EXPERIMENTAL STUDY OF PREMIXED FLAME OSCILATIONS IN PRESSURES ABOVE ATMOSPHERIC

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Abstract

Continuous combustion systems common in propulsion and power generation applications are susceptible to thermoacoustic instability, which occurs under lean burn conditions close to the flammability were most emissions and efficiency benefits are achieved. This instability is undesirable because the accompanying large pressure and heat release rate oscillations lead to high levels of acoustic noise and vibrations as well as life cycle reduction and structural damage. Both combustor geometry and flow conditions have inevitable effects on these combustion dynamics. To investigate the effects of pressure, flow rate, equivalence ratio, and other operating conditions on combustion oscillations, propane burning experimental set up designed and commissioned. In order to distinguish the combustion instability for various operating conditions, statistical methods, based on acoustic data acquisition along with Rayleigh Criterion, are utilized. The results shows that the operating and ambient conditions have fewer effects on the dominate mode frequency, in spite of their strong effects on the amplitude of normalized pressure oscillations.

Introduction

Lean premixed combustion (LPM) is highly advantageous in reducing nitrogen oxide (NOx) emission from gas-turbine engines without the loss of combustion efficiency by controlling the equivalence ratio to within an appropriate range. This combustion method has attracted considerable attention from developers of gas-turbine combustors. However, one main drawback of the lean premixed combustors is that they are susceptible to flow perturbations [1]. They suffer from combustion instabilities such as thermoacoustic oscillations, lean blowout, and flashback. Among these, thermoacoustic combustion instability, caused by the strong coupling between the variations in pressure and the heat-release rate, is considered to be a serious problem, because it can lead to a reduction in lifespan or even the total destruction of an engine. The physical mechanism underlying the onset of thermoacoustic combustion instability and the efficient suppression methods for the combustion instability have been extensively investigated for various types of laboratory-scale gas-turbine combustor with swirling flow, which is summarized in detail in recent review papers [2].

As summarized in a previous review paper the combustion instability is roughly classified into two types in terms of the oscillation amplitude and frequency obtained from the power spectrum. One is the stable combustion represented by a limit cycle with small oscillations amplitude and no dominant characteristic frequency and the other is the unstable combustion represented by a limit cycle with a large oscillation amplitude and well-defined oscillation frequencies [3].

It should be mentioned that pressure fluctuations always exist in gas turbine combustion systems, even in the stable mode of operation. The fluctuations may sustain in the form of small amplitude oscillations, called classical acoustic motions The most important factor, affecting the frequency of pressure fluctuations, is combustor geometry [4] As a rule, perturbations may provide energy to the unsteady motion and increase the acoustic fluctuations amplitude in the combustion chamber. The resulted pressure fluctuation, with the amplitudes exceeding 5 percent of combustor mean pressure, is regarded as combustion instabilities [5].

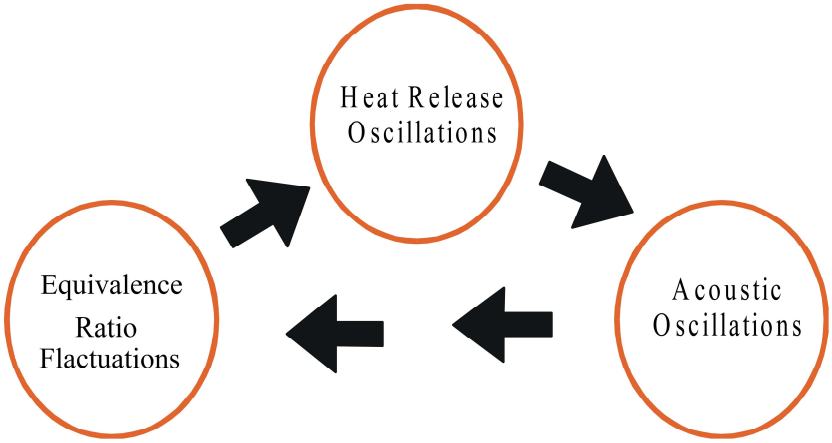

Figure 1. Mechanism of combustion instability[1]

As shown in Fig.1. combustion instabilities are normally resulted from coupling of acoustic and combustion processes in the combustion chamber. Equivalence ratio oscillation model, proposed by Lieuwen [1], can explain the instability in combustion chamber of gas turbines. The main aim of this research is statistical examination of the experimental results, obtained during unstable operation of combustor. Moreover, it is intended to study the main parameters affecting the combustor unstable operation. In addition, convective delay time, as another affecting parameter, is calculated for all experiments and obtained results are compared with Rayleigh Criterion.

