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Acoustic characteristics of premixed flames in a combustor

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Abstract

This paper experimentally investigates the operating mode of a combustor for various fuel and air velocities when it is subjected to lean premixed combustion. The preliminary investigations are done on a laboratory scaled in-house built combustor prior to the real-time experiments. The effect of air-fuel velocities on the occurrence of combustion noise as well as limit cycle oscillations are investigated in the present study to determine the operating mode of the combustor. By varying the flow speed, the combustor is observed to undergo a dynamical transition from combustion noise to limit cycle oscillations. The timehistory of the acoustic pressure fluctuations and sound pressure level spectra shows the operating mode of the combustor. It shows that at a gas velocity (Vg)= 10 m/s and air velocity (Va)= 35 m/s, the combustor shows limit cycle oscillations, which are indicated by the almost periodic fluctuations in time history of the acoustic pressure. For other operating conditions, it shows only low amplitude random oscillations (i.e., combustion noise). Further, visualizations are done to obtain the instantaneous images of unsteady flames in the lean premixed combustion regime. Thus, the preliminary investigations demonstrate the combustion dynamics of the combustor under various operation conditions. The study will be helpful in performing the real-time experiments for triggering the thermo-acoustic instabilities by adjusting the fuel and air velocities and hence to suppress them with the aid of an acoustically driven fuel injector.

Keywords: Premixed combustion, unsteady flame, acoustics, thermoacoustic instability

1. Introduction

A lean premixed combustion is essential in gas turbines, boilers, industrial furnaces, aero-engines,etc. to reduce the exhaust emissions such as NOx, sulfur, etc. Further, it is beneficial from the economic point of view since the fuel price keeps on increasing nowadays. The lean premixed combustion systems are generally preferred as mentioned above, but they are highly prone to heat-driven self-excited oscillations of large amplitude, which is commonly known as thermoacoustic instability. The phenomenon of thermoacoustic instability is the result of positive feedback coupling between the acoustic modes of the combustion chamber and the unsteady flames[1]. Such instability continues to hinder the advancements of reliable low-emission combustion systems. Heat release fluctuations are caused by unsteady flames. The unsteady flamesare known to be the source of acoustic waves. The acoustic waves travel to the ends of the combustor, get reflected, and perturb the flame. The perturbation in flame leads to further generation of acoustic pressure and velocity fluctuations. Rayleigh criterion is the necessary condition to establish the initiation of thermoacoustic oscillations, which states that instability results from the coupling between heat release rates and acoustic fluctuations [2], which is quantified in terms of the Rayleigh index [3]. These

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instabilities are characterized by large-amplitude periodic unsteady pressure oscillations and could cause additional noise and vibration of large amplitude leading to combustor's component damage and reduced lifetime of systems [4]. There are numerous undesirable consequences of thermoacoustic instability, like structural vibrations [5], high NOx emissions [6], flame flashbacks [7], and flame blowoff [8]. In any combustor, some parameters affect the generation mechanisms of thermoacoustic oscillations and are investigated by several authors [9], [10], [11], [12]. Such parameters include acoustic resonance and reflection, hydrodynamic features, and entropy waves. Therefore, thermoacoustic oscillations attain the status of prime research for the aero-engine and other such systems using lean premixed combustion. The phenomenon of combustion instability and the associated frequencies in a specific gas turbine engine could be of specific value and generally be classified by the oscillation frequencies and grouped into low-frequency, intermediate-frequency, and high-frequency instabilities. To solve the problem of combustion instabilities, the driving mechanisms must be deeply understood, the prediction tool should be developed, and the control strategy needs to be prepared to develop a combustor [13]. Some authors assumed such oscillations as the composition of low-frequency hydrodynamic oscillations and high-frequency acoustic oscillations [14]. The hydrodynamic oscillations represent periodic flow features such as vortex shedding. Two different types of feedback loops are often responsible for combustion instabilities. The first involves feedback between the combustor's acoustic modes and flame. Combustion system's cavity thermoacoustic mode is formed by this feedback, which indicates that the cavity modes are always locked on the pure acoustic modes. The coupling between the pressure waves of a mode and the unsteady heat release rate is the second mechanism, which may not depend on the pure acoustic modes of the burner. This mode is known as Intrinsic Thermoacoustic modes (ITA). The interaction between the perturbation and the flame oscillation drives both thermoacoustic instabilities of cavity modes and ITA modes. The cavity mode is driven by a global feedback loop, in contrast to the ITA mode, which is controlled by a local feedback loop. To study combustion instabilities, a variety of numerical, analytical, and experimental methodologies have been employed. In the previous investigations, intermittent oscillations were considered as the superposition of two vibrations with similar frequencies [15],[16].In most real-world systems, the downstream end of the combustion chambers is typically linked to other parts like turbine blades and tailpipes. These elements lower the exit are, which can change the process that leads to thermoacoustic instabilities by either reducing the acoustic reflection at the exit or choking the flow. In such cases, instability might happen in the situation of decreasing acoustic reflection coefficient at the exit due to an intrinsic thermoacoustic (ITA) feedback loop [17]. For a duct with no exit area contraction, the combustion noise gets amplified around the acoustic modes of the combustor [17], [18]. In such ducts, a rise in acoustic energy near the acoustic resonant modes of the combustor undergoes a transition to instability from combustion noise [19]. Sun et al. [20] conducted large eddy simulations to examine the generation and mitigation of thermoacoustic instability in a methane-fuelled swirling combustor. They presented the effect of area change by considering a nozzle at the exit of the combustor. In the present work, the acoustic characteristics of an unsteady flame are studied in an in-house build combustor to identify the various operating modes of the combustor at different flow rates of air and fuel.

