LEAN FLAME STABILIZATION BY MEANS OF A COAXIAL SYNTHETIC JET

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Abstract. In the present paper the effect of a synthetic jet, coaxial with an annular type combustor, has been investigated in order to infer aerodynamic interaction between the two gaseous flows. The experimental investigation has the purpose to find the existence of synthetic jet excitation frequency able to extend the stability limits of a lean air/propane mixture flame. Lean flame is widely adopted in low thermal NOx emission combustors. As it is well known for gaseous premixed flame increasing the air/fuel ratio (lean flame) the flame propagation velocity is decreasing until it is getting comparable to the velocity of supplied fresh gaseous mixture. At this point, the flame is flushed away from the combustor mouth and the combustion process is quenched (blow off). In order to avoid those effects, for very low air/combustible ratio the modern premixed industrial combustors control the flame stability by means of the so called “pilot flame”, a small secondary relatively rich flame. The pilot flame, fed by a few percent of the total amount of supplied combustible, represent a relatively high source of thermal NOx. The experimental investigations have been performed by means of a Particle Image Velocimetry (PIV), in order to obtain instantaneous two dimensional velocity distribution overall the entire gaseous reacting jet, in order to stretch the influences of coherent structures generated in the jet, by means of natural aerodynamic effect and by means of perturbation forced into the flow by means of the synthetic coaxial jet under combustion conditions.

Nomenclature

| Symbol | Quantity | SI Unit |
|--------|----------|---------|
| $V$    | Air velocity | m/s |
| $V_0$  | Average air velocity at nozzle exit | m/s |
| $V/V_0$ | Normalized air velocity | dimensionless |
| $\phi$ | Stoichiometric equivalent ratio | dimensionless |
| $\nu$  | Kinematic viscosity of air | m$^2$/s |
| $\rho$ | Density of air at std condition | Kg/m$^3$ |
| $D$    | Nozzle diameter | m |
| $d_{eq}$ | Equivalent jet diameter, referred to annular exit section | m |
| $Re$   | Reynolds number, based on $d_{eq}$ | dimensionless |
| $f$    | Excitation frequency | Hz |
| $h$    | Section–Nozzle exit distance | m |
| $r$    | Radial distance | m |
| $r/D$  | Normalized radial | dimensionless |
| $h/D$  | Normalized height | dimensionless |
1. Introduction

