Stabilization of a Non-Premixed Lifted Flame in an Acoustic Field

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Introduction Non-premixed lifted flames are often used in industrial processes for security reasons insofar as they do not damage the burner. At the same time, these flames are very unstable. They are sensitive to the least perturbation and may be blown out when the flame is essentially located in the pure liftoff zone, or anchored when it is in the hysteresis zone. Most of models which have been proposed to explain the liftoff mechanism, are registered in [1][2]. Some explanations have been turned towards purely combustion models such as partially premixed flamelet models and triple flame models [3], or jet interaction models. The jet structures appear to play an important role in the stabilization process of a lifted flame, *e.g.* in local mixing or extinction. Due to the essentially turbulent nature of flows, physical mechanisms of the liftoff are difficult to point out finely. Fortunately, some characteristics of such processes may be underlined by studying more organized jets. Such jets develop ordered vortices caused by hydrodynamic instabilities. In round jets, the primary Kelvin-Helmholtz instability leads to large vortex rings [4], and secondary three-dimensional instabilities are responsible of lateral ejections of matter, (also called “filaments”), composed of small counter-rotating streamwise vortices (Fig 1). Several experiments and numerical simulations involving secondary instabilities in non-reactive jets or shear layers [5][6][7] have been conducted in order to understand their mechanism, insofar as it is expected they act on the mixing transition [8]. Though it was belatedly investigated, the role of filaments has been clearly shown in the stabilization of lifted flames[9][10].

As the jet operates as a finely tuned amplifier of external disturbances which develop into orderly eddy structures [11], noise or acoustic perturbations are expected to influence the jet and the flame. In such a way, few experiments, e.g. [12][9], have already pointed out some lifted flames responses to acoustic perturbations. Investigating the coupling between lifted flames and acoustics is all the more important as acoustics, present in industrial environment, generally appears to be a nuisance for the flame. Knowing the nature of these fields will help to avoid combustion difficulties or even to control the process.

The aim of this present work is to better understand the mechanism of the stabilization of a non-premixed lifted flame in the hysteresis zone submitted to an acoustic excitation. The different flame responses for a large range of frequencies and amplitudes of the perturbation, are analyzed by using high speed tomography, Particles Image Velovimetry and Laser Doppler Anemometry techniques. First results are presented hereafter.

Experimental facility The burner is conceived to obtain an organized jet of pure methane. This burner consists of a vertical convergent profiled tube with a core of 62 mm diameter and a nozzle of 6 mm diameter, $D0$, with a thin tip of 0.2 mm. The mean axial vertical velocity, U_0, is 13.5 m/s at 0.7 mm from the burner exit. The nozzle is contracted to have a “quasi-top hat” vertical velocity profile with low fluctuations (Urms/U_0 <4 % with Urms the root mean square of the axial vertical velocity measured at 0.7 mm from the burner exit) in spite of a turbulent Reynolds number $U_0 D0/\nu$ of 5000. To force the jet acoustically, the bottom of the burner is closed by a loudspeaker, driven by a 130 W amplifier and a sine wave function generator. Fuel and/or ambient air is seeded with olive oil particles in order to carry out jet visualizations and LDA measurements. The outer seeding is performed by a large homogenized quiet air coflow of 196 mm diameter with a sufficiently low velocity (<0.05 m/s) to avoid any influence on the jet.

Flow with no acoustic excitation A lifted flame (Fig 1 a)) is stabilized in the jet at the height, H0, of about 20 mm from the burner exit. Its base is composed of 4 or 5 lobes rounded towards the air. Vertical and transversal tomographic cross-sections of the jet are observed with a high speed camera at 9000 images per second (Fig 1). The pictures show eddy structures due to primary instabilities (Kelvin-Helmholtz vortices) and secondary instabilities (filaments). The temporal signal of the external radius of the vortex rings, measured from successive tomographic views of the horizontal cross-section at 20 mm (near the flame base), gives access to following characteristic frequencies of the jet: the natural one at 1200 Hz and its first sub-harmonic one corresponding to the eventual first pairing of the primary vortices.