2. Objectives

The objective of the present paper is to investigate the far-field acoustic characteristics of an unsteady flame for different flow rates (i.e., flow velocities) of air and fuel in an in-house build combustor to identify the various operating modes (stable and unstable) of the combustor operating in the lean premixed mode. The acoustic characteristics are expressed in terms of the timehistory of acoustic oscillations, amplitude spectrum, and sound pressure level (SPL) spectra for various flow rates (i.e., flow velocities) of air and fuel. The present study could be a preliminary benchmark to identify the various operating modes of the combustor under different operating conditions. The study will be helpful in conducting the real time experiments and hence identifying the operating conditions of the combustor, which could help to devise an acoustic driven injector/control system to suppress the thermoacoustic oscillations of the combustor over a wide range of frequencies.

3. Experimental setup and methodology

3.1 Details of Experimental setup

The layout and actual schematic of the combustor setup with a reduced exit cross-sectional area is shown in Fig. 1. It comprises fuel and air supply devices, control valves, a mixing chamber to mix the fuel and air homogeneously, and a combustor. Air is supplied using a blower, and liquefied petroleum gas (LPG) fuel is supplied from a cylinder. Experiments are carried out for different fuel and air flow velocities (i.e., different flow rates of fuel and air). From the mixing chamber, the air-fuel mixture flows through a feeder duct, and the burning of this mixture happens through a burner. The burner is placed in a duct of rectangular cross-section 31 cm × 35 cm which has a length of 80 cm. This rectangular cross-section duct has a converging terminating duct with a reduced area. The reduction in the exit area is quantified in terms of the area ratio (AR) of the combustor. The area ratio in the present study is taken as 0.16. The burner is connected to the mixing chamber through a 25.4 mm diameter tube, which is placed at a distance of 22 cm from the beginning of the combustion chamber duct. The mixing chamber measures 64 cm in length, and two cylindrical tubes are connected individually for(i) gas supply from the cylinder and (ii) blower for air supply. To visualize the flame, transparent sections made of quartz having a cross-section 35 cm × 15 cm are placed on both sides of the combustion chamber. Three fuel flow velocities 10 m/s, 15 m/s, and 20 m/s and air flow velocities, 25 m/s, 30 m/s, and 35 m/s, are considered in the present study to ensure that the combustor is operating in the lean premixed combustion regime.

