# ANALYTICAL AND EXPERIMENTAL ANALYSIS OF REACTANTS VELOCITY EFFECT ON INSTABILITY OF PREMIXED COMBUSTION CHAMBER

Nasser SERAJ MEHDIZADEH[1,2,*] (Assistant Prof.), Nozar AKBARI[1,2] &
Reza EBRAHIMI[3] (Assistant Prof.)
[1] Aerospace Eng. Dept. - Amirkabir University of Technology
[2] Center of Excellence in Computational Aerospace Engineering
[3] Aerospace Eng. Dept. - Khaje Nasir Toosi University of Technology Tehran, Iran
(*Corresponding author: seraj@aut.ac.ir)

## ABSTRACT

Nowadays, combustion chambers of gas turbines, in order to be utilized in low NOx emission applications, take advantage of lean premixed combustion, extensively [1]. However, this category of gas turbines is susceptible to combustion instability [2]. This paper aims at investigating of reactants velocity effect on oscillations generated during combustion instability of premixed combustion chambers. In this regard, experimental and analytical approaches are employed and good agreement is observed between both methods. In experimental phase, histogram of density functions and the state space distributions of the pressure oscillations are derived to distinguish the combustion instability for divers operating conditions. In analytical phase, reactants velocity effect on combustion instability if studied. According to the results, it is observed that by increasing the reactants velocity, instability frequency and oscillations amplitude are intensified. Moreover it is confirmed that the variation of instability frequency and oscillations amplitude with respect to the reactants velocity is linear.

**Keywords:** Combustion Instability- Gas Turbines- Premixed Combustion- Reactants Velocity

## INTODUCTION

For performing experimental study of instability in lean premixed combustion chambers, a laboratory setup is designed and manufactured. The general sketch of the setup is shown in figure 1.

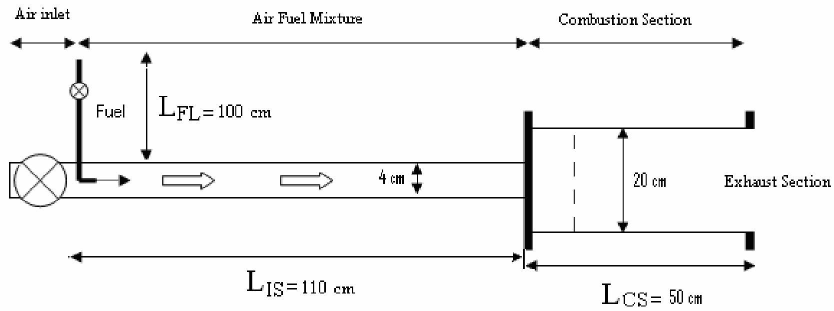



Figure 1. Schematic drawing of experimental combustion chamber

For the analytical part of the research, acoustic equation, as below, is implemented:

$$(\frac{\partial}{\partial t}+\bar{u}\frac{\partial}{\partial x})^2 P'-\bar{c}^2\frac{\partial^2 P'}{\partial x^2}=0 \tag{1}$$

where $\bar{c}$ and $\bar{u}$ are sound velocity in the gas and reactants mean velocity, respectively. By solving this equation and assuming harmonic oscillation, acoustic velocity ($u'$) and acoustic pressure ($P'$) can be derived as below [3]:

$$P_j{}' = (D_j^+ e^{ik_j x/(1+M)} + D_j^- e^{-ik_j x/(1-M)})e^{-i\omega t} \tag{2}$$

$$u_j{}' = \frac{1}{\rho_j c_j}(D_j^+ e^{ik_j x/(1+M)} - D_j^- e^{-ik_j x/(1-M)})e^{-i\omega t} \tag{3}$$

where $M$, $\bar{\rho}$, and $D_j^{\pm}$ denote Mach number, average gas density, and magnitude of acoustic disturbance propagation in the positive (+) and negative (-) x directions, correspondingly. The subscribe j stands for the region of interest. In order to find the amplitude and phase of these waves, it is necessary to specify the appropriate boundary and matching conditions, as followings [4]:

