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THE HISTOGRAM OF PRESSURE OSCILLATIONS AMPLITUDES, IN LEAN PREMIXED COMBUSTIONS, CAUSED BY THERMO-ACOUSTIC INSTABILITIES

Nasser Seraj Mehdizadeh
Aerospace Eng. Department and Center of Excellence in Computational Aerospace Engineering, Amirkabir University of Technology
Tehran, Iran

Nozar Akbari
Azad University, Shahre-Rey Branch
Tehran, Iran

ABSTRACT

Lean premixed combustion is widely used in recent years as a method to achieve the environmental standards with regard to NOx emission. In spite of the mentioned advantage, premixed combustion systems, with equivalence ratios less than one, are susceptible to the combustion instability. To study the lean combustion instability, by experiments, one premixed combustion setup, equipped with reactant supplying system, is designed and manufactured in Amirkabir University of Technology. In this research, gaseous propane is introduced as fuel and several experiments are performed at nearly atmospheric pressure, with equivalence ratios within the range of *0.7* to *1.5*. In this experiments fuel mass flow rate is varied between *2* and *4 gr/s*. Unstable operating condition has been observed in combustion chamber when equivalence ratio is less than one. To distinguish the combustion instability for various operating conditions, probability density functions, spectral diagrams, and space distribution of pressure oscillations, along with Rayleigh Criterion, are utilized. Accordingly, effect of equivalence ratio on stabilizing the unstable combustion system is investigated. Moreover, convective delay time is calculated for all experiments and the results are compared with Rayleigh Criterion. This comparison has shown good agreement the experimental results and Rayleigh Criterion. Finally, stability limits are identified based on inlet mass flow rate and equivalence ratio.

INTRODUCTION

In order to limit NOx emission, flue gas temperature may be decreased by using LPM1 combustors. Nevertheless, the pressure oscillations might be developed due to the coupling of unsteady heat release and acoustic pressure. This phenomenon, in turn, may cause thermo-acoustic instability problem (1).

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 (2).

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 (3). Following two important phenomena appear during the unstable operation of combustion chamber:

1- Excessive heat release
2- Pressure oscillations with large amplitude

As shown in Fig. 1., combustion instabilities are normally resulted from coupling of acoustic and combustion processes in the combustion chamber.

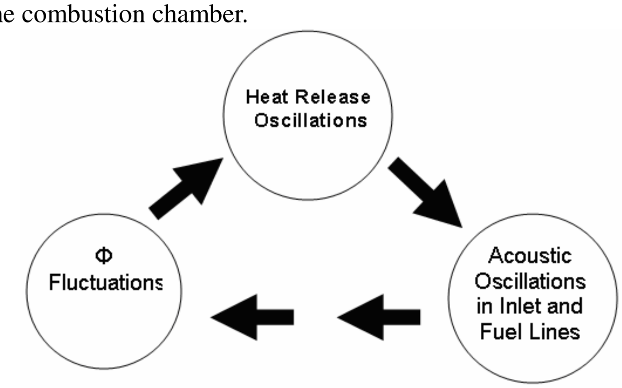

Figure 1. MECHANISM OF COMBUSTION INSTABILITY (1)

[1] Lean Pre-Mixed

Equivalence ratio oscillation model, proposed by Liewen (4), 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.

NOMENCLATURE

p	pressure
p'	pressure oscillation
q	heat release
q'	heat release oscillation
t	time
T	oscillation period
x	displacement
$\bar{\phi}$	Equivalence ration
τ	convective delay time
ω	oscillation frequency

EXPERIMENTAL SETUP

In order to perform experiments, in the field of LPM combustion chambers, an experimental setup is designed and fabricated (Fig. 2.).

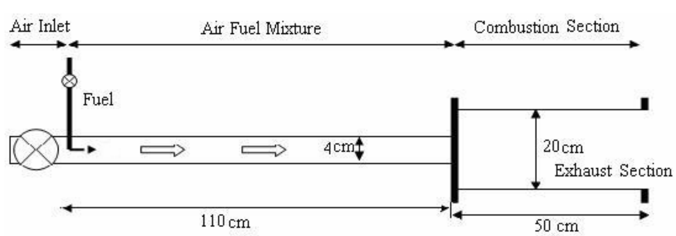

Figure 2. SCHEMATIC DRAWING OF EXPERIMENTAL COMBUSTION CHAMBER

This setup consists of:

