Experimental study about instability in global lean combustion

Marcel Martins Alves, Rogério Corá, Pedro Teixeira Lacava
Aeronautical Technology Institute - ITA
São José dos Campos, São Paulo, Brazil

1 Introduction

Combustion instabilities were first observed in 1777 by Higgins but were first explained by Rayleigh in 1878. If a high density of energy is released into a small volume, which may happen in a combustion chamber, there will be a favorable condition for excitation and conservation of oscillations [1]. It's already known that Rayleigh's criterion must be satisfied for oscillations to occur. Rayleigh's criterion is shown below, where *Q'* is the rate of instantaneous thermal energy that is transferred to the flow, *p'* is acoustic pressure, *t* is time, and the integral is calculated in an oscillation cycle. Pressure oscillation amplitude is increased when the result of the integral is higher than zero. This integral comes from conservation equations [2], and represents the energy increment of the acoustic perturbation after each oscillation cycle. In other words, pressure oscillation and heat addition must be in phase for the combustion instability to be amplified. When pressure oscillation and heat addition are not in phase, heat addition damps pressure oscillations [3].

$$\oint Q' p' dt > 0$$

It's important to point out that Rayleigh's criterion is a necessary condition to combustion instability occurrence, but it's not sufficient because it doesn't explain combustion instability origin. If a premixed combustion system has deficiencies to homogenize the mixture, there will be flame regions at different equivalence ratios [4]; and these different equivalence ratios may induce spatial and temporal energy release fluctuations. Depending on the intensity of these fluctuations, they may be accompanied by pressure oscillations thereby a coupling between pressure fluctuations and chamber acoustic properties is possible, generating an oscillating combustion process. Besides, for a lean combustion process, flame velocity is lower [5], therefore it's more difficult for the flame to recover its structure when there are energy release fluctuations. This is the main mechanism that induces oscillations in lean premixed combustion processes.

There are some harmful effects caused by combustion instabilities, such as non-uniform temperature profile of combustion gases, combustion efficiency reduction, high thermal NO_x release, and thermal stresses on the wall of the chamber, which are induced by local temperature peaks, and vibrational phenomena. All of these effects affect the system performance [6, 7]. A theoretical analysis of laminar premixed flames response to equivalence ratio perturbations was developed by Cho and Lieuwen [8], showing that heat release responses are directly controlled by heat of reaction and flame velocity.

The main objective of the present paper is to study experimentally acoustic instabilities in extreme global lean combustion situations. Although it's a fundamental work, the main motivation is the fact that some gas turbine low NO_x emission combustors have these lean combustion conditions in the reaction zone.

Correspondence to: marcel_alves_eq@yahoo.com.br or placava@ita.br

2 Methodology and Experimental Setup

The combustion chamber that was used for the experiments was built of 304 stainless steel and it is divided into 6 non-refrigerated modules, which are fastened to each other by flanges and screws. The last module has a cone shape and was built in order to reduce the exit area by 56%, giving the chamber the acoustic condition of a closed tube. The length of the six modules are respectively 0.10 m, 0.40 m, 0.25 m, 0.25 m, 0.20 m, and 0.10 m; and the inner diameter of the chamber is 0.15 m. A scheme of the combustion chamber is shown in Figure 1.

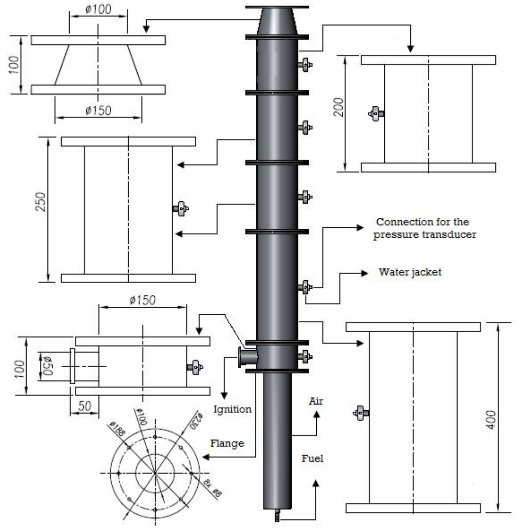


Figure 1. Combustion chamber scheme (dimensions in millimeters).

