MECHANICAL ENGINEERING | RESEARCH ARTICLE

Effect of pointed and diffused air injection on premixed flame confined in a Rijke tube

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Abstract: The coupling between pressure fluctuations and unsteady heat release in a combustion systems results in acoustic oscillations inside the combustion system. These acoustic oscillations, when grow sufficiently, may cause serious structural damage thereby reducing the lifespan of jet engines, gas turbines, and industrial burners. The aim of the first part of study is to define acoustically stable and unstable regions. The second part is focused on studying the effect of change in pressure field near the flame on the amplitude and frequency of the oscillations of instability. This study is carried out for three-burner positions and equivalence ratio of 0.7 by varying heat supply and total flow rate. The results show two acoustically unstable regions for 0.1 and 0.2 burner positions and only one acoustically unstable region for 0.25 burner position. The effect of pointed injection and diffused injection over a premixed flame on the sound pressure level was studied. The results show for burner position of \( x/L = 0.2 \) there is 25 dB suppression is possible using pointed injection at higher total flow rate. The experiment of diffused injection shows sound amplification more than 12 dB was observed.

Subjects: Acoustical Engineering; Aerospace Engineering; Energy & Fuels

Keywords: thermo-acoustics; Rijke tube; premixed flame; equivalence ratio

1. Introduction

To meet the stringent emission norms, the development of lean combustion system is the necessity. But the lean combustors are more prone to combustion instabilities. These instabilities produce the large amplitude oscillations of one or more natural acoustic mode of combustor and thus degrading.

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PUBLIC INTEREST STATEMENT

Combustion instability occurs when the pressure fluctuation coupled with unsteady heat released. These acoustic oscillations, when grow sufficiently, may cause serious structural damage thereby reducing the lifespan of jet engines, gas turbines, and industrial burners. The acoustic oscillation is very useful in heat exchanger to increase the effectiveness of heat exchanger. This study focuses on establishing the boundaries of instability for lean combustion as well as study the effect of pointed and diffused air injection over the flame. The pointed air injection able to completely suppress instability, whereas diffused air injection over the flame amplifies the instability. The diffused air injection over the flame can be used in heat exchanger to increase its effectiveness.
performance as well as reduces the combustor life. The combustion instabilities are observed during operation of propulsion (e.g. rockets, ramjets, and afterburners), power generation (land-based gas turbines), and industrial furnaces. The occurrence of combustion instabilities produce large amplitude pressure and velocity oscillations that results in thrust oscillations, severe vibrations, and enhanced heat transfer to the combustor walls. It can result in premature component wear that could lead to costly shut down or mission failure. Lieuwen, Torres, Johnson, and Zinn (2001) explain the mechanism of combustion instability and also explain the factor responsible for combustion instability to grow. Zhao, Li, Yang, and Zhang (2015) numerically investigated the conversion of heat to sound in T-shaped system. The increase in heat transfer rate with instabilities is advantageous in certain mechanical systems where exchange of heat is essential. Martins, Ferreira, and Carvalho (2009) and Martins, Lacava, Ferreira, and Carvalho (2003) in their experiments on water-jacketed Rijke tube, wherein the heat content of water was found to increase by about 10% with the occurrence of the instability over most equivalence ratios ranging from 0.7 to 1. To develop the approaches for preventing or controlling combustion instabilities, an understanding of the mechanisms and predicting the conditions under which instabilities grows must be developed. To study the instability in the combustor, a Rijke tube was conveniently used by various researchers to study the combustion instability (Juniper, 2010; Matveev, 2003; Raun, Beckstead, Finlinson, & Brooks, 1993; Zhao, 2012; Zhao & Chow, 2013).

In 1878, Rayleigh (1878) had formulated a criterion to explain how acoustic waves could be excited and sustained by heat addition. When the heat is given to the air at the moment of greatest condensation, or be taken from it at the moment of greatest rarefaction, the vibration is encouraged. $RI(x, t)$ is the local Rayleigh Index determined per cycle, $T$ is the period of oscillation, $p'(x, t)$ is local pressure fluctuation at position $x$, and $q'(x, t)$ is local unsteady heat release at position $x$. In mathematical terms, Rayleigh's criterion can be formulated in terms of the Rayleigh integral (Carvalho, Ferreira, Bressan, & Ferreira, 1989; Ferreira & Carvalho, 1997; Kopp-Vaughan, Tuttle, Renfro, & King, 2009),

$$RI(x, t) = \frac{1}{T} \int_0^T p'(x, t)q'(x, t) \, dt > 0.$$  \hspace{1cm} (1)

If, $RI < 0$, then acoustic oscillations will damp out.

If, $RI > 0$, then acoustic oscillations will grow.

If, $RI = 0$, then oscillations will neither be damped out nor amplified.