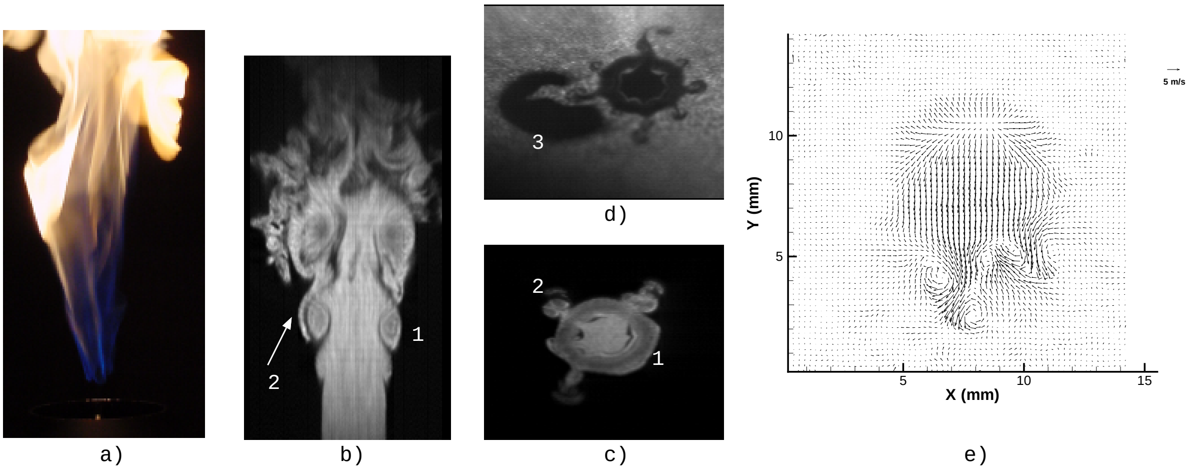

FIG. 1 – *Study of the natural case. a) Lifted flame. b) Vertical cross-section with jet seeding. c) Horizontal cross-section at 20 mm from the burner exit with jet seeding. d) Horizontal cross-section at 20 mm from the burner exit with coflow seeding.1: Kelvin-Helmholtz ring, 2: filaments, 3: flame impact. e) Instantaneous PIV transversal velocity field at 20 mm.*

Filaments appear in the horizontal plane as long arms of matter ejected from the jet. This star-shape is similar to the photographs published by Liepmann and Gharib [6]. The importance of these filaments in the stabilization mechanism of the lifted flame is clearly revealed by the horizontal tomographic views with external seeding (Fig 1 d)): a lobe of the flame, identified by evaporated oil droplets which define a horseshoe shaped domain, is always located on the streamwise counter-rotating vortices. This fact can be explained by the secondary structures dynamics. First, we have measured that filaments are ejected periodically at the same frequency as the primary vortex frequency and are merged at the same place during about 100 ms. Therefore, filaments ejections towards the quiet air provide some fresh fuel to feed the flame rapidly and during a relatively long time. Secondly, the counter-rotating vortices of filaments provide an efficient mixing between fuel and air. This efficiency can be evaluated by comparing the thickness of a CH4-air premixed laminar flame, $\delta_l \simeq 0.1$ mm and the diffusion length, d. As the matter is transported by a streamwise vortex during the time, $t_m = n\pi r/U_\theta$, $d \sim \sqrt{\nu t_m}$. Using PIV techniques [10] (an example of the transversal velocity field is given in Fig 1 e)), we found U_θ of about 3 m/s at r=0.5 mm. n, the number of half turnovers made by a filament from its locus of formation to the flame, is about 4. Thus, the flame can propagate in a well-mixed zone. Finally, the filaments dynamics is not so great to extinguish the flame, but causes a curvature responsible of the flame aspect, composed of separate lobes.

Flow with an acoustic excitation First observations of the flame responses to acoustic perturbations are investigated. Fig 2 summarizes them as a function of frequencies, f, and amplitudes, Urms (as mentioned above), of the imposed perturbation. Note that the boundaries between regions are not as well defined as the figure may imply. We have verified that the frequency of LDA signals of the vertical axial velocity at the exit is equal to the forcing one.