Experimental Setup

In order to perform experiments in the field of LPM combustion chambers, following setup is designed and fabricated. The experimental facilities consisted of a laboratory combustor and an acoustic data acquisition system with microphones.

As shown in the figure 2, the experimental setup consists of:

1. Preheated air inlet
2. Main and pilot fuel lines
3. Combustion section
4. Exhaust section

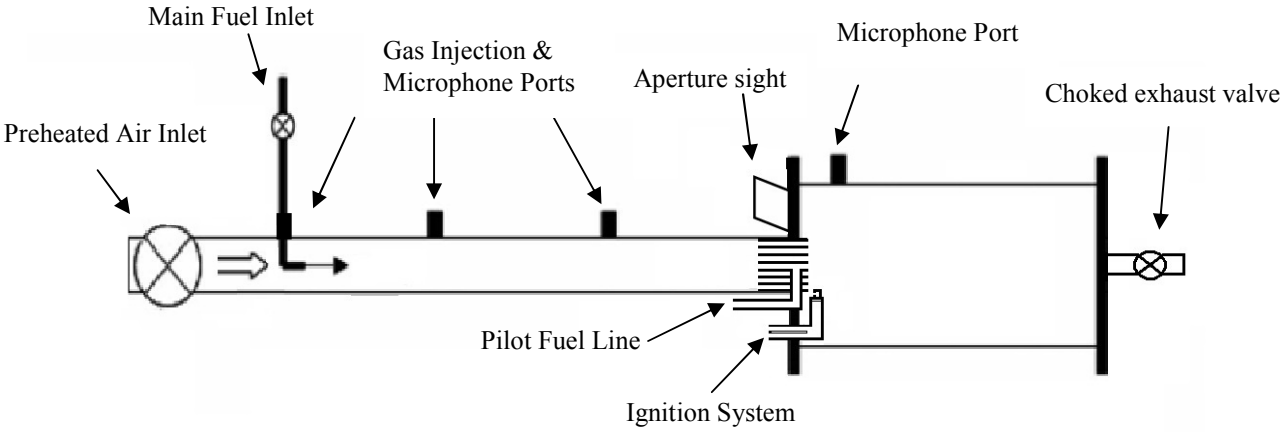

Figure 2. Schematic drawing of experimental combustion chamber

Setup is arranged so that air is supplied by using an air compressor, at 9 bar constant pressure. Main and pilot fuel (propane) is introduced, from a pressurized (10 bar)vessel, via fuel line (with two regulators on each, for pressure regulations) to the mixing section. It has to be mentioned that the air heated with an electric heater before reaching the air injector in the premixed section. As the fuel and air mixture goes through the pipe, they mix with each other, and finally homogenized mixture enters into the combustion chamber. In the combustion chamber, reactions take place and temperature increases. In order to facilitate the study of premixed length effect on the combustion instability, setup is designed to have a variable premixed length, and it can be modified as it is necessary during the tests. Figure 3 shows the experimental setup used in this research.

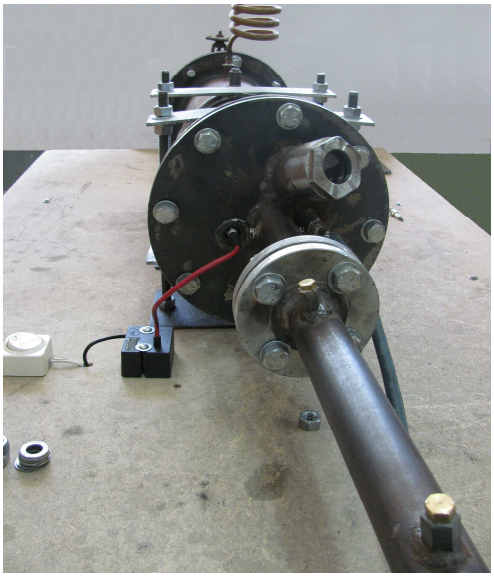

Figure 3. Experimental combustion chamber setup

It should be noted that the air and fuel streams shall impose no disturbance when entering into the mixing section. These disturbances may affect the instability frequency. For this purpose air and fuel streams are choked by using suitable size of injection nozzles. In order to visualize the flame, a glass window, made of quartz, is provided (figure 3). Thickness of glass is selected to withstand high temperature and high pressure. In addition to these a modified ignition system used for system starting.

