High Frequency Combustion Oscillations Induced by Transverse Acoustic Modulations [1]

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Introduction

Much research in combustion has focused on instability mechanisms. Recent work has focused on gas turbines of the premixed type with an emphasis on low frequency oscillations. Less experimental work has been carried out on high frequency oscillations. This type of instability is most often observed in rocket engines where it is coupled by transverse chamber modes but it also appears in annular gas turbine combustors. Most of the data in this frequency range were generated during the early development of rocket where instability problems were continuously encountered [1]. Little progress has been made in this field because of a lack of fundamental information. It was therefore timely to take a new look at the problem and use state of the art experimental tools in well controlled model scale experiments [2]. The mismatch between real and laboratory scale systems has been one important difficulty of experimental research and it is not overcome in the present study. One may however envisage to study some of the fundamental processes by suitably designing the experiment and properly choosing operating conditions and injection parameters [3]. It is not possible to reproduce all the complexity of rocket motors but some of the essential aspects are conserved.

To this purpose, a model scale combustion chamber has been designed in collaboration with ONERA. It is fed with real cryogenic propellants, it operates at an elevated pressure, injection conditions are in the range characterizing real engines. The three injectors are similar to those used in engines. The combustor geometry features well separated resonant modes and characteristic eigenfrequencies in the standard range where high frequency instabilities usually occur ($f > 1$ kHz). The momentum flux ratio between gaseous methane and liquid oxygen is in the range corresponding to real engines. The flame lengths are typical of those found in practice ($l/d \simeq 50$).

One idea explored in the present work is that collective interactions constitute a fundamental source of combustion instability. This is supported by recent experiments on premixed flames which indicate that strong sources of instability are most often related to interactions [4]. Other experiments on flame/flame interactions indicate that this too can be a strong source of self induced oscillations [5]. The closely packed flame geometry of rocket engines produces interactions in the vicinity of the chamber back plane. Collisions between adjacent streams may enhance turbulence and augment the volumetric rate of reaction. There is a natural delay in this

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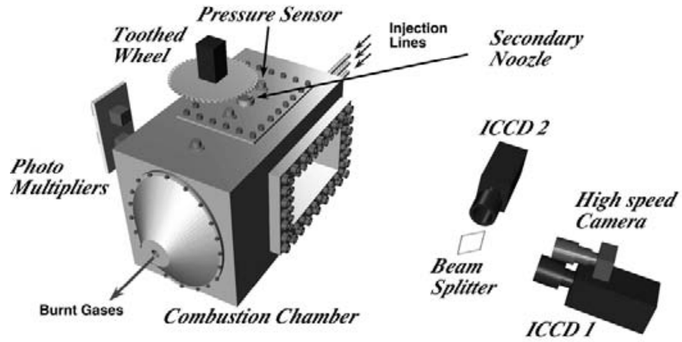


Figure 1: Experimental set up with diagnostics

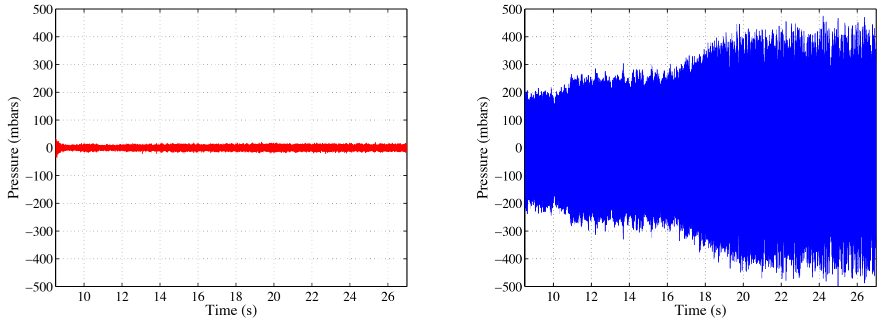
process and a possibility of tuning the collision process with one of the acoustic resonances [6]. These fundamental effects have not been extensively investigated in the past or at least no conclusions were given on the possible collective effects of such arrangements of closely packed highly reactive jets.