Modern design of low emission combustors is characterized by swirling air in the combustor’s dome coupled with distributed fuel injection to maximize mixing. Various flow dynamics processes control the mixing between the fresh fuel/air mixture and hot combustion products and fresh air in premixed combustors. They include large-scale vortices that evolve in a separating shear layer downstream of premixed combustors. Interaction between these vortices which are related to flow instabilities, acoustic resonant modes in the combustion chamber and the heat release process was shown to cause undesired instabilities in combustors [1]. The stability of industrial burners, like jet or swirl burners, depends on a coupling between fluid mechanical and combustion mechanisms. The structure of the flow field and the formation of the jet break-up as well as the onset for vortex breakdown in case of a swirled exit is predetermined by the fluid dynamic. This is due to the large temperature and density differences incorporated in the flow field combustion can modify the flow field to a wide extent. The combustion stabilization by vortex breakdown are controlled by the flow dynamics associated with this particular flow phenomenon. Vortex breakdown is defined as a flow instability that is characterized by the formation of an internal stagnation point on the vortex axis, followed by reversed flow with low velocity [2]. The sensitivity of vortex breakdown to pressure gradients can cause coupling between pressure perturbations in the combustion chamber and the heat release from the flame which is anchored at the recirculation region produced by the breakdown, thus forming a feedback loop that may lead to combustion instability and change in pollutants formation [3]. Beside the flow properties stability of the flame with respect to pulsations can be influenced by the air/fuel mixing profile [4]. In particular for lean flame, characterized by low NOx production, the quenching effect increase with an unsustainable flame instability. Gagnepain et al. [5] report that the evaluation of turbulent premixed flame regimes by measuring the conditional (in the reagents) turbulence parameters is meaningful as the non-conditional ones incorporate part of the flame response to the turbulence structure in the reagents. The experiments showed a large difference between cold flow turbulence and the conditional velocity measured in the reagents with flame. The mean axial velocity decay rate and the turbulent fluctuations are smaller in the reagents. Also, the radial turbulence fluctuations decrease more strongly in the reagents compared to the cold-flow case. All this information indicate, that turbulent mixing is reduced due to the presence of the flame. One obvious effect is the retardation of the entrainment due to the presence of the flame in the shear layers and the subsequent reduction of the strength of turbulent eddies penetrating inside the flame due to increased viscous dissipation. Some extent similar burner was investigated by Lee et al. [6] The authors investigated a particular experimental set-up consisting in a burner formed by two concentrically premixed burners that were found to provide a stable turbulent premixed flame for a wide range of turbulence conditions. Both exits have independent gas supply and can be independently controlled. The paper reports that the stabilization is achieved via the exit velocity of the inner premixed burner which increases turbulence intensity. A gradually increase of turbulence intensity from outer to inner flame acts to stabilize the flame. Durox et al. [7] studied a conical burner with acoustical perturbation. Acoustic forcing was only acting to the premixture thus no equivalence ratio oscillations were investigated. Two different burner exits were examined, one thin edged burner and one wide edged burner. While the first represents a tube, the latter represents an exit in a wall. It was found that, beyond a given (strong) acoustic amplitude, the wide edged burner generates cells oscillating at half of the excitation frequency. It is stated that these cells are characteristics of a secondary parametric instability. The instability could be maintained because of a better anchorage of the flame on it than on the thin-edged burner. The conical shape of the burners interior upstream the exit is explained to have a rather strong influence on the exit velocities in interplay with the acoustics. During the half-cycle of the acoustic period in which the acceleration is directed toward the burned gases, any difference in altitude with respect to an equipotential surface will create pressure gradients that tend to displace the fluid and decrease this difference. During the other half-cycle, the opposite effect occurs. However, taking inertia into account, the situation is not symmetrical. That the flame anchorage capabilities are mentioned argues for a generally weak flame stabilization. Lieuwen and Zinn [8] reported on theoretical investigations on the
role of equivalence ratio oscillations in driving combustion instabilities in low-NOx gas turbines showing that equivalence oscillations play a key role in driving instabilities. The author claims for measurements of equivalence ratio oscillations during instable burner combustion to be missing and to be needed.

Not equivalence ratio measurements but instability diagnostics on gas-turbine burners, under high-pressure full load operation, have been performed by Essman et al. [9] in a power station. They conducted phase matched OH-PLIF diagnostics with high frame acquisition rate. The laser pulse frequency was chosen close to the humming frequency and digital filtering of the image sequences, in the Fourier space, with backward transformation into image sequences. The sequence then, showed which part of the burner flame reacts resonantly and how it moves in the light sheet plane. Later experiments on the same burner in a water tunnel at identical Mack number conditions, generated almost identical flow field motion within the area investigated before with a flame. Therefore it was concluded, that the axial pulsation detected from the PLIF images was in fact a rotating helical flow-field structure. The 2-D representation of such a 3-D structure is a Von Karman vortex flow and vortices like that where periodically passing through the OH-PLIF images.

The same was actually detected by Ji and Gore [10] when finding coherent vortex structures from time to time in PIV images taken downstream a swirl burner. These vortices were described as instantaneously appearing and vanishing at different locations. But if the images were phase sorted to the frequency of the burner, the same Von Karman vortices would certainly have appeared. Unsteady simulations as well as phase matched laser diagnostic imaging have demonstrated that the formation of a stable axisymmetric flow field is limited to defined parametric areas and that a swirl burner is not in general a simple solution to stabilize lean premixed flames with equivalence ratios close to the flammability limits [11, 12]. As representing a periodic system by itself, swirl flames tend to periodic instabilities and might couple into resonant processes leading to malfunctioning of the system and, in worst cases, to the resonance catastrophe (quenching flame).

In the present paper we will discuss about our activity on a premixed lean flame (near the flammability limit), generated by means of an annular combustor, stabilized by means of a coaxial synthetic jet.