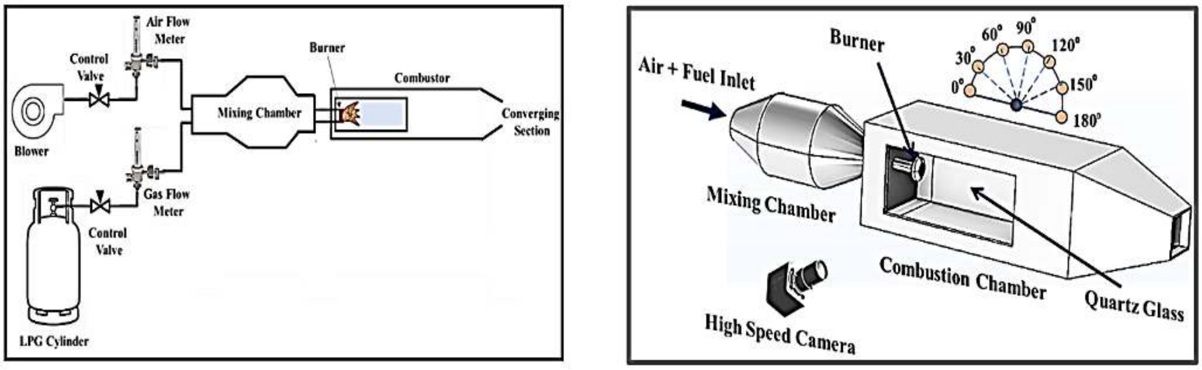


Fig. 1— Layout and actual Schematic of the combustor setup

3.2 Measurement systems

The far-field acoustic data are acquired using a quarter inch condenser microphone (Make: GRAS, Model 40PH 277551) having a sensitivity of 50 $mVPa^{-1}$ at 250 Hz to determine the time-history and amplitude spectrum. The characteristics of the regimes of combustion dynamics, namely, combustion noise and thermoacoustic oscillations are explored from the amplitude spectrum. The acoustic measurements are performed for a 5s duration at a sampling frequency rate of 50 kHz. The measured noise is transferred to a PC using NI 15 LABVIEW version 4.0 software through a 4-channel simultaneous sampling data acquisition system (NI, Channel Chassis CDAQ 9174, NI 9222 C Series). Uncertainties in the measurement of air and gas velocities are within ±1% and ±1%, respectively. Uncertainty in the flame noise measurement is within ± 0.5 dB, including repeatability factors.

4. Results and discussions

4.1 Acoustic Spectra of Flame

In order to do the spectral analysis of unsteady flames for various fuel velocities (V_g) and air velocities (V_a), the recorded time series pressure data are segmented into FFT blocks of 1024 data points. The acoustic spectra estimated from each FFT block are averaged, and the Hanning window is applied to get FFT, as shown in Fig. 2. The measured spectra indicates that the background noise levels are well below the measured spectra of combustion noise for the frequency range from 100 to 1.5 kHz. Thus, the background noise does not affect the acoustic spectra of unsteady flames.