- Boundary condition according to impedance correlation ($Z = p'/u'$):

$$Z_{IS} = \frac{p'_{IS}}{u'_{IS}} \qquad Z_{FL} = \frac{p'_{FL}}{u'_{FL}} \qquad Z_{CS} = \frac{p'_{CS}}{u'_{CS}} \tag{4}$$

- Momentum matching condition for both sides of the flame zone:

$$A_{CS}(P'_{CS} - P'_{IS}) + 2\bar{\dot{m}}(u'_{CS} - u'_{IS}) = 0 \tag{5}$$

- Energy matching condition for both sides of the flame zone:

$$A_{CS}(P'_{CS}\bar{u}_{CS} + \bar{P}_{CS}u'_{CS}) - A_{IS}(P'_{IS}\bar{u}_{IS} + \bar{p}_{IS}u'_{IS}) = \frac{\gamma-1}{\gamma}Q' \tag{6}$$

- Matching condition between oscillations of fuel and air mass flow rate at inlet section, according to the orifice equation:

$$\frac{\dot{m}'_f}{\bar{\dot{m}}_f} = \frac{\Delta P'_{or}}{2\Delta\bar{P}_{or}} = \frac{P'_{FL} - P'_{IS}}{2\Delta\bar{P}_{or}} \tag{7}$$

In equation 6, heat release oscillation can be calculated based on the equivalence ration oscillation model, as below:

$$\frac{Q'}{\bar{Q}} = \kappa\varsigma_2 \frac{\phi'}{\bar{\phi}}\Big|_{Flamebase} e^{i\omega\tau_{eff}} \tag{8}$$

It is worthy to mention that equations 2 to 8 can be set as system of equation for which matrix form is ***AX=0***, where ***A*** and ***X*** are matrix of coefficients and unknowns vector, respectively. The components of the unknown vector are the followings, taking the sections, shown in figure 1, into account:

$$(D^{+}_{FL}, D^{-}_{FL}, D^{+}_{IS}, D^{-}_{IS}, D^{+}_{CS}, D^{-}_{CS}) \tag{9}$$

Equating determinant of the matrix ***A*** to zero, results in the angular velocity, as complex eigenvalue ($\omega_n = \omega_{n,r} + i\omega_{n,i}$). The real and imaginary parts of the mentioned eigenvalue correspond to the frequency and oscillation growth rate, respectively. It should be emphasized that positive value of imaginary part represents the growth of the oscillation amplitude by time; therefore, the situation is unstable. Table (1) describes the various parameters value used in this study. A computer code is developed for performing the simulation, numerically, and the corresponding results are illustrated in the succeeding section.

Table 1
Value for parameters used in experimental study and computer code

| | | |
|---|---|---|
| $\phi = 0.1 \sim 0.99$ | Combustion pressure = 1 *atm* | $T_{IS} = 300$ *(K)* |
| $L_{IS} = 5 \sim 110$ *cm* | Inlet reactants velocity = 5~20 *m/s* | $T_{product} = (T_{IS} + T_{WSR})/2$ *(K)* |

## ANALYTICAL RESULTS

Figure 2 shows the relation between fuel injector locations and inlet velocity to combustion chamber during instable operating condition. It is significant to mention that by increasing the inlet velocity, the instable condition appears for smaller values of fuel injector distance. To explain the case, it should be noted that the imaginary part of the eigenvalue, corresponding to the growth rate of the nth combustion mode, must be positive.

Relation between inlet velocity and instability frequency, during unstable operation, is illustrated in figure 3. As it can be observed, increasing the reactants velocity causes increasing the instability frequency.

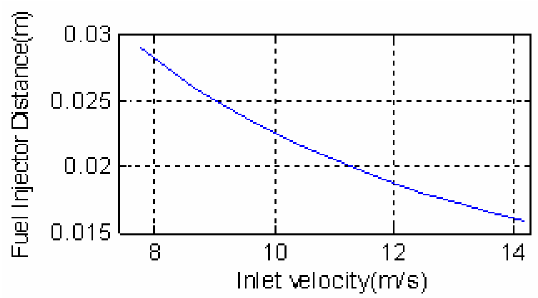



Figure 2. Effect of inlet velocity on fuel injection location during unstable operating condition

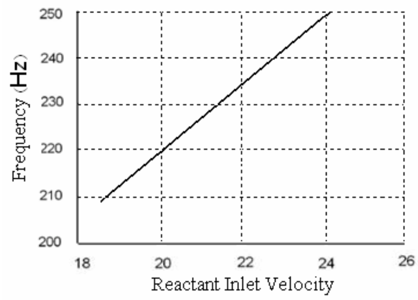



Figure 3. Effect of inlet velocity on instability frequency during unstable operating condition

The same behavior is detected by using experimental results, shown in figure 4.