- Air inlet section
- Air and fuel mixing section
- Combustion chamber section
- Flue gas Exhaust section

Air is supplied, by using an air compressor, at *7.5 bar* constant pressure, and fuel is introduced from a pressurized vessel, via fuel line to the mixing section. As the fuel and air mixture goes through the pipe, mixing is performed and homogenized mixture enters into the combustion chamber. Chemical reactions take place in the combustion chamber, and flue gas temperature increases. In order to facilitate the study of premixed length effect on the combustion instability, setup is so designed to provide variable mixing length. Figure 3. shows the experimental setup used in this research. 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 appropriate nozzles. In order to visualize the flame, inside the combustion chamber, a glass window, made of quartz, is provided (Fig. 3.).

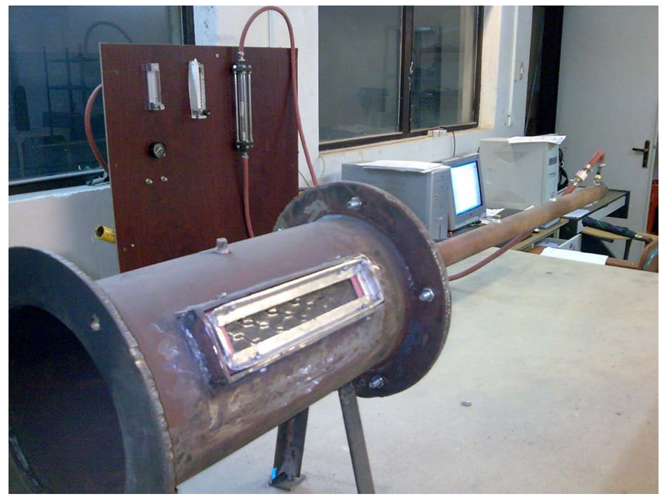

Figure 3. EXPERIMENTAL COMBUSTION CHAMBER SETUP

Thickness of glass is selected to withstand high temperature and high pressure. Air and fuel flow rates are controlled using special check valves. Following instruments are employed to measure various parameters during the tests:

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

Acoustic pressure oscillations are captured using suitable microphone. The accuracy of the microphone is checked by means of COOL EDIT software. For this purpose one signal, with pressure amplitude of *80 dB* and frequency of *200 Hz*, is generated and then recorded by the microphone. Afterwards, the output of the microphone is compared with the base signal, produced by the software. Slight difference ensures that the microphone is fairly calibrated.

Microphone output is transmitted to A/D card, with *10 kHz* speed of data transferring. These data are processed by data processing software, installed on personal computer. System is pressurized by employing piston type air compressor, equipped with a reservoir. Reservoir outlet pressure is controlled by using an adjustable valve. The setup is so elaborated 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 flame instability. By employing above-mentioned experimental setup following parameters can be measured and analyzed:

1. Instability frequency
2. Amplitude of instability oscillations
3. Instability limits

The manufactured setup allows the operator to study the effects of air flow rate and equivalence ratio on the thermo-acoustic instabilities. Following table summarizes the range of changes, implemented by the setup:

Table 1. RANGE OF PARAMETERS VARIATION CONSIDERED IN THE SETUP

Equivalence ratio	*0.8 ~ 1.5*
Inlet mixture velocity	*10 ~ 25 (m/s)*
Inlet air flow rate	*0.002 ~ 0.004 (kg/s)*

In this research propane and air are used as fuel gas and oxidizer, respectively. Various experiments are performed by changing equivalence ratio within the range of *0.7* to *1.5*. Moreover, mass flow rates of fuel gas and air mixture are varied between *2* to *4 gr/s*.

Sensible microphone is implemented for measuring the sound pressure level, generated during the tests. It should be noted that the pressure inside the combustion chamber is maintained at *1 atm*, during all tests. It is observed that for the most cases, the combustion chamber becomes unstable when fuel air ratio is lean.

HISTOGRAM OF PRESSURE OSCILLATIONS

The histograms of the experimental pressure oscillations amplitudes, for two cases of stable and unstable operating conditions, are depicted in the Fig. 4. and Fig. 5.