Experimental configuration and diagnostics

The experimental set-up involves three main elements : a combustion chamber and a cryogenic feed system, three coaxial injectors forming interaction jet flames inside the chamber, an external source of modulation to excite one of the chamber transverse modes. The chamber has a rectangular section. Its upper and lower walls are respectively equipped with three and two pressure transducers while the lateral side walls comprise large transparent quartz windows allowing direct observation of the three flames in the visible and near UV range. The methane flow velocity is around 100 to 200 m/s. The momentum flux ratio between the gas and liquid streams is then chosen in a range which is typical of real engines. Velocities outside the jets are admittedly lower than those found in practical systems because the available cross section is larger. However, the flame is located between the inner oxygen stream and the co-annular hydrogen jet and it is only weakly influenced by the outer flow. The chamber volume is relatively large to obtain a transverse mode in the proper frequency range. The power density is therefore not equal to that found in a practical devices but it is already sizable.

Results

Different injection parameters have been tested to obtain a flame sensitive to pressure fluctuations. These hot fire tests have shown that at low injection velocity (U_{CH_4} = 90 m.s^{-1}) and ambient temperature of methane, the interactions between flames and acoustic were strong enough to be observed. At low injection velocity, the flame is longer, the hydrodynamic frequency decreases and the differential pressure trough the injectors diminishes, making the flame sensitive to pressure fluctuations. The toothed wheel was linearly accelerated at 150 Hz.s^{-1} from 0 to



(a) Non modulated test

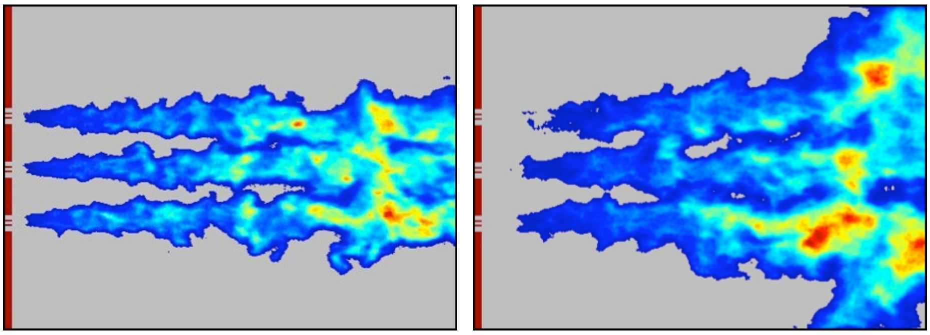
(b) With external modulation at 1680 Hz

Figure 2: Pressure fluctuations in the combustion chamber without and with external modulation (sampling rate (40 kHz).

3500 Hz to determine eigenfrequencies of the chamber. The Fast Fourier Transform of the pressure signals allowed to determine three resonant frequencies : the first longitudinal mode (1450 Hz), a coupled mode (1680 Hz) and the first transverse mode (2345 Hz). The coupled and the first transverse mode are similar to those observed in real engines, and generate the strongest flame disturbance. In the second step, the system was modulated successively at 1680 Hz and 2345 Hz. The pressure signals with and without external modulation are presented in Fig.2. With the modulation, the pressure fluctuations reached 10% of the nominal pressure chamber. These high amplitude pressure variations generated strong modifications on the flames. Figure 3 shows the spontaneous emission of OH with 1680 Hz modulation and without external excitation. The modulation has two main effects on the reaction zone : the flame expanses and larger reactive structures appear. Photomultipliers and high speed camera (20,000 f/s) allowed to see the oscillatory motion of the flames at the modulation frequency and the collective interactions appearing in the flame shear regions. When modulated at 2345 Hz, the system reacted the same way. The acoustic perturbations had similar repartition in the chamber leading to the identical flame response. In both cases, the oscillations are not self sustained. When the exciting wheel is stopped, the high amplitude pressure fluctuations vanish and the flame response is similar to the one observed without modulation.

Conclusions

The dynamics of a multiple injector combustor is investigated under high frequency transverse excitation. The study is carried out on a rectangular cross section system featuring three coaxial injectors fed with cryogenic propellants. A modulation system is used for external excitation. The system eigenmodes are first identified by performing a linear frequency sweep. Injection parameters were varied to determine conditions where combustion is sensitive to external oscil-



(a) Non modulated test (b) Modulated test at 1680 Hz

Figure 3: Instantaneous OH emission with and without external modulation (exp. time: 4 μs)

lations. Such conditions are observed when the gaseous stream of methane has a relatively low velocity. A strong coupling is observed which manifests itself in a visible modification of the flame structure and motion. When this coupling occurs, radiation from the flame is augmented by a large factor. Thermocouples placed on the lateral walls detect a rapid increase in temperature. The various measurements clearly indicate that a coupling of this nature may be at the source of transverse instabilities of rocket motors.

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