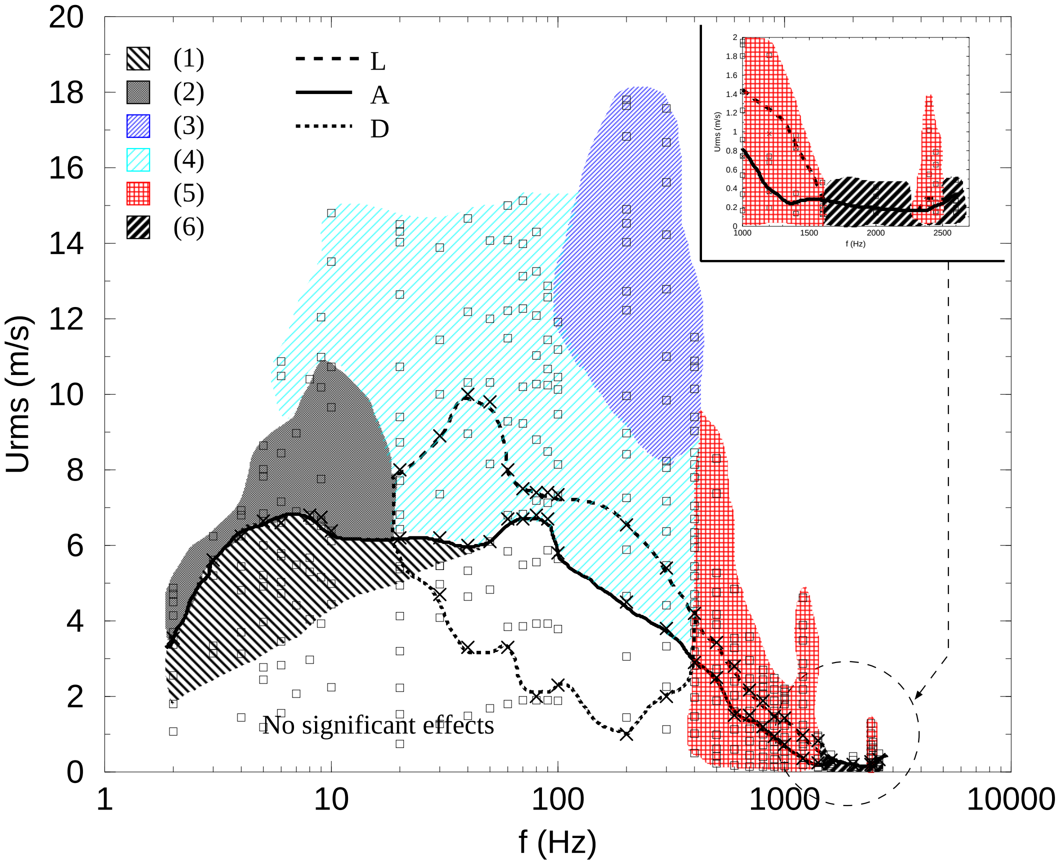

FIG. 2 – *Response chart of an excited flame*

Three lines are the boundaries of regions where liftoff-anchoring mechanisms are noticed. Under line A, the lifted flame reattachment may occur. When it happens, the flame is definitively anchored. Above line L, the flame is always lifted. Between both lines, an anchored flame cannot be lifted by acoustics, but if it is lifted, anchoring is impossible. Between lines D and L, when anchoring occurs, two superimposed flames coexist: the first one is attached to the nozzle, the second one is lifted and stabilized in the plume of the first one.

Six zones of flame responses are defined. (1), "*weakened flame*": the lifted flame stability is weakened, *i.e.* the flame can be easily anchored by the least perturbation. (2), "*flapping flame*": as the presence of strong reverse flows of air inside the burner is noticed, periodic inward and outward flows of air and methane make the lifted flame oscillate with a large height amplitude. Depending on the value of Urms, the flame can be alternatively anchored or lifted. (3), "*blue lifted flame*": this amazing case shows a flame whose aspect is totally changed, the liftoff height can reach 2.5 times the natural liftoff height H0 and is very much larger than the natural one. The sooted plume has practically disappeared, forming a turbulent blue flame (Fig 4 b)). (4), "*transitional blue flame*": the blue flame phenomenon is not achieved yet, although the liftoff height is increased and the plume is reduced. (5), "*resonating zone*": it is centred on 1200 Hz, the natural jet frequency. Changes in the flame behavior are visible even for very low amplitudes: it is larger than the natural one; some finer lobes form and move back upstream immediately. As the amplitude is increased, the flame stabilizes closer to the nozzle. Note that around the first harmonic frequency (2400 Hz), we obtain the same features. (6), "*thin flame*": the flame width and the liftoff height (H≃H0/2) are immediately reduced at very low amplitudes. Under line A, when the flame, very weakened, is anchored, some streamwise streaks appear on the flame.

The physical interpretation of the flame responses strongly depends on jet structures. Their fine study shows that stability of the flame and combustion regimes rely on the capability of acoustics for changing the conditions of primary and secondary vortices formation. In order to enlighten this, we have chosen to present some zones more precisely: (3) and (5) illustrate the weakness of the flame stability; (6) and (1) are two examples of a more robust flame.