Air and fuel flow rates are controlled using special check valves. Following instruments are employed for measuring various parameters during the tests:

1. Gaseous rotameter for measuring air and fuel volumetric flow rates. Rotameters are installed on the fuel and air lines, before mixing section.
2. Pressure gauges for measuring pressures at mixing section, fuel line and air line and combustor
3. Microphone for measuring sound pressure level, generated during the tests

Microphone output is transmitted to A/D card, with 10 kHz speed of data transfer. Afterwards, the data are processed using data processing software, installed on personal computer.

In order to promote the atmospheric test rig represented by one of the authors [4], a new test rig for achieving high pressures with a pilot fuel designed. System is pressurized by employing piston type air compressor, equipped with a reservoir. Reservoir outlet pressure is controlled by using an adjustable valve and a regulator. The test pressures varied between 1 to 7 bar.

It is foreseen to enable the operator to change the flow parameters, i.e. pressure and flow rate. In addition it is possible to change and adjust the length of mixing section. This ability permits the operator to investigate the mixing length effect on the combustor instability. By employing above-mentioned experimental setup following parameters can be measured and analyzed:

1. Instability frequency
2. Amplitude of instability oscillations

Experimental results

The probability density functions of the pressure oscillations amplitudes, obtained experimentally, for two cases of stable and unstable operating conditions, are depicted in the figures 4 and 5. It should be noted that the equivalence ratios are 1.24 and 0.70 for the stable and unstable operating conditions, respectively.

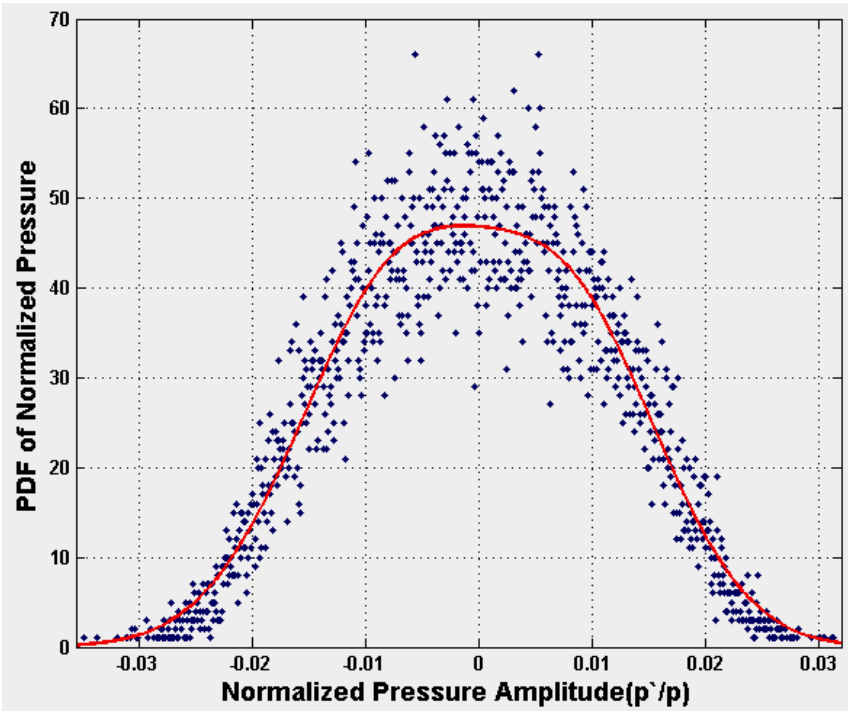

Figure 4. Probability density function of stable operating condition
Mass rate=5.9 gr/s. Equ ratio=1.24 . P=1.2bar

As can be seen the distribution of oscillations amplitude repetitions, for stable condition in figure.4., is so like as Gaussian distribution curve. Increasing of the air flow rate and, subsequently, decreasing of the equivalence ratio, change the Gaussian distribution form. The altered curve is as shown in figure 5. It can be observed form the latter case, that two maximums are appeared instead of one maximum. Moreover, for the stable condition represented in figure.4. the maximum amplitude probability percent corresponds to the oscillations sound pressure level equal to -0.005. However, the maximums of amplitude probability percents, for the unstable condition, correspond to the oscillations with 0.051 of the main combustor pressure. Accordingly, it can be concluded that during unstable operating condition, the two maximums, in term of amplitude probability percent, are appearing which are spread over the higher range of normalized pressure oscillations amplitude.