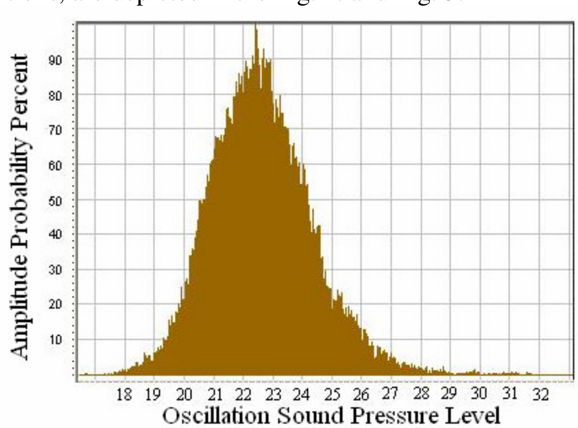

Figure 4. HISTOGRAM FOR STABLE OPERATING CONDITION ($\bar{\phi}$ =*1.4*)

It should be noted that the equivalence ratios are 1.4 and 0.8 for the stable and unstable operating conditions, respectively. As can be seen, the distribution of oscillations amplitude repetitions, for stable condition, 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.

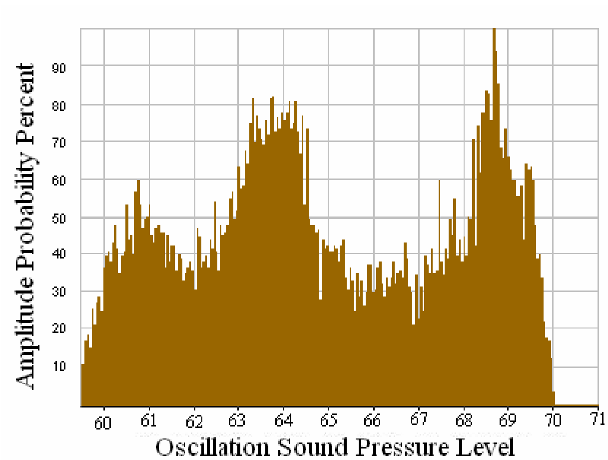

Figure 5. HISTOGRAM FOR UNSTABLE OPERATING CONDITION ($\bar{\phi}$ =*0.8*)

The altered curve is shown in Fig. 5. It can be observed that three maximums are appeared instead of one. Moreover, for the stable condition, the maximum amplitude probability percent corresponds to the oscillations sound pressure level equal to *22.5 dB*. However, the maximums of amplitude probability percents, for the unstable condition, correspond to the oscillations sound pressure levels equal to *60.8*, *63.7*, and *68.8 dB*. Accordingly, it can be concluded that during unstable operating condition, the several maximums, in term of amplitude probability percent, are appearing which are spread over the higher range of oscillations sound pressure level.

In this research the first longitudinal mode of oscillations is studied, as well. During the tests, fuel flow rate is kept constant at *5.6 l/min* and air flow rate is varied from *116* to *172 l/min*. Accordingly, equivalence ratio is changed within the range of *0.7* to *1.15*.

Figure 6. shows that the frequency of oscillations varies in the range of *225* to *250 Hz*. It is worthy to mention that the higher frequencies correspond to the lower equivalence ratios. So, decreasing the equivalence ratio increases, linearly, the instability frequency.