The feeding system of the combustion chamber consists of a device that is responsible for burning natural gas. Natural gas is supplied by a central duct and air is supplied by an annular region that is concentric to the central fuel region, according to Figure 2. It must be pointed out that the reactants are not premixed before their injection into the chamber; however air and fuel injections are carried out in a way that a mixture is formed before the flame region. Fuel is injected radially through ten holes that are at the end of the duct. A disk is positioned slightly below the fuel injection holes in order to create a recirculation zone by air passage through the holes, as presented in Figure 2. On the disc, there are two rows of ten holes each for axial injection of air over the radial flow of fuel, creating a mixture between air and natural gas, which is involved by the recirculation zone and then ignited. A pilot flame of liquefied petroleum gas and air is ignited by a spark plug system in order to start the operation and cut off when the main combustion of natural gas is established.

In order to measure the RMS acoustic pressure of each frequency, it was used a piezoelectric pressure transducer Kistler model 7261. The electric charge generated by the pressure transducer was converted into proportional tension by a charge amplifier model Kistler - 5011B. Data acquisition was carried out by the programming language LabVIEW. The data acquisition system consists of an AMD Athlon x2 Dual Core computer and a PCI-6071E acquisition board, which was manufactured by National Instruments. The SCB-100 sensors and the acquisition board were connected by a terminal block. Electrical signals were acquired by the pressure transducer under the rate of 5000 points per second. The pressure transducer was placed at the central position of the first module of the chamber in order to be located as close as possible to fuel and air injections; due to the fact that the highest acoustic pressure amplitudes are presented in this region.

Natural gas was supplied by gas cylinders and atmospheric air supply was accomplished by a radial vane compressor. Mass flow rate measurements were obtained from orifice plates (radius tap for the air and flange tap for natural gas). A type J thermocouple was placed on the inner wall of the chamber, measuring the wall temperature at the first module, close to the flame region.

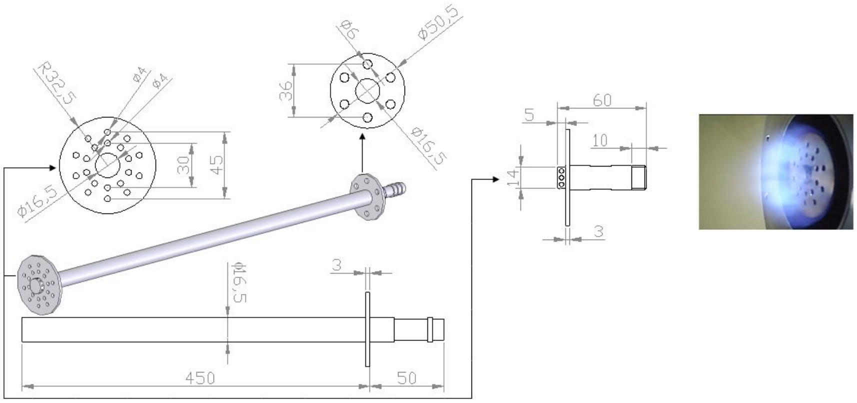


Figure 2. Combustion chamber feeding system and a typical flame.

3 Results and Discussion

The tests were carried out in order to verify the effects that cause self-excited instabilities in the chamber. Two different air flows were chosen, 20 g/s and 30 g/s, respectively. The fuel mass flow rate was adjusted to provide different global equivalence ratios. The minimal fuel mass flow rate was the limit of flame extinction and the maximum was the condition close to the wall temperature limit for safe operation, around 890K.

