Impact of acoustic boundary conditions on confined combustion noise

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Combustion noise is experimentally investigated on a 40 kW burner composed of two identical stages fed with air and propane. The purpose of the study is to characterize combustion noise depending on the boundary impedances and injection conditions (i.e. staging ratio, equivalence ratio and air mass flow rate).
Noise study can only be accurately performed if the test bench provides a broadband spectral sound emission. However in such laboratory high power experiment, combustion and acoustics may easily couple to generate strong instabilities. The amplitude and frequency of these instabilities depend on the operating points but also on the acoustic boundary conditions, an issue that is rarely investigated. Work presented in this paper shows that operating point and inlet boundary conditions can be adjusted to create the best experimental conditions for investigation of combustion noise.

1 Introduction

The noise produced by aircraft engines at take-off and landing can be very harmful for airport neighbors, an issue that became recently particularly crucial. For many years, combustion noise has been studied on a fundamental point of view, mainly in open situations [1, 2, 3] and more recently [4]. In confined situations, combustion instabilities, where a strong coupling between flames and acoustic modes of the combustion chamber cause very high levels of harmonic sound, have been extensively studied [5]. However, the wide bandwidth noise emitted by confined flames in stable situations is less well-documented [6]. This is mainly due to the fact that it is very difficult to build clean acoustic conditions in burners, making the combustion noise analysis barely possible. It has been recently shown by Tran et al. [7] that varying the burner upstream acoustic boundary condition was a very efficient method for damping combustion instabilities and creating ideal conditions for the study of combustion noise. This original passive control system will be described and the effect of such well-adapted inlet acoustical condition on sound emission in the injector and the chamber will be presented.
The test bench is first described with the diagnostics used to record pressure fluctuations and heat release oscillations. The test bench consists in a swirl stabilized burner, connected to a rectangular combustion chamber, equipped with microphone ports for acoustic measurements. A filtered photomultiplier measures the CH* spontaneous emission from the flame, which is strongly correlated to heat release fluctuations. Time-resolved measurements are carried out and spectral analysis of pressure measurements and light emissions are performed for various inlet impedances and injection parameters.
Then, systematic investigation of the combustor operating points is reported to identify stable modes. The present report shows the influence of crucial parameters like the equivalence and staging ratios on the test bench behavior. These results are used to select the optimal running point for combustion noise investigation.

2 Experimental setup

The experimental facility sketched in Fig.1 is composed of a partially premixed burner connected to a 50 cm long rectangular combustion chamber with a square 10×10 cm^2 cross-section. The burner is composed of two identical stages in which tangential injections of air and propane create a strong swirl movement (swirl number above 0.6) in a $D = 30$ mm diameter injection channel. This burner is operating in lean conditions (equivalence ratio Φ stays between 0.7 and 0.95). It is connected to the combustion chamber through a ceramic junction, with an important area constriction ratio, $S_2/S_1 = 14$. The chamber is composed of two quartz windows on each side and refractory concrete walls on top and bottom. The upper plate is equipped with three regularly spaced plugs for acoustic measurements (M5, M6 and M7) inside the chamber. As sketched in Fig.1 the injector is also equipped with microphone plugs up and downstream of each stage (M1, M2 and M4) to characterize the injector acoustics.

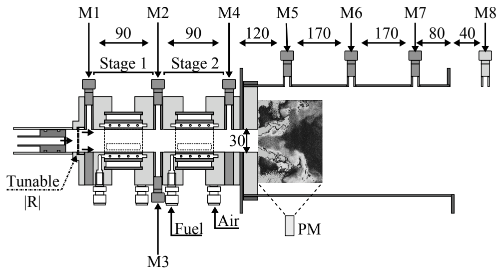


Figure 1: Schematic view of the EC2 burner with detailed injection head. A mobile piston is ajusted to control the input impedance. Fuel and air are injected through two successive stages equipped with microphones.