2. Experimental Set-Up
The experimental investigation has been performed on a simple combustor with an internal nozzle for the synthetic jet generation surrounded by an annular exit section for the lean mixture as reported in Fig. 1.
The burner has been realized with two coaxial tubes. The internal tube is connected at his bottom section with a converging nozzle which collects the acoustic oscillations generated by a loud-speaker. The synthetic jet so obtained crosses the internal tube up to his top end, while the air propane mixture passes through the annular section realized between the internal tube and the external one. In order to obtain a homogeneous mixture the reagents are mixed in a T-way connection which is positioned from the outlet section of the burner at the distance of forty times the burner's diameter. In order to avoid flash-back phenomena, frequently present in case of low flow rates, the mixture emerges from the outlet section crossing a conical reduction which realizes an annular section with a thickness of 0.5 millimeters. This arrangement permits to realize a conical flame with an annular base at the center of which emerges coaxially the synthetic jet. The outlet section of the synthetic jet and the base of the flame are coplanar. A PIV system has been employed to analyse the instantaneous behaviour of the velocity field. The adopted system (whose layout is reported in Fig. 1) is based on two pulsed Nd:YAG lasers firing on the second harmonic (green 532 nm). The beams, properly separated in time, are recombined on the same optical path by a polarized dichroic filter. Then the beams are expanded in one direction, by combinations of spherical (negative) and cylindrical lens, to obtain a 80 mm wide and approximately 0.3 mm thick laser sheet in the measuring region. The laser sheet is used to illuminate the airflow over the nozzle. A powder cyclone has been used to disperse zirconium dioxide powder seeding in the feed duct to the test burner. Due to its high melting temperature which makes it survive a flame front, the adopted zirconium dioxide powder was a good choice [13].
Figure 2. PIV set-up and system components

The images have been collected by of a double frame 1280 x 1024 pixels PCO CCD camera synchronized with the two laser beams and with the frame grabber by means of a dedicated electronic synchronizer. In order to reject the flame luminosity a narrow band pass optical filter has been positioned before the 50 mm camera objective. The adopted filter was centered at $\lambda = 532$ nm with a passband of $\pm 3$ nm. The images are formed by two different layers, each of them containing information about the seeding positions obtained by firing one of the two lasers. So the initial seeding positions (first laser beam, image on the first layer) and the final one (second laser beam, image on the second layer) is spotted.

The images were then post-processed by means of the TSI Insight V.3.2 software in order to extract the sub-images formed by 32 X 32 pixels from each layer, and to perform a cross-correlation between the two corresponding sub-images. An interrogation algorithm extracts the correlation peak position from the cross-correlation domain with a sub-pixel precision, and performs the calculation of the two velocity components for those sub-images, by a pixel-to-mm conversion factor. Interrogations are repeated using a recursive algorithm for the entire set of double frames images. The measured velocities are reported in a grid with size of 32 x 32 pixels with a 50% overlap (Nyquist criteria). The two laser beams have been fired at about 100 mJ per pulse (second harmonic), and with separation time of 40 ms. The measurement volume has been stretched up to 1 mm from the impinged plate. The overall estimated error has been evaluated, according to [14 to 16], as about 4% on $V_{av}$.

3. Results and discussion
The experiments have been performed starting with the characterization of the combustor behavior without the activation of the synthetic jet. In practice we run the combustor, under reacting conditions, fed with more and more lean mixture in order to find the stability limit under the combustion condition. Those limits, according with [1] are a function of the equivalent ratio $\phi$ and $Re$. For the adopted combustor the minimum $\phi$ compatible with a stable flame was equal to 2.0 with a $Re \approx 1600$. In order to realize the equivalent ratio $\phi = 2.0$ the air mass flow rate was equal to $1.15 \times 10^{-4}$ kg/s and the propane mass flow rate equal to $3.72 \times 10^{-6}$ kg/s. At a $Re \approx 1600$ corresponds an exit velocity of about 4.0 m/s in the combustor exit section. The stability of the flame was reached when the flame was lighted for more than 20 minutes, time long enough to declare that the obtained flame is stable.

After the individuation of those conditions, we progressively decreased the amount of propane, forming the mixture, reaching an equivalent ratio of $\phi = 2.2$, with a propane mass flow rate equal to $3.33 \times 10^{-6}$ kg/s. With this equivalent ratio, the flame was very instable with a very frequent blow off. In practice the flame was quenched about every 2÷3 seconds and even less. At this point we activated the synthetic jet coaxial with the annular combustor at different activation frequency, finding an optimum frequency.
of $f = 330$ Hz able to stabilize again the flame on the mouth of the annular combustor. Under different activation frequency the flame was still unstable and in several case the instability was more accentuate. The effect of the synthetic jet on the flame stabilization was investigated by means of the previously described PIV technique.