Global equivalence, defined as ϕ, refers to the ratio between fuel and air that are injected into the chamber by the stoichiometric equivalence ratio. It's shown in the following equation, where N_F, m_F, N_{OX} and m_{OX} are fuel number of moles, fuel mass, oxidant number of moles and oxidant mass, respectively [9].

$$\phi = \left(\frac{N_F}{N_{OX}}\right)_{ACTUAL} \Big/ \left(\frac{N_F}{N_{OX}}\right)_{STOICHIOMETRIC} = \left(\frac{m_F}{m_{OX}}\right)_{ACTUAL} \Big/ \left(\frac{m_F}{m_{OX}}\right)_{STOICHIOMETRIC}$$

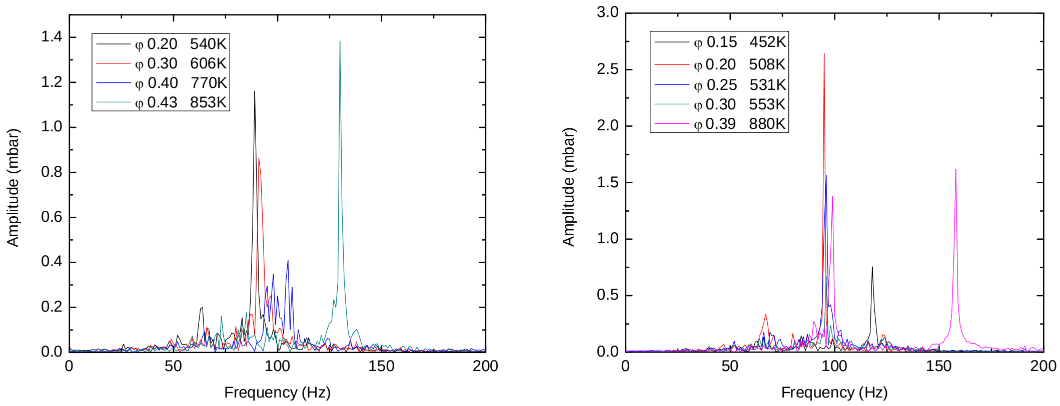
Based on Nyquist criterion, the sampling frequency must be set higher than twice the maximum frequency of interest. The tests were conducted for a resolution of 1 Hz and a sample rate of 4,000 Hz. When data acquisition was carried out, Fast Fourier Transform was applied to the measured pieces of data in order to obtain a frequency spectrum containing each frequency and its respective pressure oscillation amplitude, thereby enabling peak frequencies for each experimental condition to be determined. In other words, pressure oscillation amplitudes that are obtained by the Fast Fourier Transform does not represent instantaneous pressure amplitudes of oscillations, but correspond to maximum amplitude values that pressure oscillations can attain.

Figure 3 shows the results for 20.0 and 30.0 g/s of air, respectively. Significant amplitude values were found just in the range from 10 to 200 Hz, therefore values for frequencies over 200 Hz are not shown. This oscillation range is described as low frequency instabilities, which generally occur due to interactions between reactant feeding system (mixture preparation), combustion process (energy release fluctuation presence) and chamber acoustic characteristics [10].

For both air mass flow rate conditions, it’s possible to observe that frequency of oscillation increases when global equivalence ratio is raised. The frequency of oscillation depends on the sound velocity, therefore when equivalence ratio is raised, the temperature inside the chamber is increased, and consequently sound velocity is changed. The wall temperature, close to the flame, is available in the legends of Figure 3.

When comparing the items (a) and (b) of Figure 3, it can be verified that generally pressure amplitude is amplified when air flow rate is increased from 20 to 30 g/s. It occurred because there's an increase in the fuel mass flow rate for 30 g/s of air in order to maintain the equivalence ratio constant, therefore burning power is increased and the system releases more energy. Part of this energy increase is used to enhance self-excite oscillations in the combustion chamber.

It was also observed, in Figure 3, that an increase in equivalence ratio, despite the change of frequency, causes attenuation in the amplitude. Combustion instabilities can be aggravated at lean conditions because flame velocity is lower; therefore it's more difficult for the flame to recover its structure when there are fluctuations in the rate of energy released. When equivalence ratio is raised, the flame velocity was increased, facilitating for the flame to recover its structure, thereby attenuating the pressure amplitudes. However, this oscillation damping has a limit due to the fact that an increase in fuel injection provides more energy to acoustic excitation. It can be clearly observed in Figure 3(a) for global equivalence ratio φ = 0.43 and in Figure 3(b) for φ = 0.39, when the amplitude increased again. Hence, it seems to be is a sum of effects between the flame velocity and available energy to excitation.



