameter which is useful to take into account the time dependent fluctuations of the liquid fuel release into the combustion chamber.

$$FFI_t = \frac{n_{d rew} D_{30 rew}^3}{\sum_{d rew} n_{d rew} D_{30 rew}^3 \times 100}$$

The FFI$_t$ expresses for each measuring point the ratio between a quantity proportional to the flow rate related to a single time window $T/n_{d rew}$ and the total amount of the same quantity during the entire period $T$, in percentage.

Figure 11 highlights significant fluctuations of the liquid fuel release (related to FFI$_t$ values) within a flow field characteristic period for each point belonging to the traverse. These fluctuations confirm and explain the fuel release intensity difference pointed out by the instantaneous

Fig. 8 Periodic fluctuations and spectra of the axial velocity at $r=0$ and $r=56$ mm, $T_{air}=450K$

Fig. 9 Mie-scattering liquid fuel visualisation

Fig. 10 FFI$_s$ radial distribution
Mie-scattering visualisation.

![Graph](image)

**Fig. 11** FFI distributions within the fluctuation period

In order to better understand this phenomenon a second set of Mie-scattering visualisations has been taken, from a frontal point of view, allowing an instantaneous representation of the fuel release unhomogeneity along the premixing duct exit lip. In particular, has been possible, to evaluate the circumferential extension of the fuel release peak in about 150° (see fig 12).

![Image](image)

**Fig. 12** Phase-locked Mie scattering visualization and stereoscopic PIV measurements

Figure 12 also shows the air axial velocity distribution in the same frontal plane, revealing a close link between the unsteady air flow field and the liquid fuel discharge; in particular higher axial velocities are associated to higher intensity of fuel droplets release.

The high axial velocity region, besides having a wide extension, presents a varying radial placement along its circumferential development (see fig 13 and 15). Figure 14 shows the axial velocity distribution within a characteristic period for different measuring points along a radial traverse.

![Graph](image)

**Fig. 13** Phase-locked axial velocity PIV measurements

![Graph](image)

**Fig. 14** PDA data concerning axial velocity fluctuations

![Graph](image)

**Fig. 15** Axial velocity peak radial placement varying with phase

The droplets velocity distribution, as shown in figure 14, allows reporting the relationship between the presence of the axial velocity peak at a given radius and its phase within a characteristic period. What can be inferred from figure 15 is that the axial velocity peak, increasing time, shifts to outward radii. This evidence, together with the observation of the high axial velocity region shape (see fig 13), leads to state a counter clockwise rotation of this unsteady perturbation.

5. **ANALYSIS**

The liquid fuel break-up, as experimentally observed and reported in the previous chapter, has been interpreted as the consequence of an impingement phenomenon of the
Fuel hollow cone, as generated by the atomizer, on the converging premixing duct (see fig 16). In particular, the presence of significantly large droplets [18], discharged by the exit lip of the premixing duct, induces the idea that a liquid fuel film is formed by the impingement of the atomized fuel spray on the premixing tube walls, and subsequently roughly broken-up by the sliding air flow.

Fig. 16 Fuel spray impingement hypothesis

Due to the impossibility of performing experimental measurements within the converging premixing duct, a set of numerical simulations have been carried out in order to verify the fuel droplets trajectories. Figure 17 reports the results obtained setting the numerical boundary conditions as to simulate the experimental ones. Fuel impingement on the premixing duct wall is predicted as well as a significant fuel discharge from the premixing duct exit lip.

Fig. 17 Fuel droplets trajectories

As previously highlighted with reference to figure 9, a significant difference in fuel release from diametrically opposite side of the premixing duct exit lip can be observed. An explanation of such phenomenon has been sought in the periodical air flow field oscillations. Figure 18 compares air axial velocity and fuel droplets count fluctuations within a characteristic period in two different measuring points (r=44 mm and r=60 mm) located on the radial traverse. It is immediately evident the phase accordance between the two distributions due to an enhanced secondary break-up of the liquid fuel film, as a consequence of the sliding air flow action increase, associated to the axial velocity peak.