## EXPERIMENTAL RESULTS

Figure 4 shows that the frequency of oscillations varies in the range of 212 to 230 *Hz*. It is worthy to mention that the higher frequencies correspond to the higher reactant inlet velocities, so that, decreasing the reactant inlet velocity, decreases instability frequency, proportionally. By applying Least Square method the corresponding line equation is found as $y = 162.059 + 3.262X$.

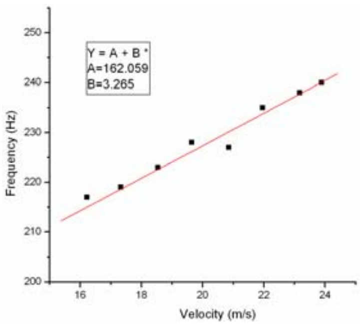



Figure 4. Effect of inlet velocity on instability frequency (unstable condition)

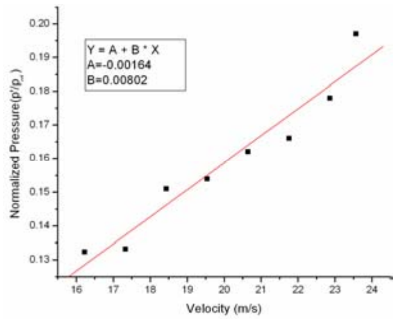



Figure 5. Effect of inlet velocity on normalized oscillations amplitude (unstable condition)

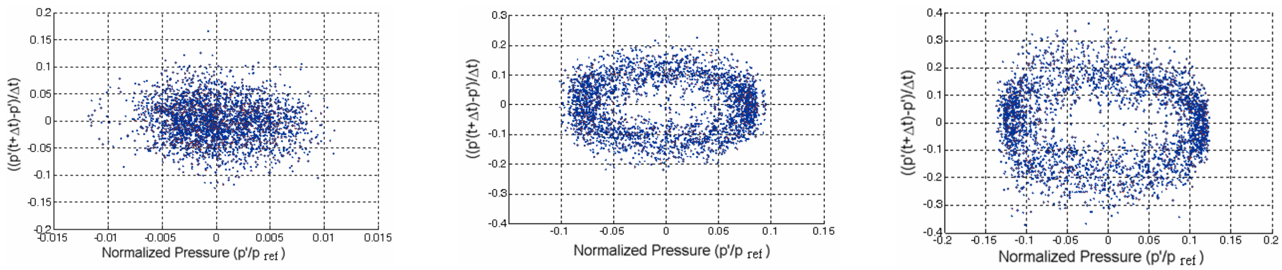
Variation of normalized pressure oscillations amplitude based on reactant inlet velocity is demonstrated in figure 5. It can be seen that oscillations amplitude increases by increasing reactant inlet velocity, and this variation is, approximately, linear. This figure has good agreement with the results obtained analytically, shown in figure 3.

Figures 6a, b, and c illustrate the state space distribution of the pressure oscillations based on the normalized pressure oscillations amplitudes, for various reactant inlet velocities.

As can be confirmed by using figures 6a, b, and c, increasing the reactant inlet velocity from 16 *m/s* converts the state space distribution of the pressure oscillations to ellipsoid, and further increasing of reactant inlet velocity results in expanding the ellipsoid. The reason of expanding the ellipsoid is increasing the pressure oscillations amplitude.