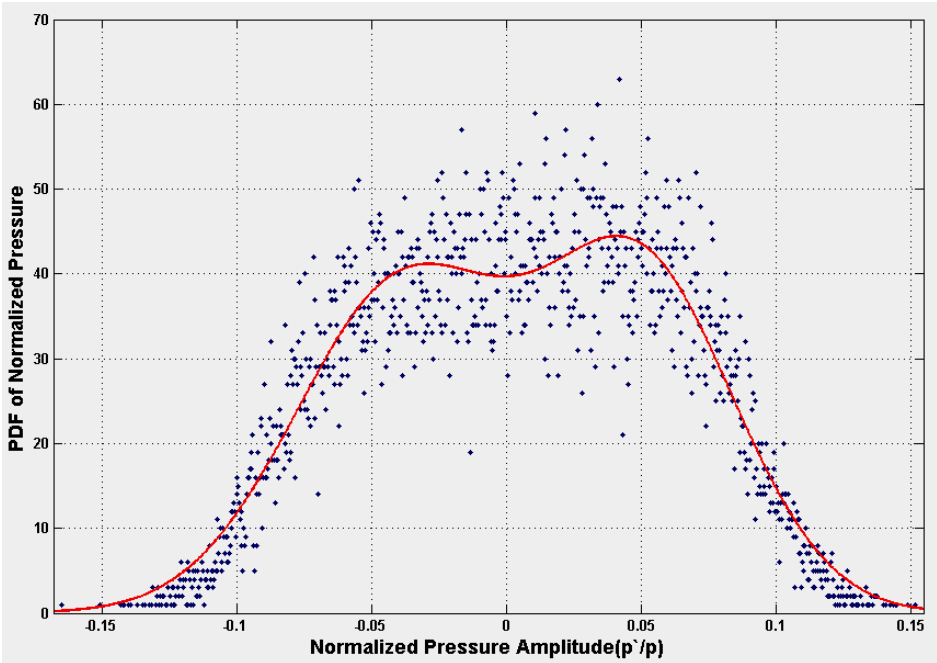

Figure 5. Probability density function of unstable operating
Mass rate=9.6 gr/s. Equ ratio=0.7 .P=2.5bar

As generally the first longitude mode became the practical and dominant unstable mode, this mode is consider to studied. During the tests, in order to achieve the ideal equivalence ratio fuel flow rate is kept constant and air flow rate is varied accordingly, equivalence ration is changed within the range of 0.7 to 1.35.

Figure 6 shows that the frequency of oscillations varies in the range of 120 to 160 Hz in all equivalence ratios. It is difficult to mention that the higher frequencies correspond to the lower equivalence ratios, and it's fair to say that decreasing the equivalence ratio, has a little effect in increasing instability frequency. It should be mentioned that dominate instability frequency takes less effects from equivalence ratio in spite of the amplitude of pressure oscillations, represented in figure 7.