This configuration can present strong combustion instabilities depending on the fuel staging ratio, defined as the ratio of the fuel mass flow in the stage furthest from the chamber (stage 1) to the total fuel mass flow injected [8]. Practically, this staging parameter varies between 10% and 55%, beyond this value swirling flame enters and heat dangerously the injector.
To prevent flashback inside the burner, air is injected axially from the rear side of the burner, the axially injected massflow corresponds to a small fraction of the total tangential mass flow ($\approx 2.5\%$). The swirled flame has a conical shape with a strong precessing vortex core, typical of swirl-stabilized configurations (Fig.2). The flame is compact, about 15 cm long, and its base given at scale with the burner geometry in Fig.1. The exhaust is a square open end. Hot gases flow out of the facility and are then collected by a large diffuser.
A photomultiplier tube (PMT), equipped with a narrow band filter centered on λ=431 nm collecting CH^* spontaneous emissions from the flame, is used to measure fluctuations of the heat release rate. Microphones are flush-mounted on water-cooled waveguides (not shown

in Fig.1) and their signals are corrected to account for acoustic propagation in these waveguides. Microphones M1, M2 and M3 are used to measure the upstream acoustic reflection coefficient R at the burner inlet [9] and acoustic fluxes inside the burner through S1 [10]. Microphones M6, M7 in the hot product region are used to estimate acoustic fluxes through the chamber exhaust S2 using the same method. These reconstructions require careful calibration in gain and phase of the microphones (B&K type 4938 1/4 inch) and the use of a switching technique. Microphone M5 is placed just above the combustion region to correlate with the photomultiplier PMT. In this region pressure oscillations can be considered roughly uniform because the flame is compact. Long acquisition times are chosen, $T = 16$ s, at a sampling rate of $f_s = 16384$ Hz to ensure statistical convergence of the spectral analysis operators.
The original upstream boundary condition was a rigid wall located at the rear side of the burner, providing an almost perfectly reflecting condition for incident acoustic waves. This rear rigid plate is replaced by a 1 mm-thick perforated plate backed by a cavity, which depth L is controlled by a piston and can be varied from $L = 0$ to 50 cm. Air is fed in this cavity through the piston head and flows through the plate apertures of radius a with a bias flow velocity U. These apertures are spaced by a distance d (Fig.1) yielding a porosity σ of 5%. This complete system enables to control the burner inlet acoustic boundary condition in the low frequency range $100 \leqslant f \leqslant 1000$ Hz [7]. Details are given in section 5 on the design parameters of this impedance control system and its performances.

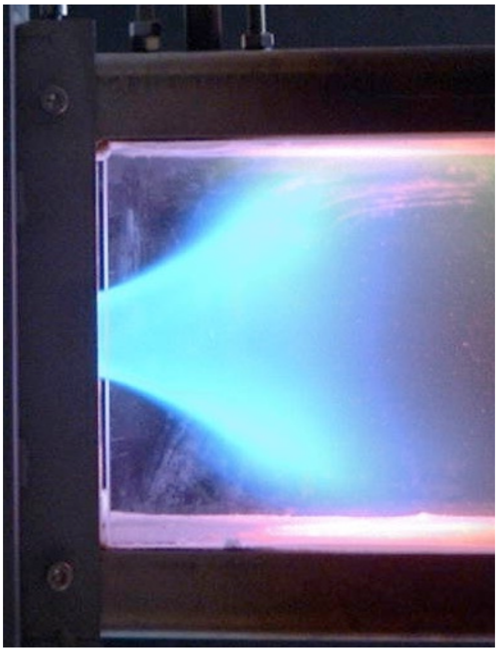


Figure 2: Typical swirl-stabilized flame shape.

3 Choice of operating conditions

The combustor rig behavior is mainly controlled by three parameters : the equivalence ratio Φ_t, the staging ratio α and the total air flow rate $Q_{a,t}$. Systematic investigation of operating points proved that equivalence ratio can vary between 0.7 and 0.95 while staging can vary between 10 and 55% The influence of equivalence and staging ratios was studied by Dioc in her thesis [8]. Practically, it was shown that operating points corresponding to staging ratios beyond 55% are sensitive points since the flame tends to enter the injector and stabilize in the second stage.This makes the investigation of combustion noise in these conditions too risky. Pressure fluctuations are recorded in the chamber (M5) and the corresponding Power Spectral Density (PSD) is plotted for each experimental condition (i.e. for a given couple of staging and equivalence ratios). The interest of such systematic investigation for the noise study is to determined the running point where the instability is the less pronounced (i.e. the point where the PSD maximum is at its minimum).