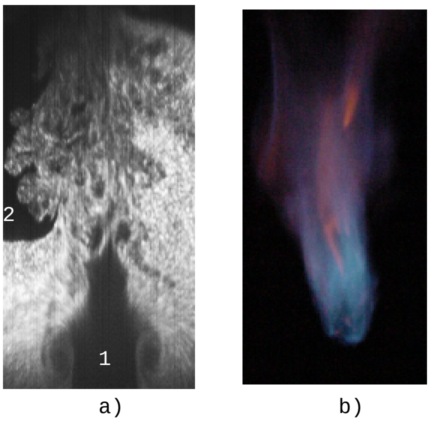

FIG. 3 – *Flame response analysis in zone (3). a) Vertical cross-section with air seeding. (f=200 Hz, Urms=9 m/s), 1: vortex ring, 2: flame impact. b) No sooted blue flame (f=200 Hz, Urms≃17 m/s)*

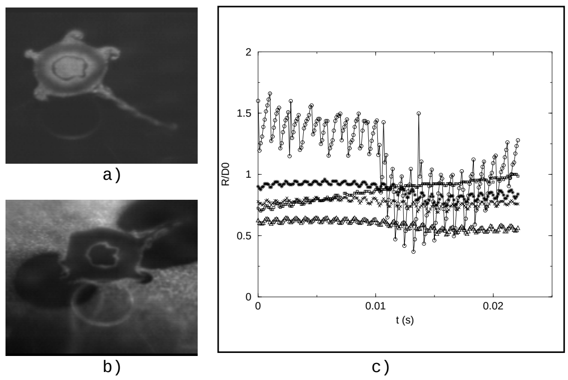

FIG. 4 – *Flame response analysis in zone (5) at H=7 mm (f=1200 Hz, Urms=1 m/s). a) Horizontal cross-section with jet seeding. b) Horizontal cross-section with air seeding. c) Temporal evolution of the filaments length*

During a cycle of zone (3), two main phases are observed. When the jet is accelerated, vortex rings due to acoustics engulf much air. Their strength is sufficient to maintain the flame downstream at a distance H>H0 where the jet begins to be disordered. Then, vortices break more violently than in the natural case. Their breakup and the great jet deceleration are able to create a CH_4-air mixture with small scales which improves combustion (Fig 3 a)). The rapid repetition of both phases stabilizes the flame in a no sooted regime (Fig 3 b)). Fig 4 is an example of the jet excited at the natural frequency (f=1200 Hz) in zone (5). The horizontal views show long arms of ejected matter, even near the nozzle (Figs 4 a) and b)). Their lengths, R, whose temporal signals are presented in Fig 4 c), follow a sinusoidal evolution at the forcing frequency.

Because resonant effects affect the secondary instability, the filaments are more organized and their dynamics, characterized by their length, is amplified. Therefore, as the flame is attracted by a long filament close to the burner, the liftoff height is reduced and the flame diameter is increased. Moreover, the more active dynamics of the filaments avoids reattachment of the flame. In zone (6) (f=2600 Hz, Urms=0.3 m/s), the jet seems similar to the natural case as shown in Fig 5): primary eddy structures, developed at the forced frequency, are rapidly paired, leading to structures characterized by the same frequency and size as naturally at the flame base. But secondary structures do appear nearer the burner. Following the filaments, the flame moves back upstream, so close to the nozzle that, unlike previously, the filaments are not strong enough to avoid anchoring. Zone (1) is characterized by a partial or whole disappearance of filaments during a cycle as illustrated in Fig 6 (f=10 Hz, Urms=5 m/s): at t, the jet has no filament and no flame is present (it exists downstream); but at t+T/2, it can be seen several filaments among which one stabilizes the flame. The fluctuating existence of filaments is expected to be responsible of fluctuations of the flame stabilization point, hence of some fragility of the lifted flame stability.

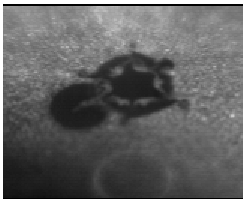

FIG. 5 – *Flame response analysis in zone (6) at H=12 mm.(f=2600 Hz, Urms=0.3 m/s). Horizontal cross-section with air seeding.*

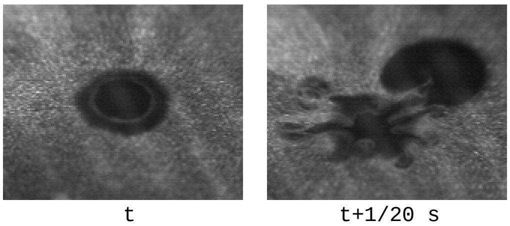

FIG. 6 – *Flame response analysis in zone (1) at H=16 mm (f=10 Hz, Urms=5 m/s). Horizontal cross-sections with air seeding.*

Conclusion The study of the flame responses underlines that, depending on ranges of frequencies and amplitudes, an acoustic perturbation can either weaken stability of lifted flames (zones (1) and (6)) or reinforce their robustness (zones above line A). Acoustics is also able to improve combustion (zone (3)) by reducing soot. Finally, acoustic perturbations increase the influence of secondary instabilities, observed in the unforced jet, on the behavior of lifted flames.

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