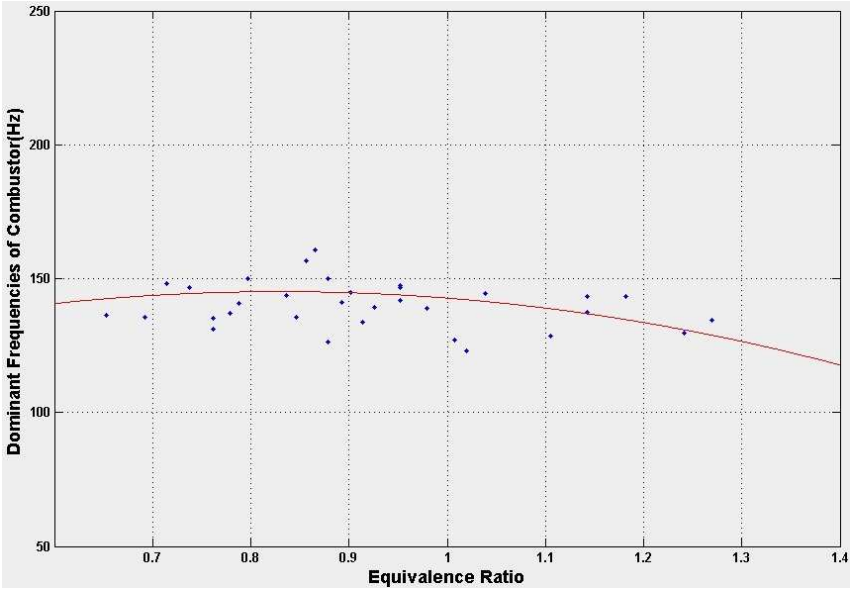

Figure 6. Relationship between equivalence ratio and instability frequency

Variation of normalized pressure oscillations amplitude based on equivalence ratio is demonstrated in figure 7. It can be seen that oscillations amplitude decreases by increasing equivalence ratio, and this variation is, approximately, linear.

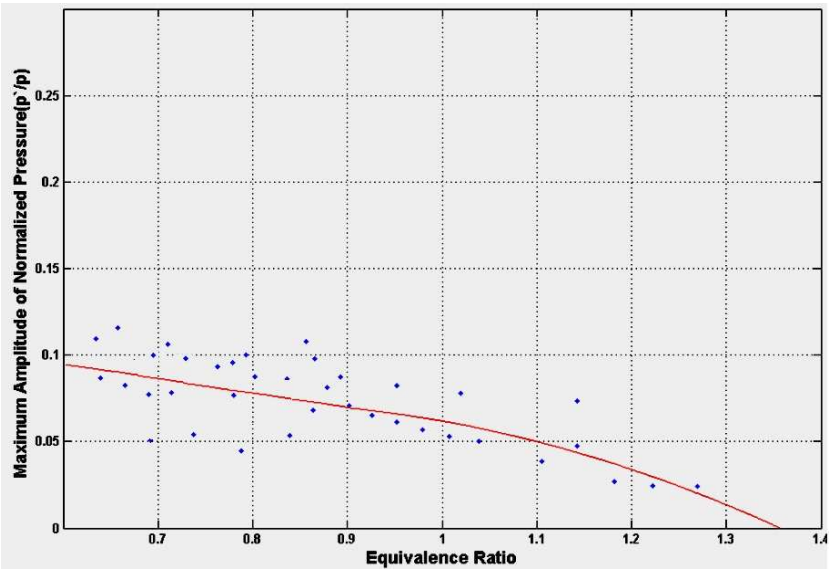

Figure 7. Variation of oscillations amplitude based on equivalence ratio

The dependence of frequency and the amplitude of oscillations with the total mass flow rate is somehow like the dependence of equivalence ratio. The dominate frequency not changes a lot with the changing of the flow rate (Figure 8), in spite of its apparent effect on the amplitude of normalized pressure (Figure 9).

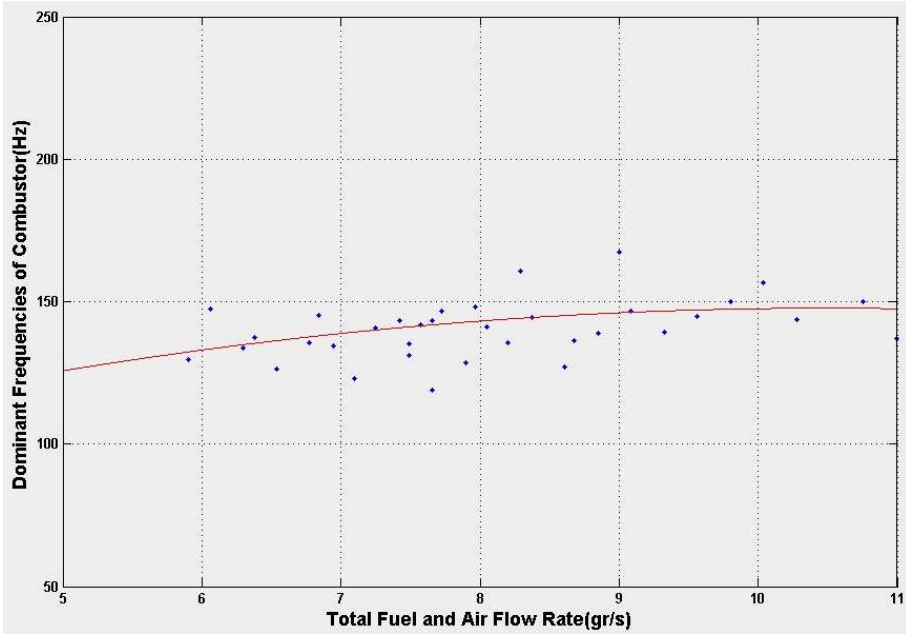

Figure 8. Relationship between total mass flow rate and instability frequency

The effect of mass flow rate on the oscillations amplitude represented in figure 9. With the increase of the mass flow rate the amplitude of the oscillations is also increased. The mass flow parameter displays the reactant velocities in the combustion chamber entry and this shows that in order to reduce the fluctuations, reducing the reactant enters velocity could be effective. In designing the combustion chamber.