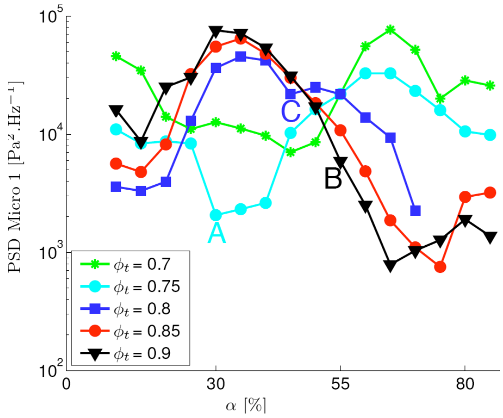


Figure 3: Evolution of the PSD with fuel equivalence ratio and staging ratio.

Maximum PSD values are shown in Fig.3 for different equivalence and staging ratios. Three points of interest have been selected. First point is obtained for an equivalence ratio equal to 0.75 and staging ratio of 30% (Point A). This represents a local minimum where the PSD amplitude varies slowly when staging ratio increases. The second point is obtained for a staging ratio of 50% and an equivalence ratio equal to 0.9 (Point B). A third intermediate point corresponding to an operating condition studied by Dioc [8], has also been selected in order to allow comparison. It corresponds to an equivalence ratio equal to 0.8 and a staging ratio of 40% (Point C).

4 Influence of the total air flow rate

The previous operating conditions (Points A, B, and C) are obtained for a total air flow rate of 40 Nm^3 h^{-1}, the two stages being fed equally. To analyze the influence of this parameter on PSD maximum, total air flow rate was varied from 20 to 53 Nm^3 h^{-1}. For the different operating conditions A, B, and C, the PSD maximum is at its minimum for a total air flow rate equal to 35 Nm^3 h^{-1}. Fig.4 shows the evolution of the PSD maximum in the operating condition C for microphones M2 and M5 (equivalent ratio $\Phi = 0.8$ and staging ratio $\alpha = 0.4$).

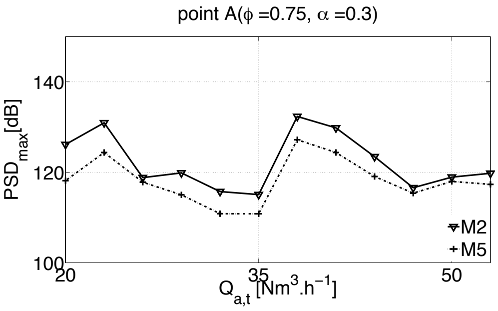


Figure 4: Evolution of the PSD with total air flow rate for point A $\Phi = 0.75$ and $\alpha = 0.3$.

Finally the appropriate regimes for combustion noise investigation correspond to an air injection in each stage of 17.5 Nm^3h^{-1}, and 1.15 Nm^3h^{-1} injected axially to prevent flashback inside the burner. Propane injection in each stage depends on the global fuel equivalence ratio and the staging. The operating points are summarized in Tab.1.

	Point A	Point B	Point C
Staging ratio α	0.3	0.5	0.4
equivalence ratio Φ	0.75	0.90	0.80
Power	29 kW	34 kW	31 kW

Table 1: Operating conditions chosen for combustion noise investigation $Q_{a,t} = 35$ Nm^3h^{-1}.

In the following, for ease of illustration, we will only focus on point A. The same analysis has been carried out for points B and C.