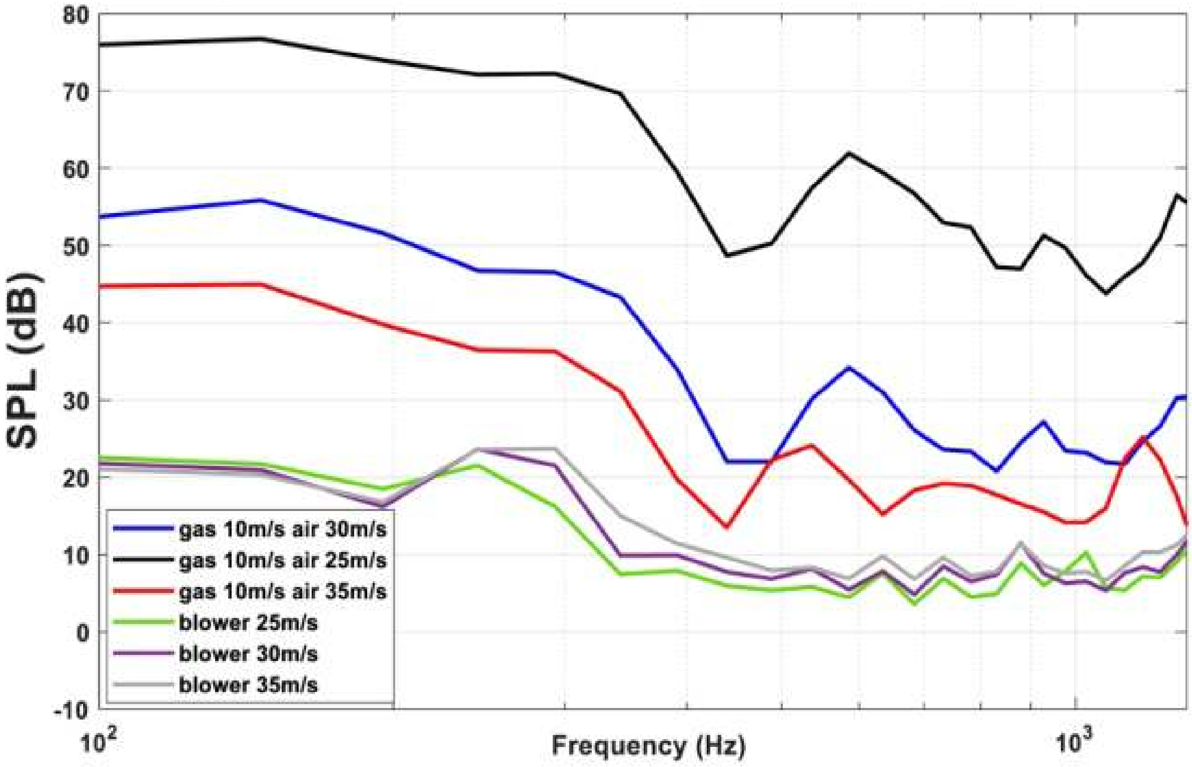
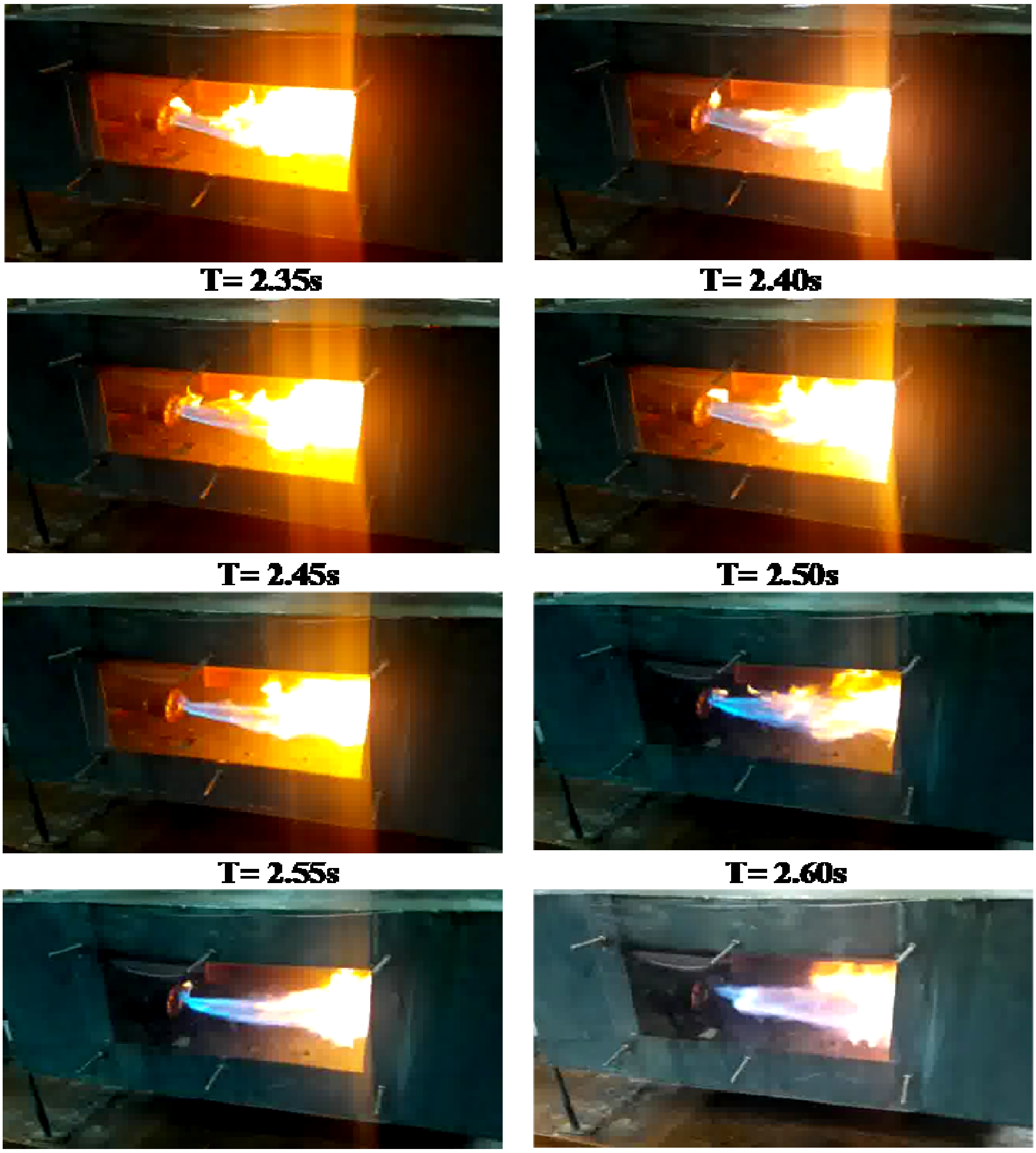