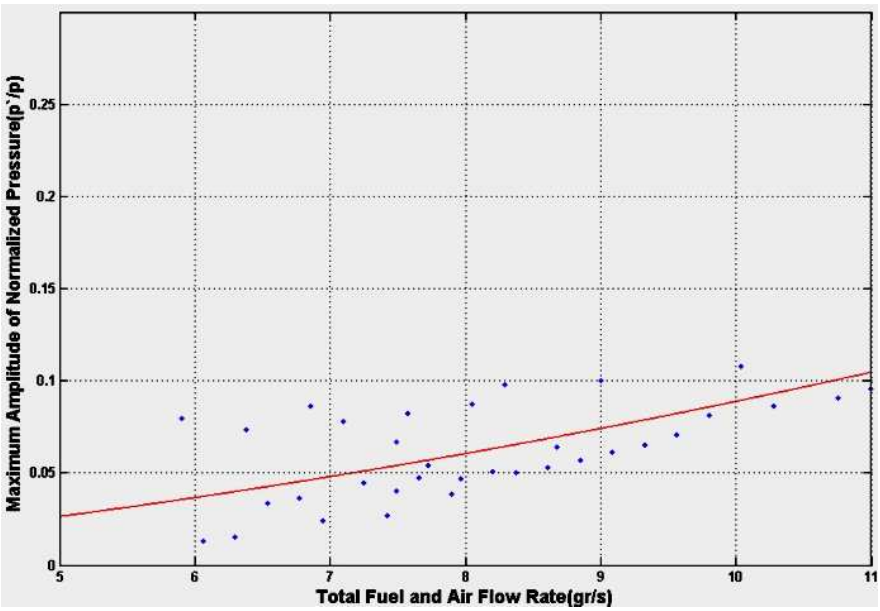

Figure 9. Variation of oscillations amplitude based on total mass flow rate

The last parameter that discussed in this paper is the combustor pressure. Most of the laboratory tests and published papers from many researchers were performed in the atmospheric conditions but the designed test facility can tolerate to 20bar pressure. But the data's just get up to 7bar for insuring safety conditions.

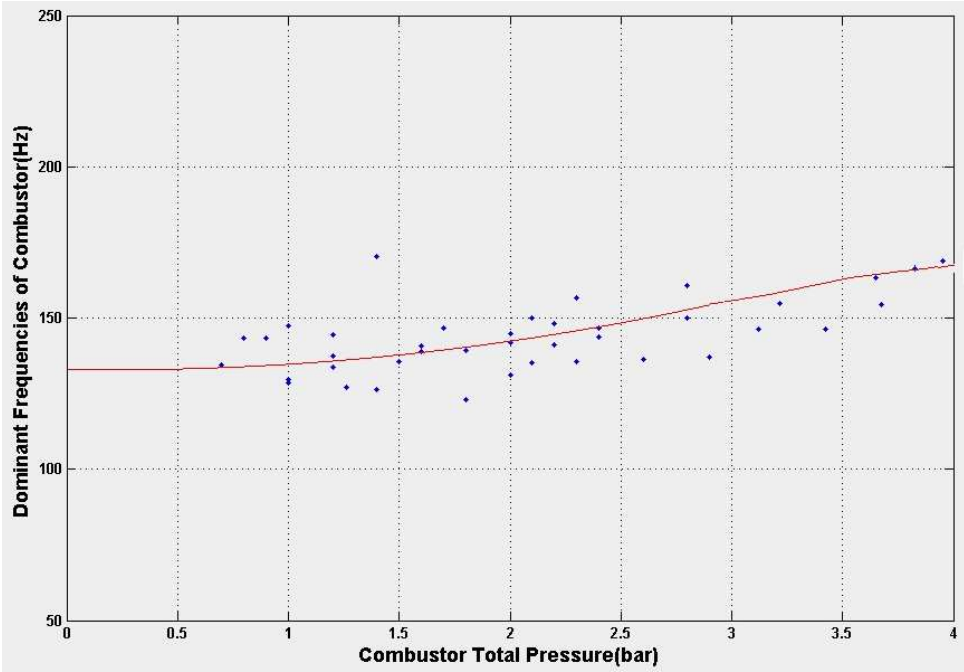

Figure 10. Relationship between mean combustor pressure and instability frequency