5 Perforated panel backed by a cavity

The passive control system is composed of a perforated plate backed by an adjustable cavity with a mean bias flow. Once optimized, it can efficiently control the modulus of the reflection coefficient of the burner inlet for incident pressure oscillations of high amplitude [11]. This control system was adapted to the combustion facility and its effects are presented in the following section.
The reflection coefficient R of a perforated plate backed by a cavity with bias flow was modeled and experimental data were successfully compared with theoretical predictions for plates with small porosity ($\sigma \leqslant 10\%$), compact with respect to the incident wavelength ($a \ll d \ll \lambda$) and without interactions between apertures ($a \ll d$) [12, 13]. These models are based on an evaluation of the pressure gradient through the perforated plate that can be linked to the pressure jump via the Rayleigh conductivity K_R of the apertures. This conductivity is a function of the Strouhal number $St = \omega a/U$ based on the bias flow velocity U and the aperture radius, as shown by Howe [12] : $K_R = \gamma - i\delta$ where the real and imaginary parts γ and δ are fully determined by Bessel functions of the Strouhal number St. Using these elements, an expression for the complex reflection coefficient R at the front face of a perforated plate can be obtained as a function of its geometrical parameters a and d, the cavity depth L, the bias flow velocity via the Strouhal number and the frequency via the wavenumber $k = 2\pi f/c_0$ [13]. An intermediate parameter $\eta = 2a/d^2 K_R$ (the effective appliance) is introduced, so that:

$$R = \frac{(ik/\eta) + 1 - (i/tan(kL))}{(ik/\eta) - 1 - (i/tan(kL))} \quad (1)$$

Five parameters (a, d, L, f, U) can be used to control the reflection coefficient. This number can be easily reduced due to geometrical constraints and operating conditions envisaged. The combustion facility presents strong instabilities at low frequencies, associated with longitudinal acoustic modes. The first unstables modes are typically observed between 100 and 1000 Hz, for which the impedance control system was therefore optimized. It can nonetheless be adapted for higher frequencies. The validity of the model is limited to plates of low porosity ($\sigma < 10\%$), without any restriction for the aperture radius a or the spacing d. These two parameters were thus optimized to fixed values for practical reasons: $a = 0.5$ mm and $d = 4$ mm. Finally it was shown that a single bias flow velocity $U = 9$ m s^{-1} can be used to maximize the damping properties of the system within the frequency range of interest once the geometrical parameters are set [7, 11]. The only remaining control parameter, the cavity depth L, was chosen to pilot the damping properties of the proposed system. Its maximal value $L = 50$ cm is imposed by the lowest frequency at which control must be effective.

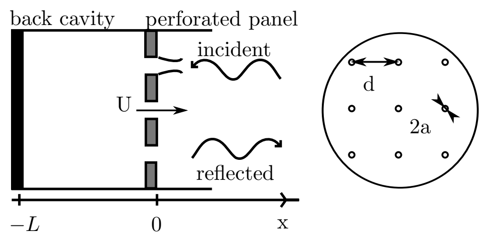


Figure 5: Perforated plate backed by a cavity, in presence of mean bias flow.

6 Influence of perforate plate on combustion instabilities

The optimal cavity depth (L_{opt}) depends on the instability frequency to be damped. It was investigated for the different operating conditions. As shown in Tab.1, experimental point A corresponds to $\Phi = 0.75$ and $\alpha = 0.3$. Tests are performed to compare the effect of the perforated back panel on the sound emission spectrum. As described previously, the back panel is used to adapt the inlet impedance and damp the resonant coupling between acoustic waves and combustion in the chamber.
The Power Spectral Densities (PSD) of microphones M2 and M5 are plotted to evaluate the effect of the back