Fig 2—Sound pressure level spectra comparison at V_g = 10 m/s and V_a = 25 m/s

Figures 3 and 4 show the instantaneous flame images of the lean premixed combustion recorded using a high-speed camera at different combinations of air (V_a) and fuel velocities (V_g). At V_g = 10 m/s and V_a = 35 m/s (Fig. 3), a series of flame images can be seen extended to a considerable distance from the zone of the burner. The combustion happens for a duration of 5s, however, the images presented are the intermediate ones. There are recirculating zones in flames, the occurrence of which could be due to reflection from reduced area exit. For the higher fuel velocity V_g = 15 m/s at V_a = 35 m/s (Fig. 4), flame behavior is entirely different. The next sub-section describes the behavior of flames through analysis of time series of acoustic pressure acquired by microphones.



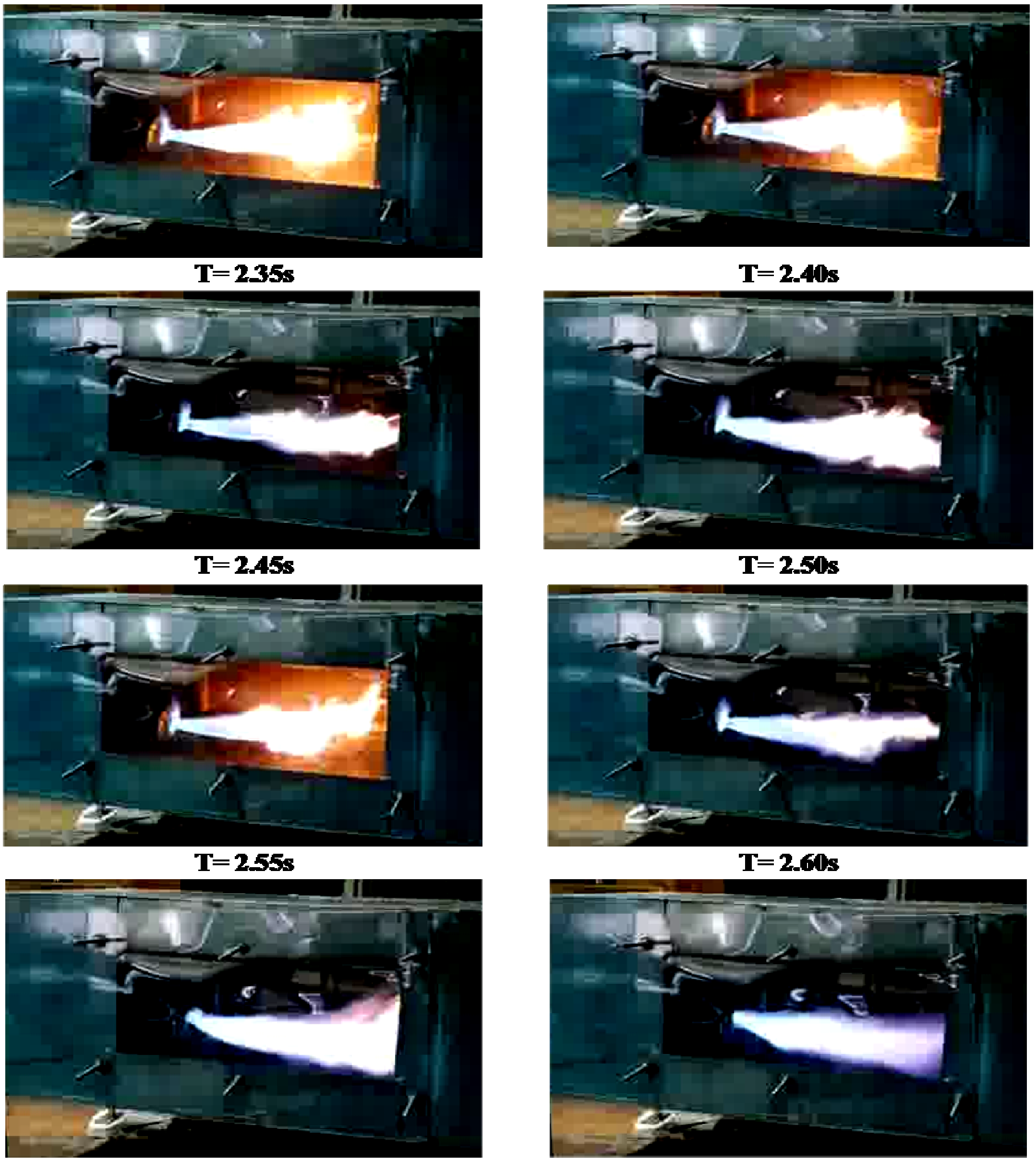
T= 2.35s **T= 2.40s**

T= 2.45s **T= 2.50s**

T= 2.55s **T= 2.60s**

T= 2.65s **T= 2.70s**

Fig.3—Instantaneous flame images at V_g = 10 m/s and V_a = 35 m/s



T= 2.35s

T= 2.40s

T= 2.45s

T= 2.50s

T= 2.55s

T= 2.60s

T= 2.65s

T= 2.70s

Fig.4—Instantaneous flame images at V_g = 15 m/s and V_a = 35 m/s