Again it is very obvious that there is a little dependence between the combustor pressure and the dominant frequency of the combustor, especially in the range of 1 to 3 bar but totally with the combustor presser increasing the dominant frequency of the combustor increases too. It has to be mentioned that all the data's represented in this paper are achieved from high pressure situations of the combustor.

The amplitude of oscillations is more dependent to the combustor pressure. As shown in figure 11 with the increase of the combustor mean pressure the normalized pressure amplitude increases too and this variation is approximately, linear.

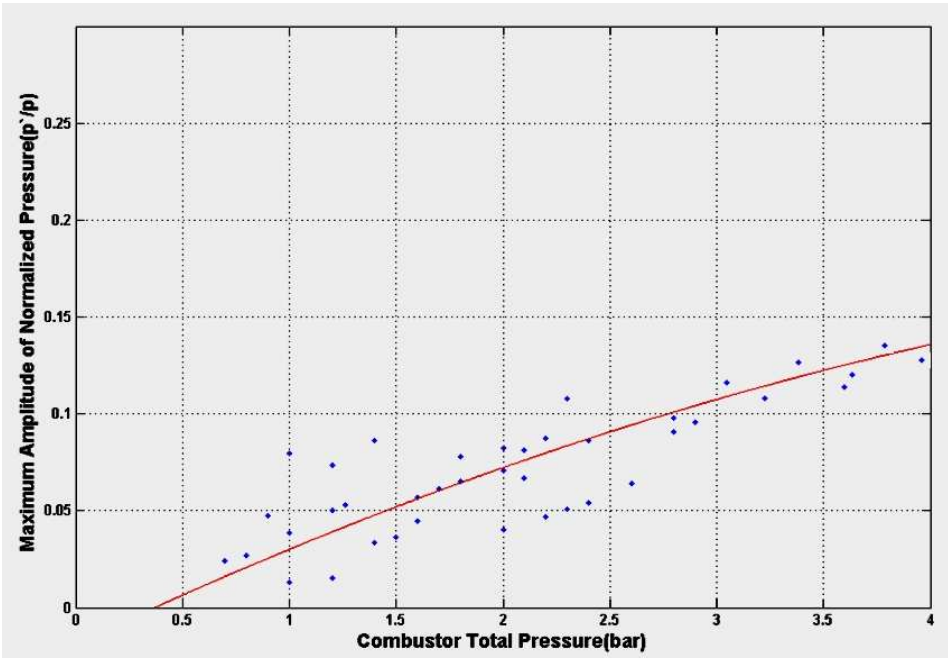

Figure 11. Variation of oscillations amplitude based on equivalence ratio

Convective Delay Time Calculation and Comparing with Rayleigh Criterion

In order to evaluate the experimental results, the Rayleigh criteria can be exploited. As mentioned before, thermo-acoustic instability is the result of coupling of heat release from chemical reactions and acoustic pressure. The integral form of Rayleigh criteria is as below [6]:

$$R = \int_0^T p'(t)\dot{q}'(t)dt \tag{2}$$

Furthermore, for pressure and heat release oscillations following equations can be considered.

$$\begin{aligned} \dot{q}'(t) &= \bar{\dot{q}} \sin \omega(t-\tau) \\ p'(t) &= \bar{p} \sin(\omega t) \end{aligned} \tag{3}$$

Using equations 2 and 3:

$$\bar{p}\bar{\dot{q}} \int_t^{t+2\frac{\pi}{\omega}} \sin(\omega t) \sin \omega(t-\tau) dt = \bar{p}\bar{\dot{q}} \frac{\pi}{\omega} \cos \omega\tau > 0 \tag{4}$$

where, $\bar{p}$, $\bar{\dot{q}}$, τ and ω are average pressure, average heat release, convective delay time, and oscillation frequency, respectively. According to Rayleigh criteria, in order to instability condition be occurred, convective delay time shall be within the following limits:

$$o < \tau < \frac{T(2n-1)}{4} \qquad n = 1,\ 2,\ 3,\ \ldots \tag{5}$$

$$o < \tau < \frac{T}{4} \qquad \text{for the first instability limit}$$

$$\frac{3T}{4} < \tau < \frac{5T}{4} \qquad \text{for the second instability limit}$$