cavity length on the resonant peak amplitude. The reflection coefficient R at burner inlet is measured using the three microphones located in the injector (M1, M2 and M4).
Without the back panel system, the inlet reflection coefficient modulus is slightly lower than unity ($|R| = 0.8$), a value that would be expected for a rigid wall. This may be due to the airflow through the perforations that attenuates incident acoustic waves or to the cavities created by the apertures in the perforated plate that may create sound scattering. In this situation, a strong oscillation peak corresponding to an unstable regime is obtained at the frequency $f = 272$ Hz, in spite of the fact that point A is associated with a low amplitude coupling (Fig. 4). Fig. 6 shows the temporal evolution of microphone M3 (placed in the injector) during a few cycles of oscillation. Periodic pressure fluctuations can clearly be seen when the cavity depth is set to zero. PSD of pressure fluctuations are plotted in Fig. 7, for M2 in the injector, and M5 in the chamber. PSD during these tests reached up to 135 dB in the injector and 128 dB inside the combustion chamber. A cyclic fluctuation of the light emitted by the flame is also observed by the PMT, with the same main peak frequency. This peak frequency is present in the signals measured by all the microphones, confirming a flame-acoustic coupling.
When the perforated panel is used (the cavity depth is increased from 0 to $L = L_{opt}$), the modulus of the reflection coefficient decreases from $|R| = 0.8$ to $|R| = 0.15$ at $f = 272$ Hz. The intensity of the peak is considerably reduced by roughly 20 dB in the injector and a little less in the chamber (Fig. 7). Fig. 6 shows that the pressure signal in the injector does not present periodic patterns anymore. For higher depths, the modulus increases again. It is also clearly visible on Fig. 7 that the rest of the spectrum is hardly modified when the reflection coefficient is changed. This means that while the passive control system acts on resonant coupling between flame and acoustics, it modifies the natural noise emitted by the flame. This original passive control method of the upstream acoustic boundary condition is of great interest to study combustion noise. When the cavity depth is at its optimum value, the instabilities are considerably damped and the combustion noise should be more perceivable.

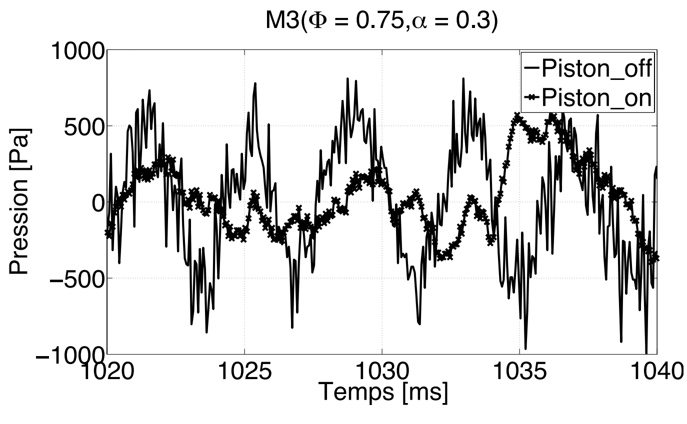
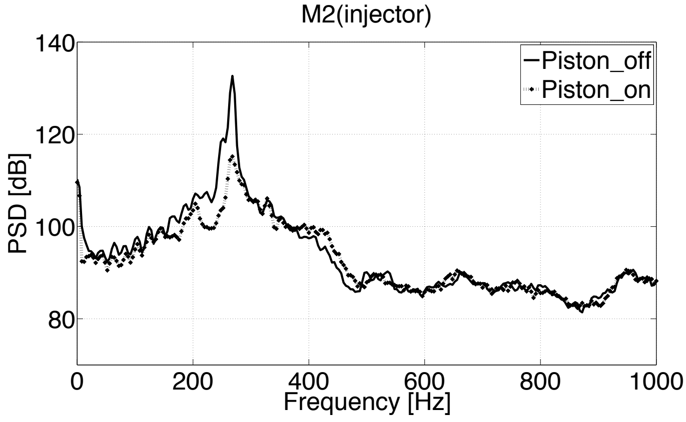
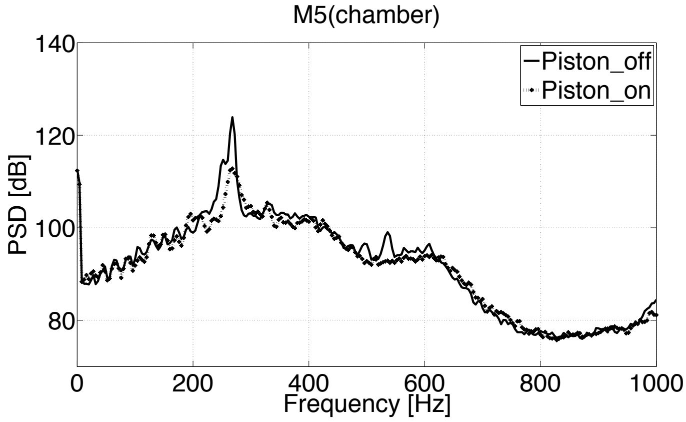


Figure 6: Pressure fluctuations in the injector (M3), with the cavity depth set at zero and at its optimum value.