4.2 Time history of acoustic pressure and amplitude spectrum

The timehistory of acoustic pressure and the corresponding amplitude spectrum at fixed gas and varying air velocities are presented in Fig. 5. The results of acoustic pressures presented are measured by a microphone placed at 90 deg to the axis of the flame. The low-amplitude random fluctuations (Fig. 5(a)) for V_g = 10 m/s and V_a = 25 m/s represent the combustion noise. It's amplitude spectrum, as shown in Fig. 5(b), also shows a broadband nature with low amplitude peaks. With the increase in V_a to 30 m/s, the unsteady acoustic pressure also shows the condition of combustion noise (Fig.5(c)). The corresponding pressure amplitude spectra shows increased amplitude(Fig.5 (d)), with the peaks appears to be getting raised than for the previous case. Now, with the further increase in air velocity to 35 m/s, the combustion dynamics shows the limit cycle of oscillations (Fig.5(e)) which are indicated by the almost periodic fluctuations in time history.

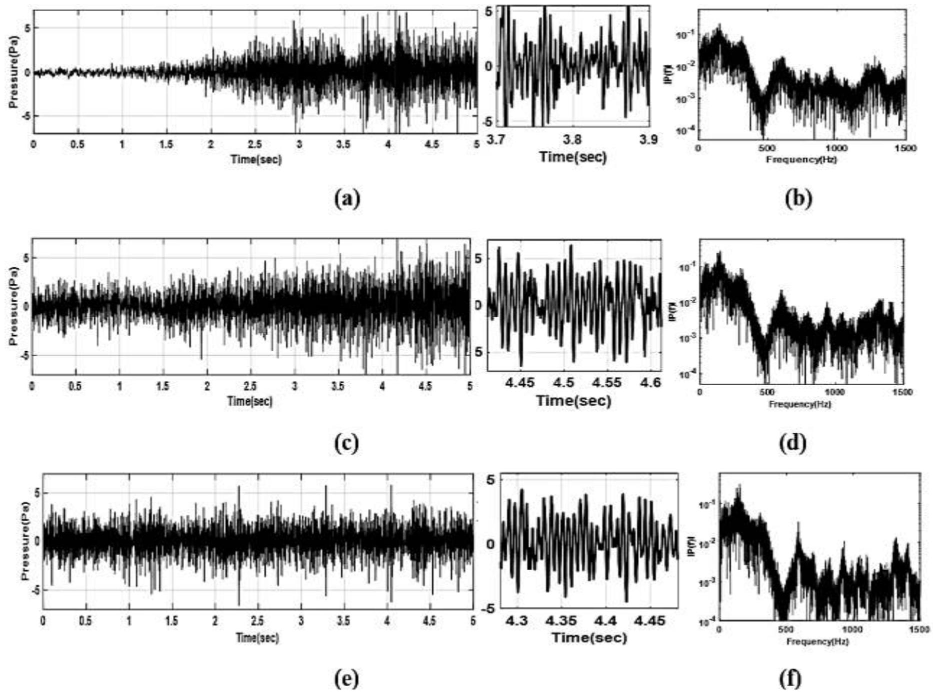


Fig.5—Time-history of acoustic pressure and the amplitude spectrum at V_g = 10 m/s for V_a = (a,b) 25 m/s (c,d) 30 m/s, and (e,f) 35 m/s