In Fig. 3 A and B are reported images (in a reversed gray scale) of the flame (the visible component take with the CCD camera used also for the PIV investigations) respectively without and with synthetic jet perturbation. As it is well visible, the second one is shorter and closer to the exit nozzle than the first one. That means that the effect of the activation of the synthetic jet, at list at a frequency of $f = 330$ Hz, is able to induce a recirculation of, reagents radicals and hot gas, from the reacting region back to the combustor mouth, according with [2]. This recirculation is able to stabilize lean flames. Tis effect is more visible in Fig. 4 A and B, in which a graduated scale has been superimposed at the flame images with and without the synthetic jet.

![Figure 3. Images, in a reversed gray scale, of the flame. Image A no synthetic jet; image B synthetic jet with an excitation frequency $f = 330$ Hz.](image)

![Figure 4. (A) Synthetic jet off (B) Synthetic jet on at 330 Hz](image)

This effect is clearer in the following images. In fact in the Fig. 5 it is possible to observe a comparison between two gross half PIV images, organized in a mirrored image. In the semi image on the left ,the not perturbed flame is reported. In the right semi image, the perturbed one is reported. In the two semi images the visible reacting zone is highlighted by means of a line, showing the previously mentioned effect of flame extension reduction and localization much closer to the combustor mouth. In the right
part of the Fig. 5, some arrows are also reported in order to highlight vortex present on the external surface of the seeded hot gas.

![Figure 5. Two PIV images. Image on the left not perturbed flame; Image on the right perturbed flame.](image)

The PIV velocity distribution reported in Fig. 6, also shows clearly the recirculation effect induced by the synthetic jet perturbation. In this figure, a clear counter flow is generated in the inner zone. Due to the low spatial resolution adopted in this PIV image, necessary for catch the whole flow field, the vortex formation observable in the right part of the Fig. 5, are not visible in the velocity distribution reported in Fig. 6.
Figure 6. PIV velocity distribution of the flow field generated by the burning gas. Image A perturbed flame; B not perturbed flame.

In the Fig. 7 the axial velocity component (measured on the combustor axis, $r/D = 0$) is reported for the case of combustion without synthetic jet and with synthetic jet generated at a frequency $f = 330$ Hz. The comparison of the two velocity components profile shows the reverse flow, measured with synthetic jet active, ending at a $h/D$ ratio of 6. Without the perturbation of the synthetic jet, this region is practically negligible. Observing the velocity distribution over the ratio $h/D = 1.5$ the effect of external vortex induced by means the synthetic jet, is also visible as periodic small velocity oscillation.
Figure 7. Axial velocity component, $r/D=0$, for the case of combustion without synthetic jet and with synthetic jet.

The effect of reverse velocity is also clearly observable in Fig. 8, in which the axial velocity components measured in a radial section (at $h/D=0.5$) are reported, for the two cases.

Figure 8. Axial velocity components measured in a radial section (at $h/D=0.5$) for the two cases.

Figure 9. Flammability diagram of propane and air mixture.
In Fig. 9, the operative condition (reached with the action of the synthetic jet) of $\phi = 2.2$, are reported. The flame stabilized by the synthetic jet, stable even with a higher stoichiometric mixture ratio ($\phi = 2.2$), produced a lower NOx level, if compared with the level of those produced by the non-stabilized flame, as shown in the Table 1. This result was measured with a NOVA COMPACT® MRU combustion smoke analyzer which captured the combustion fumes in the exhaust pipe at a flame distance of about 0.3 m.

| Table 1. | Flame stable at an equivalent ratio | NOx measured in the exhaust manifold |
|----------|-------------------------------------|--------------------------------------|
| Without Synthetic jet | $\phi = 2.0$ | 11 ppm |
| With Synthetic jet (at 330 Hz) | $\phi = 2.2$ | 2 ppm |

4 Conclusion
A lean premixed flame, generated by means of an annular burner, have been stabilized by mean of a synthetic jet coaxial with the combustor. The experimental results show the formations of coherent structure, due to the interaction of the annular jet and the synthetic one, for both reacting and isothermal conditions. Feeding the annular combustor with a very lean air propane mixture, without the presence of the synthetic jet, generate a very unstable flame quenched every couple of seconds and even less. The activation of the synthetic jet, drive with a sinusoidal signal at a frequency of 330 Hz, was able to reattach the flame at the mouth of the burner. This effect is clearly obtained by means of coherent vortex able to generate a recirculation of reagents down to the burner mouth.

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