Due to the, the equation that represented by Lieuwen [1] and the frequency range of data's (120-160Hz) the value of , for all tests, $\frac{\tau}{T}$ falls inside the following range:

$$0.72 < \frac{\tau}{T} < 0.96 \tag{6}$$

Unstable operation ranges, resulted from methods, experimental data and Rayleigh criteria, are shown in figure 12. As it can be seen, the range of τ/T for unstable operation based on Rayleigh criteria is 0.72 to 0.96 which is comparable with the experimental results.

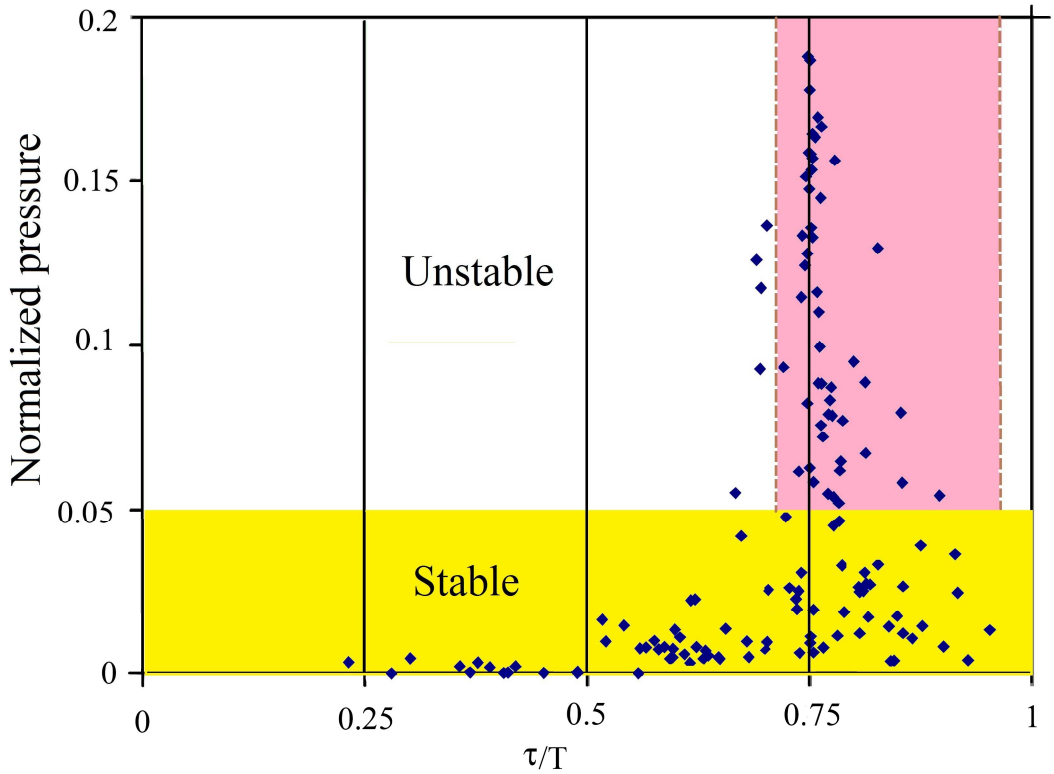

Figure 12. Unstable operation range of τ/T resulted from Rayleigh criteria and experimental data

CONCLUSION

The outcomes of this research include experimental data resulted from LPM combustion chamber. The achieved results showed that there is close dependence between instability amplitude and combustion chamber operating conditions like equivalence ratio, mass flow rate and combustor pressure. However the dependence of these parameters to instability frequency is less than instability amplitudes. It seems that the combustor geometry affects the instabilities frequency and the operating conditions affect the .amplitude of oscillations.

For the studied, probability density function and some statistical methods for pressure distribution are derived. It is shown stable condition in PDF point of view have Gaussian distribution curve but the unstable situation has two maximums, Furthermore, the experimental results are compared with the result of Rayleigh criteria and good agreement is detected.

References

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