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

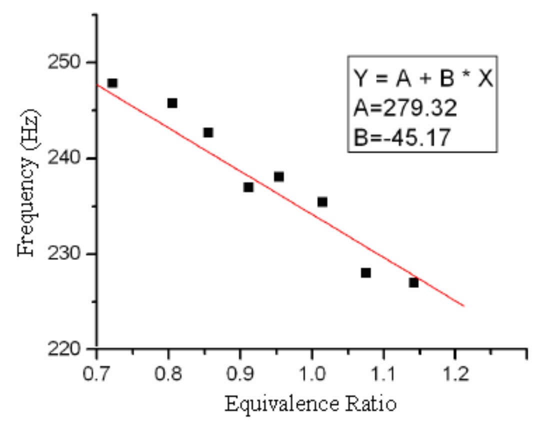

Figure 6. RELATIONSHIP BETWEEN EQUIVALENCE RATION AND INSTABILITY FREQUENCY

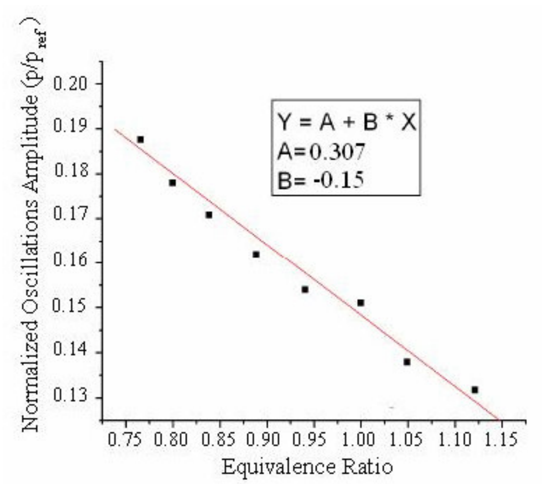

Figure 7. VARIATION OF OSCILLATIONS AMPLITUDE BASED ON EQUIVALENCE RATIO

Statistical analysis of pressure oscillations is considered as sophisticated method to develop comprehensive understanding of stable and unstable operating conditions. In this regard, state space distribution of pressure oscillations can be employed to describe and analyze the experimental data. The behavior of the system can be described, for two-degree harmonic system, by the following terms (5):

$$\left[x(t), \frac{dx(t)}{dt} \right] \tag{1}$$

For this purpose it is sufficient to calculate the first derivative of the signals with respect to time. Figures 8. and 9. illustrate the state space distribution of the pressure oscillations based on the normalized pressure oscillations amplitudes, for equivalence ratios of *1.4* and *0.8*.

As can be confirmed by using Fig. 8. and Fig. 9., decreasing the equivalence ratio from *1.4* converts the state space distribution of the pressure oscillations to ellipsoidal form, and further reducing of equivalence ratio results in expanding the ellipsoid. The reason of expanding the ellipsoid is increasing the pressure oscillations amplitude.

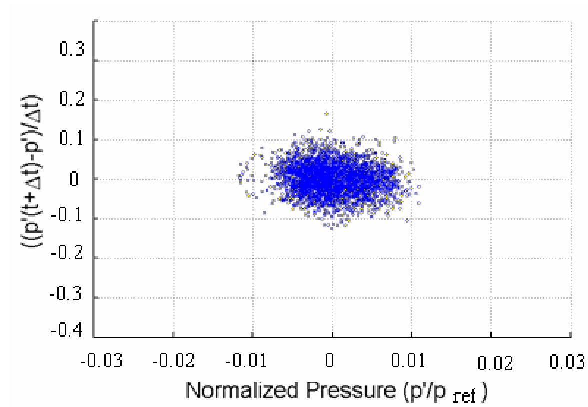

Figure 8. STATE SPACE DISTRIBUTION OF THE PRESSURE OSCILLATIONS ($\bar{\phi}$ =*1.4*)

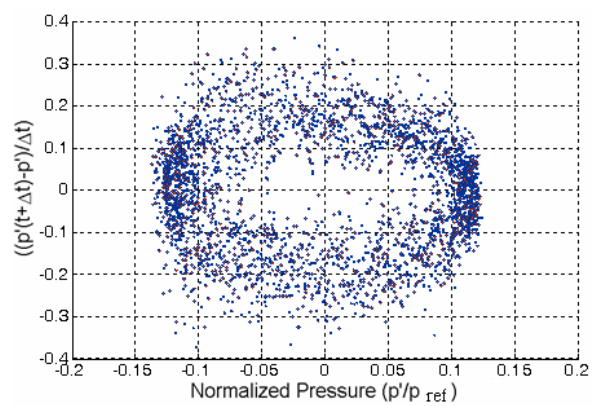

Figure 9. STATE SPACE DISTRIBUTION OF THE PRESSURE OSCILLATIONS ($\bar{\phi}$ =*0.8*)

Equivalence ratio has similar effect on Probability Density Function, which is described subsequently. Figure 10. shows the Probability Density Function histogram for stable operating condition. As can be seen, the distribution of oscillations amplitude repetitions is similar to Gaussian distribution curve. It can be observed from the figure that the maximum repetition corresponds to the oscillations with very small amplitudes, which explains the stable operating condition.

Decreasing the equivalence ratio and entering into the transition operating condition, change the Gaussian distribution form. The altered curve is shown in Fig. 11. As can be confirmed form the latter case, two maximums are appeared instead of one. Moreover, the maximums are located at the points for which p'/p_{ref} is outlying from zero. Additional decreasing of equivalence ratio produces similar histograms with maximums located in farther distances from the center.