(a) (b)

Figure 3. Frequency spectrum for air mass flow rate (a) 20.0g/s and (b) 30.0g/s at different equivalence ratios. The temperature in the legend was measured on the wall close to the flame region.

Due to the fact that air mass flow rate is much higher than fuel mass flow rate, the recirculation zone structure is not considerably affected when global equivalence ratio is changed in this present work; hence, there is little change in the reactant mixing process. Therefore, for the conditions presented in Figure 3, the oscillation situations are consequence of the flame velocity and energy availability to acoustic excitation. Hence, for the leanest global combustion operations in this work, close to the flame extinction, despite the low energy availability to excitation, the low flame velocity does not compensate energy release fluctuations. On the other hand, the increase in fuel injection will initially increase the flame velocity, thereby damping the oscillations until the increase in energy, which is available to excitation, begins to have a significant effect. Although the flame velocity is increased, it still remains low. Obviously, the continuous increase in fuel rate, despite available energy to excitation, causes higher flame velocities that compensate released energy fluctuations originated by inefficiency to form homogeneous mixtures.

In Figure 3(b), when the equivalence ratio was increased to 0.39, there's an appearance of two intensely amplified frequencies. These phenomena occurred due to an increase of energy released, thereby creating conditions to excite more than one oscillation mode, which means more energy available to acoustic excitation.

In order to verify the influence of air flow on combustion instabilities, four fuel mass flow rates were chosen for 20 and 30 g/s of air, and the results are presented in Table 1. Obviously, the increase of air flow rate decreases the global equivalence ratio and the wall temperature close to the flame due to the fact that an excess of inert gases absorb more released energy by combustion reactions. For the fuel flow rate of 0.24 g/s and the air flow rate of 30 g/s, which means a global equivalence ratio of 0.13, it could be noticed that there’s no significant combustion instability presence because there wasn’t any pronounced oscillation frequency detected. According to Figure 3(b), pressure amplitude for equivalence ratio of 0.15 was low compared to other amplitudes for the same air flow rate. It can be concluded that, under these extremely lean conditions, instabilities are damped, and even if the burning power is the same, the reduction of equivalence ratio caused by an increase of air flow rate is able to cause this instability damping. In this case, in spite of the low flame velocity, part of the energy that was originally used to excite the system was absorbed by the inert gas increase. In a study about premixed flames of swirl-stabilized combustor, it was verified that some pressure oscillation amplitudes are significantly reduced at equivalence ratios near the lean blowout limit of the burner [11]. Hence, the results of this work are in agreement with the ones obtained in the previous work. Table 1 also shows that the air flow rate raise also increases the amplitude, as consequence of the flame velocity reduction. On the other hand, for the same air flow rate, an increase of fuel initially increases the amplitude, then it’s damped, increased again, and finally, it may be damped again.

The results presented in Figure 3 and in Table 1 can be qualitatively and physically summarized by Figure 4 diagram for the same air flow rate. Five regions must be highlighted in this diagram: Region 1: despite the extremely low flame velocity, there is no energy available to sustain the excitation; Region 2: start the availability of energy to excitation and flame velocity still remains low; therefore there is amplification when there’s fuel injection increase; Region 3: the flame velocity is getting higher, damping the oscillations gradually; Region 4: the increase of energy available to sustain the instability amplifies the oscillations, despite higher flame velocity; Region 5: higher energy available and higher flame velocity; region where there’s a tendency of oscillation damping when equivalence ratio is increased, as presented in the literature. In the last case, the flame velocity is enough to recover quickly from some energy release fluctuations. It's important to emphasize that the flame velocity is increased when there's a fuel injection increase due to the fact that turbulence level is also increased, and flame velocity increase is not caused by temperature effects.

Table 1. Experimental conditions for air mass flow rates of 20 and 30 g/s.