(a)



(b)

Figure 7: Power Spectral Density (PSD) in the injector and the chamber. A large amplitude peak is observed at 272 Hz corresponding to a strong coupling between acoustic and combustion. With the perforated plate set at its optimum value, the peak is significantly damped.

7 Conclusion and perspectives

Investigations about the optimum operating point to study combustion noise have been performed based on previous systematic studies on similar burners in order to damp combustion instabilities. Systematic investigations have been performed with different equivalence ratios, staging ratios and air mass flow rates. The operating conditions allowing to damp combustion instabilities have been retained. It consists in operating points corresponding to three couples of equivalence ratios and staging ratios. Inlet acoustic impedance has been adjusted to decrease the reflection coefficient in the injector thus causing an additional damping of the instabilities.
This initial work in obtaining adequate experimental conditions for combustion noise investigation is going to allow to better understand fundamental mechanisms leading to noise in combustion chamber. First, the impact of the inlet control system on the aerodynamics will be put in evidence during a PIV (Particle Imaging Velocity) campaign. Then, the outlet acoustic boundary conditions will be modify to evaluate the influence of the exhaust on combustion noise. The complete system will then be used to study combustion noise in clean

acoustic conditions.

References

[1] S.L. Bragg. Combustion noise. *Journal of the Institute of Fuel*, 36:12–16, 1963.

[2] T.J.B. Smith and J.K. Kilham. Noise generation by open turbulent flames. *J. Acoust. Soc. Am.*, 35(5):715–724, 1963.

[3] I.R. Hurle, R.B. Price, T.M. Sugden, F.R.S. Thomas, and A. Thomas. Sound emission from open turbulent premixed flames. *Proceedings of the Royal Society*, 303:409–427, 1968.

[4] S.A. Klein and J.B.W. Kok. Sound generation by turbulent non-premixed flames. *Combust. Sci. Tech.*, 149:267–295, 1999.

[5] S. Candel. Combustion dynamics and control: Progress and challenges. *Proceedings of the Combustion Institute*, 29(Hottel Lecture):1–28, 2002.

[6] K. K. Singh, C. Zhang, J. P. Gore, L. Mongeau, and S. H. Frankel. An experimental study of partially premixed flame sound. *Proceedings of the Combustion Institute*, 30(2):1707–1715, 2005.

[7] N. Tran, S. Ducruix, and T. Schuller. Analysis and control of combustion instabilities by adaptive reflection coefficients. In *13th AIAA/CEAS Aeroacoustics Conference*, number AIAA-2007-3716, Roma, Italy, May 21 - 23 2007.

[8] N. Dioc. *Etude expérimentale des mécanismes d'instabilité dans un brûleur à injection étagée. Application aux turbines à gaz.* PhD thesis, Ecole Centrale Paris, 2005.

[9] J. Y. Chung and D. A. Blaser. Transfer function method of measuring in-duct acoustic properties. i. theory. *The Journal of the Acoustical Society of America*, 68:907–913, 1980.

[10] J. Y. Chung. Cross-spectral method of measuring acoustic intensity without error caused by instrument phase mismatch. *The Journal of the Acoustical Society of America*, 64(6):1613–1616, 1978.

[11] N. Tran, S. Ducruix, and T. Schuller. Passive control of the inlet acoustic boundary of a swirled turbulent burner. In *ASME Turbo Expo 2008, GT.2008-50425*, Berlin, Germany, June 2008.

[12] M. S. Howe. On the theory of unsteady high Reynolds number flow through a circular aperture. *Proceedings of the Royal Society of London A*, 366(1725):205–223, 1979.

[13] I. J. Hughes and A. P. Dowling. The absorption of sound by perforated linings. *Journal of Fluid Mechanics*, 218:299–335, September 1990.