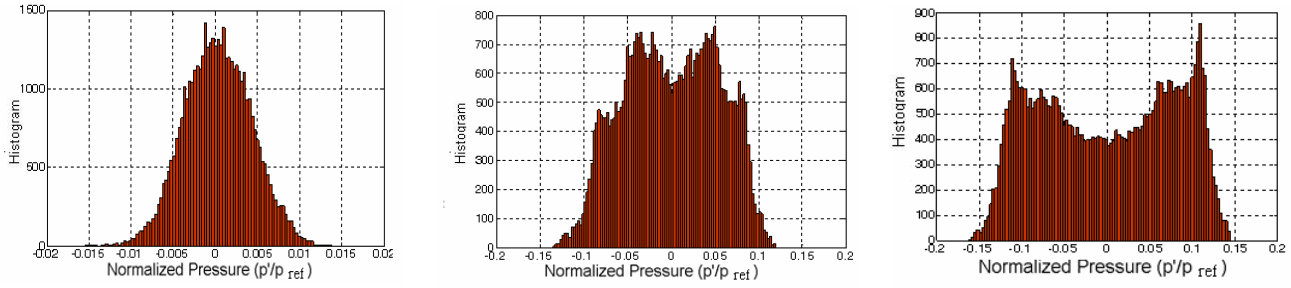
Reactants inlet velocity has similar effect on Probability Density Function, which is described as subsequently. Figure 7a shows the Probability Density Function histogram for stable operating condition. As can be seen the distribution of oscillations amplitude repetitions is so like as Gaussian distribution curve. It can be seen from the figure that the maximum repetition corresponds to the oscillations with very small amplitudes, which explains the stable operating condition.

Increasing the reactants inlet velocity and entering into the transition operating condition, change the Gaussian distribution form of the previous figure. The altered curve is shown in figure 7b. As can be observed form the later case, two maximums are appeared instead of one maximum, and more over the maximums are located at the points for which $p'/p_{ref}$ is outlying from zero.




(a) (b) (c)

Figure 6. State space distribution of pressure oscillations (a) $(\overline{u} = 16 \ \ m/s)$ (b) $(\overline{u} = 17.5 \ \ m/s)$ (c) $(\overline{u} = 21 \ \ m/s)$




(a) (b) (c)

Figure 7. Probability Density Function histogram of pressure oscillations (a) $(\overline{u} = 16 \ \ m/s)$ (b) $(\overline{u} = 17.5 \ \ m/s)$ (c) $(\overline{u} = 21 \ \ m/s)$

Further increasing of reactants inlet velocity produces similar histograms with maximums located in farther distances from the origin. Figure 7c illustrated the histogram for the case for which inlet velocity is 21 *m/s* and operating condition is quite unstable.

For the later the maximums are positioned at $p'/p_{ref}$ equal to $\pm 0.11$.

## CONCLUSION

Taking foregoing into account, following outcomes can be highlighted:

1. Fuel flow rate is to be adjusted properly, to meet various working conditions requirements. As indicated in figure 2, in case of increasing inlet velocity, in order for prohibiting instability to be occurred in the combustion chamber, one may increase fuel injection distance. This can be easily executed, by implementing necessary devices for changing the fuel injection distance.
2. In order to examine the instable behavior of the combustor, an appropriate setup is designed and then constructed. Effect of reactants inlet velocity on instable frequencies is achieved experimentally and compared with analytical results. Good agreement is detected between two approaches.
3. During stable operation of combustor, corresponding histogram curve has only one peak, and it is similar to Gaussian distribution curve. However for the instable operating condition, histogram curve includes more than one peak and the curve behavior is not similar to Gaussian curve.

## REFRENCES

[1]Lieuwen, T., and Yang, V. [2006],*Combustion Instabilities in Gas Turbine Engines: Operational, Experience, Fundamental Mechanisms and Modeling*, Massachusetts, AIAA.

[2]Lieuwen, T. [2001], A Mechanism of Combustion Instability in Lean Premixed Gas Turbine Combustor", *Transactions of ASME*, Vol.123, January, pp. 182-189.

[3]Pierce, A. [1991], *Acoustics: An Introduction to Its Physical Principles and Application*, Acoustic Society of America: New York.

[4]Lieuwen, T., and Zinn B. [1998], Theoretical Investigation of Combustion Instability Mechanisms in Lean Premixed Gas Turbine", *36th Aerospace Sciences Meeting & Exhibit*, AIAA 98-0641.