Fuel flow rate [g/s]	Wall temperature (K)		Global equivalence ratio		Peak frequency (Hz)		Amplitude (mbar)	
	Air flow rate [g/s]							
	20	30	20	30	20	30	20	30
0.24	540	399	0.20	0.13	89	0	1.16	0
0.36	606	508	0.30	0.20	91	95	0.86	2.65
0.46	770	561	0.40	0.26	105	96	0.41	2.26
0.50	853	569	0.43	0.28	130	96	1.38	1.75

4 Conclusion

In this work, instability mechanisms were experimentally studied in global lean combustion conditions. It was observed that energy, released by combustion, and flame velocity are related to each other depending on global equivalence ratio. It was also determined how the flame suffers when energy release fluctuations occur. Besides, the results showed that is possible to obtain combustion operations in extremely lean global equivalence ratios either without or with low combustion oscillation presence. These experimental results are important in case of gas turbine development of low NO_x emission combustors for lean equivalence ratios in the reaction zone.

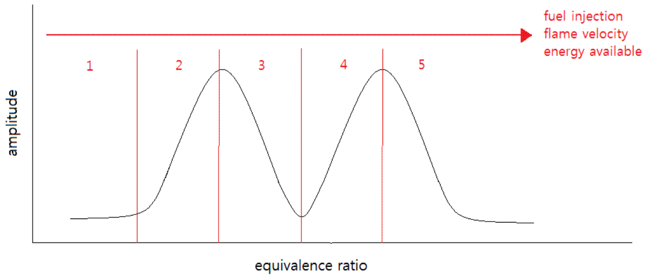


Figure 4. Qualitatively representation of oscillation behavior in global lean combustion, for the case that air mass flow is kept constant and global equivalence ratio is modified by changing fuel mass flow rate.

References

[1] Culick, F.E.C.; Yang, V. (1995) Overview of Combustion Instabilities in Liquid-Propellant Rocket Engines. In: YANG, V.; ANDERSON, W.E. Liquid Rocket Engine Combustion Instability. Washington, DC: AIAA – Progress in Astronautics and Aeronautics, v.169, chap.1, p.1-37.

[2] Chu, B.T. (1956) Stability of systems containing a heat source - the Rayleigh criterion. (NACA-RM-56D27).

[3] Auer, M.P.; Gebauer, C.; Mosl, K.G.; Hirsch, C.; Sattelmayer, T. (2005) Active Instability Control: Feedback of Combustion Instabilities on the Injection of Gaseous Fuel. Journal of Engineering for Gas Turbines and Power, v.127, p.748-754.

[4] Weigand, P.; Meier, W.; Duan, X.R.; Stricker, W.; Aigner, M. (2006) Investigation of swirl flames in a gas turbine model combustor I. Flow field, structures, temperatures and species distributions. Combustion and flame, v.70, p.205-224.

[5] Santosh, H.; Liewen, S.; Liewen, T. (2007) Premixed Flame Response to Equivalence Ratio Perturbations. American Institute of Aeronautics and Astronautics.

[6] Fichera, A.; Losenno, C.; Pagano, A. (2001) Experimental analysis thermo-acoustic combustion instability. Applied Energy, v.70, p. 179-191.

[7] Hong, B.S.; Ray, A.; Yang, V. (1998) Robust Feedback Control of Combustion Instability. In: American Control Conference, Philadelphia.

[8] Cho, H.J.; Lieuwen, T. (2005) Laminar premixed flame response to equivalence ratio oscillations. Combustion and flame, v.140, p.116-129.

[9] Turns, S. (2000) An introduction to combustion: concepts and applications. 2. ed. Boston: McGraw-Hill, 676p.

[10] Ebrahimi, R.; Mazaheri, K.; Grafourian, A. (2000) Mode Identification of High-Amplitude Pressure Waves in Liquid Rocket Engines. Journal of Sound and Vibration, v.229, p.973-991.

[11] Albrecht, P.; Bade, S.; Lacarelle, A.; Paschereit, C. O.; Gutmark, E. (2010) Instability Control by Premixed Pilot Flames. Journal of Engineering for Gas Turbines and Power, vol.132, p.041501/1-0.41501/8.

Acknowledgements

The authors are grateful to CNPq and CAPES for the fellowships and AEB for financial support for the experimental setup.