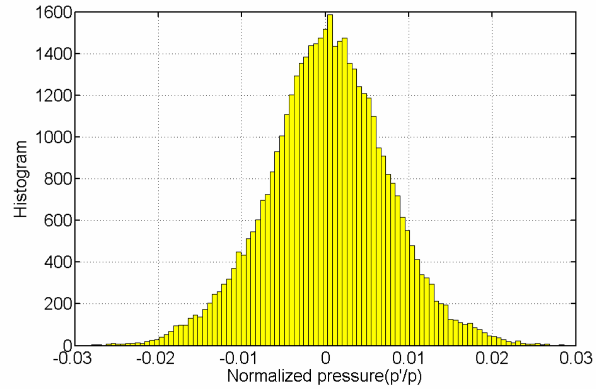

Figure 10. PROBABILITY DENSITY FUNCTION OF THE PRESSURE OSCILLATIONS ($\bar{\phi}$ =*1.4*)

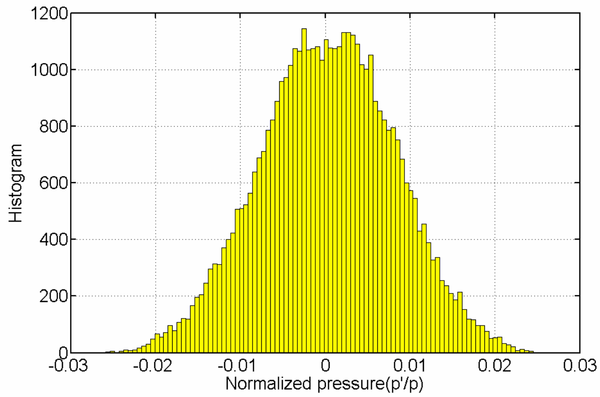

Figure 11. PROBABILITY DENSITY FUNCTION OF THE PRESSURE OSCILLATIONS ($\bar{\phi}$ =*1.2*)

Figures 12. and 13. illustrate the histogram for the case for which equivalence ratios are *1.1* and *0.8*, respectively. Relevant operating conditions are quite unstable.

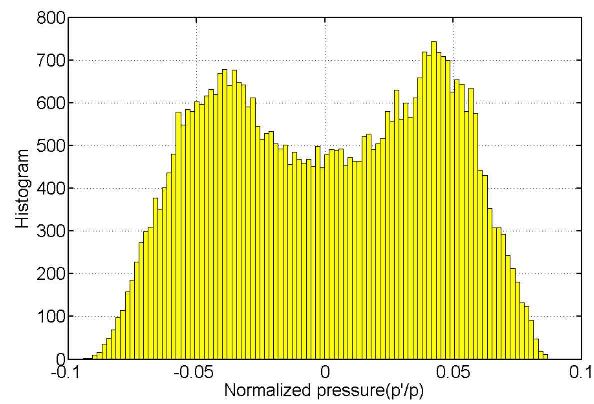

Figure 12. PROBABILITY DENSITY FUNCTION OF THE PRESSURE OSCILLATIONS ($\bar{\phi}$ =*1.1*)

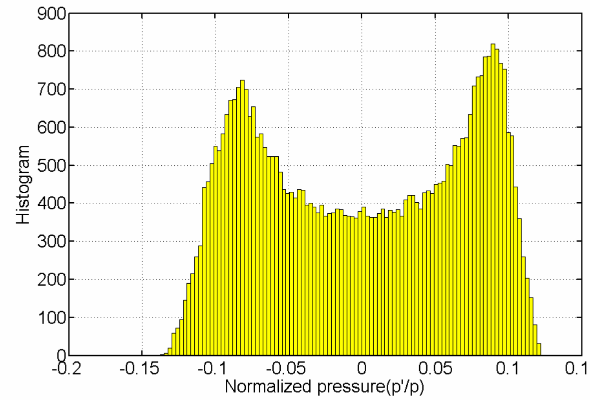

Figure 13. PROBABILITY DENSITY FUNCTION OF THE PRESSURE OSCILLATIONS ($\bar{\phi}$ =*0.8*)

Convective Delay Time Calculation and Comparing with Rayleigh Criterion

In order to evaluate the experimental results, Rayleigh criterion can be employed. 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 criterion is as below (6):

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

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

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

Using equations 2 and 3:

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

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 criterion, in order to instability condition be occurred, convective delay time shall be within the following limits:

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

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

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

Due to high length of mixing section of experimental setup, the value of τ/T falls inside the following range, for all tests:

$$\frac{43}{4} < \frac{\tau}{T} < \frac{45}{4} \qquad (6)$$

Unstable operation ranges, resulted from experimental data and Rayleigh criterion, are shown in Fig. 14. As it can be seen, the range of τ/T for unstable operation, based on Rayleigh criterion, is *10.75* to *11.25* which is comparable with the experimental results.