Figure 6 presents the time series of unsteady acoustic pressure and the amplitude spectrum for different air flow velocities at a gas flow velocity of 15 m/s. The time series of unsteady acoustic pressure and amplitude spectrum for V_g = 15 m/s and V_a = 25 m/s show similar nature reflecting the state of combustion noise. The transient pressure has random fluctuations (Fig.6(a)), and the amplitude spectrum (Fig. 6(b)) has no clean peaks. For the other cases of higher air flow velocities, Fig. 6(c)-Fig. 6(f) also show the combustion noise which are indicated by the low amplitude random fluctuations.

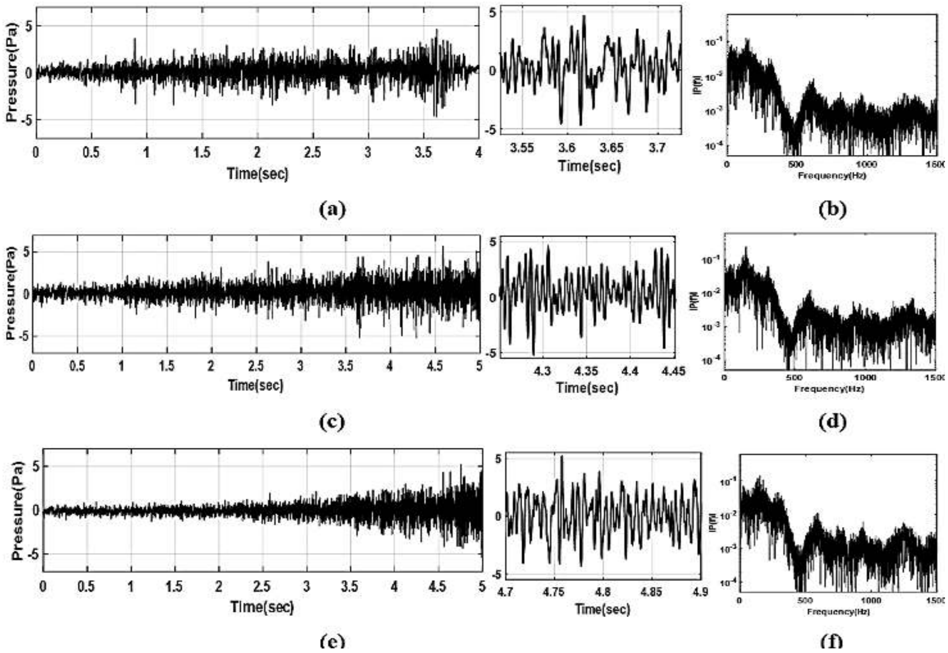


Fig.6—Time-history of acoustic pressure and amplitude spectrum at V_g= 15 m/s for V_a = (a,b) 25 m/s (c,d) 30 m/s, and (e,f) 35 m/s

5. Conclusions

The preliminary investigations of the combustion dynamics under lean premixed conditions are experimentally investigated in the present study. Experiments are carried out in a laboratory-scaled in-house built combustor. The studies were conducted for different gas and air velocities to understand the combustion dynamics under various operation conditions prior to the real-time experiments. The unsteady pressure fluctuations are measured by an array of microphones for several combinations of air-fuel velocities and processed to identify the operating mode of the combustor (i.e., combustion noise/limit cycle oscillations). The combustion flames are observed to be very sensitive to the changing flow velocities of air and fuel, and the combustion dynamics shows the limit cycle oscillations at $V_g = 10$ m/s and $V_a = 35$ m/s, which are indicated by the near periodic fluctuations in time history of the acoustic pressure. Thus, the preliminary investigations demonstrate the combustion dynamics of the combustor under various operation conditions. The study will be helpful in conducting the real-time experiments to generate thermo-acoustic instabilities by properly anchoring the flame and hence to suppress them with the aid an acoustically driven fuel injector.

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