Fig. 18 Air axial velocity and fuel droplets count fluctuations

The same enhancement of the break-up process is intrinsically characterised by a reduction of the fuel droplets mean diameter, what is confirmed by the phase opposition between the axial velocity and the droplets mean diameter fluctuations (see fig 19).

Fig. 19 Air axial velocity and fuel droplets diameter fluctuations

In order to better understand the overall effect, in terms of fuel flow rate fluctuations, is reported the comparison between the axial velocity and the FFI distributions: figure 20 highlights excellent phase accordance between the two parameters, proving that the increase in released droplets number has a more significant effect than the droplets diameter reduction.
The Mie-scattering visualisation, reported in figure 9, allows a further consideration, regarding the thickness evaluation of the liquid fuel film, generated by the spray impingement on the premixing duct walls. A qualitative estimation of the film thickness is possible on the basis of a Mie-scattering visualization enlargement (fig 21). By the comparison of the known premixing duct exit lip radius with the film thickness, has been possible evaluate it in about 13 mm.

In order to give a theoretical confirmation of the film thickness evaluation has been made the assumption that the exit section of the premixing duct could be assimilated to a prefilming airblast atomizer. For such atomizers, Lefebvre [19, 20] suggests the following general, at some extent basic, equation, relating the droplets SMD with a characteristic dimension of the atomizer:

\[
SMD = \frac{\sigma \rho_f C_a t_f}{\rho_a C_a} \left( \frac{\dot{m}_f}{m_a} \right)^{0.5} \left( 1 + \frac{\dot{m}_f}{m_a} \right) + 13.0 \cdot 10^{-3} \left( \frac{\mu_f}{\sigma \rho_f} \right)^{0.425} t_f^{0.575} \left( 1 + \frac{\dot{m}_f}{m_a} \right)^2 \tag{8}
\]

In equation (8), the second term at right-hand member represents the contribution to SMD determination given by the liquid phase properties, especially viscosity. Where a low viscosity liquid is considered, as in the present case, that term can be considered as negligible, and equation (8) simplified as follows:

\[
SMD = 3.33 \cdot 10^{-3} \left( \frac{\sigma \rho_f C_a t_f}{\rho_a C_a} \right)^{0.5} \left( 1 + \frac{\dot{m}_f}{m_a} \right) \tag{9}
\]

Equation (9) has been applied to the present case considering two extreme conditions, within the characteristic period: the high and low axial velocity peaks. To each of both conditions is associated a different value of fuel droplets SMD and axial velocity. Those values have been deduced by PDA data set, and are summarized in the following Table 2.

<table>
<thead>
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<th>SMD [µm]</th>
<th>High velocity</th>
<th>Low velocity</th>
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<tr>
<td>40.1</td>
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</table>

Substituting these values in equation (9), the theoretical liquid film thickness oscillates between 10.5 mm and 13.0 mm. These theoretical values are consistent with the value observed by means of the Mie-scattering visualisation.

6. CONCLUSIONS

The analysis of a large amount of experimental data focused at deeply characterize an LPP injector, allowed pointing out a specific problem affecting the investigated combustor, which presents significant oscillations of the air flow field determining a spatial as well as temporal lack of homogeneity in fuel release within the combustion chamber. These phenomena could be associated to a not sufficient air/fuel premixing, and the onset of combustion instabilities phenomena.

From a more general point of view, the analysis of the experimental data allowed a better comprehension of the interactions between internal fluid-dynamic of combustor and secondary break-up processes of liquid fuel. In particular, has been pointed out how axial velocity fluctuations can play a significant role in determining the fuel flow rate entering in the combustion chamber and...
afterwards reaching the flame front.

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7. NOMENCLATURE

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<th>Symbol</th>
<th>Description</th>
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<td>air/liquid mass ratio</td>
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<td>$C_a$</td>
<td>axial velocity</td>
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Overbars

~ ensemble average

— time average

8. REFERENCES