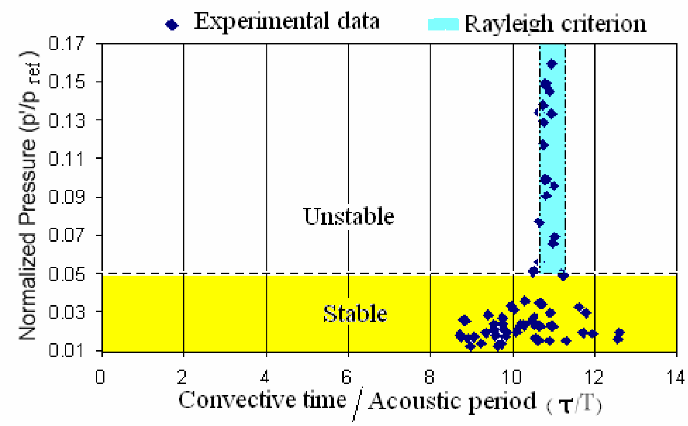

Figure 14. UNSTABLE OPERATION RANGE OF τ/T RESULTED FROM RAYLEIGH CRITERION AND EXPERIMENTAL DATA

Effect of Mass Flow Rate on Instability Limit

In this section stable and unstable regions for the tested combustion chamber are studied. The mixing length for the experimental setup (Fig. 2.) is 110 *cm*. Quite number of experiments are design and executed for diverse equivalence ratios, within *0.79* to *1.1*. For this purpose, inlet mass flow rate is varied between *2.2* and *3.4 gr/s* and inlet velocity is changed from *14* to *21 m/s*. For each test, type of operating condition, stable or unstable, is recorded. Having located the conditions, the boundary between stable and unstable conditions is obtained, as shown in Fig. 15.

It can be observed that for the higher inlet mass flow rates, the combustion chamber is stable for lower equivalent ratios. It means that the combustion chambers, with high inlet flow rates, are more sensible to instability. It should be noted that the marginal value for equivalence ratio is more restricted.

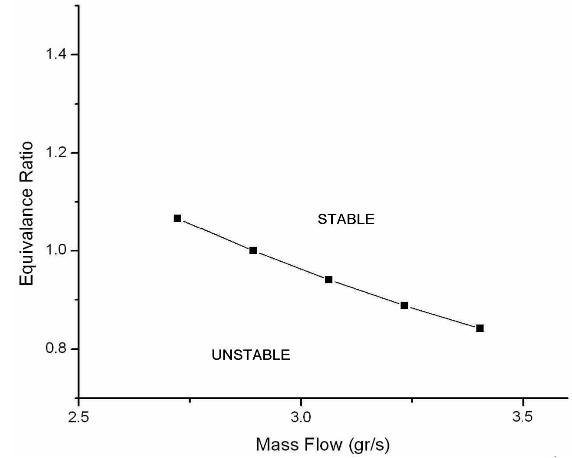

Figure 15. STABLE AND UNSTABLE REGIONS FOR THE TESTED COMBUSTION CHAMBER

CONCLUSION

The outcomes of this research include experimental data resulted from LPM combustion chamber, by implementing statistical analysis. The achieved results showed that there is close dependence between instability frequency (and amplitude) and equivalence ratio. In this research, statistical concepts are applied by using Probability Density Function and state space pressure distribution. It is shown that, for the stable condition, the mentioned state space distribution of the pressure diagram is concentrated around the center. However, for unstable conditions this diagram transforms to ellipsoid, and the points are located far from the center. Moreover, reducing the equivalence ratio expands the ellipsoid.

Furthermore, the experimental results are compared with the result of Rayleigh criterion and good agreement is detected. It is demonstrated that τ/T is useful parameter to study the instability phenomenon. So, by using this term, the regions of stable and unstable operating conditions can be identified. Accordingly, the borderline of stable and instable operating condition is depicted.

Besides, it is concluded that the combustion chamber is more sensible to instability, when it is operating under higher values of inlet flow rate.

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