So, the region where ‘$RI > 0$’ will be favorable to sustain the instabilities, hence the heat source should lie in this region. The control of oscillations is a rich field due to the complexity of the dynamics as well as the prominence of both land and air-based jet engines. These high-energy devices operate in a wide range of operating conditions, all of which are highly nonlinear due to turbulence, combustion, and other extreme conditions. The control of instabilities (active or passive) is a natural way to overcome these unwanted oscillations (Docquier & Candel, 2002). The active control is challenging due to actuator limitations including harsh conditions, high temporal frequencies, and the limited amount of control authority a finite number of actuators offers. The passive control technique involves modifying the chamber geometry by the introduction of perforated liner (Lei, Zhihui, Chengyu, & Xiaofeng, 2010), baffles or Helmholtz resonators (Zhang, Zhao, Han, Wang, & Li, 2015; Zhao & Li, 2015; Zhao & Morgans, 2009) and acoustic dampers (Richards, Straub, & Robey, 2003) change in position of fuel injection system. Unfortunately, this approach increases mass and dimensions of the power plant. Moreover, its damping efficiency is limited. The various active control strategies were used to control the instabilities. The fuel injection (Hathout, Annaswamy, & Ghoniem, 2000; Pang, 2005), air injection (LaBry, Shanbhogue, Speth, & Ghoniem, 2010; Uhm & Acharya, 2004, 2005, 2006), and phase shift (Heckl, 1988; Webber, 2003) were implemented successfully. Recently,
Zhao, Ji, Li, and Li (2015) studied mitigation of premixed flame-sustained thermo-acoustic oscillations using an electrical heater. The main focus of this study is to investigate the effect of change in pressure field near to burner for reducing and growing the pressure oscillations inside the Rijke tube. As the instability increases the heat loss increases, therefore need to develop a heat exchanger with instability to increase the effectiveness of heat exchangers. The active open loop control strategies with pointed and diffused air injection over the flame for different positions of heat source and equivalence ratio of 0.7 are investigated.

2. Experimental set-up

The quartz tube of 75 mm internal diameter and 80 mm outer diameter of length 750 mm is used. Figure 1 shows schematic diagram of experimental set-up. The air flow is provided with the help of blower, driven by 0.5 hp, three-phase electric motor which sucks air in the tube. An auto transformer (three phase, 8.1 KVA) is attached to the blower which controls the blower speed and hence the total flow inside the tube.

A 100-cm long plenum chamber is located between tube and blower to reduce the interaction between blower and tube acoustics. Inside the plenum chamber, an aluminum mesh is placed at a distance of 2 cm from tube interface. The aluminum strips are fixed at alternate location on two 2.5 cm thick circular rings made of plywood. These rings are fixed inside the plenum chamber at a distance of 5 cm from tube interface. The purpose of this is to make the flow uniform and reduce the interaction between blower and tube acoustics. For providing proper LPG and air mixer, a premixer is designed. It is designed mainly for achieving the desired mixture ratio with proper mixing of air and fuel. To accomplish this premixer has two tangential inlets for air and one inlet for LPG at the center of premixer. This promotes the required swirl for proper mixing. This premixed air and LPG is then supplied to burner where combustion takes place. The position of burner changes with the help of traverse. The air injection over the burner is achieved with the help of a ring which is 70 mm in diameter and made up of 5-mm copper tube with eight circumferentially equi-distanced holes of 1 mm diameter inward and outward (at an angle of 45°) over the burner. Figure 2 shows the rings for radial pointed and diffused air injection over the flame.
3. Experimental methodology

In the first part of study to define acoustically stable (without sound) and acoustically unstable (with sound) regions for equivalence ratio of 0.7, different burner positions L/4, L/5, L/10 (L is length of the tube), and total flow rate (20 LPM–80 LPM) experiments are carried out. In the second part of study, the effect of pointed and diffused radial inward air injection over the burner is studied. The ring position from burner surface is defined by \( g \) and burner location is defined by \( x \). In the experiments, burner positions as \( x/L = 0.25, 0.2, \) and 0.1, whereas ring positions from burner as \( g/L = 0.033, 0.02, \) and 0.006. For each burner position the effect of radial air injection on sound pressure level (SPL) for different ring positions, quantity of air injection, and total flow rate at equivalence ratio of 0.7 is studied. Figure 3 shows pointed air injection over the flame inside the quartz tube.

Figure 4 shows diffused air injection without deflected ring over the flame inside the quartz tube. In this method, ring with outward holes is used, which inject the air towards the wall of quartz tube. These air jets will strike the quartz tube wall and get diffused at wall surface and will return back over the flame.

Figure 5 shows diffused air injection with deflected ring over the flame inside the quartz tube. In this method, ring with inward holes is used, which inject the air towards the deflected ring. The air jets will strike the deflected ring and get diffused. Then, the diffused air will flow over the flame.
3.1. Measurement of sound pressure level
As shown in Figure 1, a Bruel and Kjaer (B&K) condenser-type microphone (model 4939 having dynamic range of 28–164 dB and sensitivity of 4 mV/Pa) is placed at a distance of 600 mm looking into the Rijke tube from an oblique angle of 30º for measurement of SPL. The microphone output is given to data acquisition system through a B&K signal conditioning amplifier, NEXUS Microphone Conditioner—Type 2690-A.

3.2. Measurement of pressure
The pressure fluctuations are measured in the plane of burner head on wall of the Rijke tube. A pre-calibrated, ultra-low differential pressure transducer RS 395–257 (Range 0–60 mm of water with accuracy of ±2%) is connected through PVC tubing to Pitot tube. Pitot tube with its tip touching the wall of Rijke tube in the plane of the burner head is used to measure wall pressure. A digital Alnor micromanometer (Model AXD610) is used to calibrate the pressure transducer. An 8 volt DC power supply is used as external source of excitation for the pressure transducer.

4. Results and discussion
4.1. Stability regions
Experiments in the present investigation were carried out to demarcate the boundaries of thermo-acoustic instability with three burner positions inside the Rijke tube, x/L 0.25, 0.2 and 0.1, respectively, for the total mass flow rate varying from 0.33 to 1.33 × 10⁻³ m³/s in steps of 0.2 × 10⁻³ m³/s and the heat power varying from 50 to 600 W in steps of 50 W keeping the equivalence ratio of 0.7. Figure 6 shows the map of instability regions for the different burner position inside the Rijke tube. With change in heat supplied and total mass flow rate the boundaries depict the regions of existence and non-existence of instabilities. What is to be noted is that the boundaries between these regions are nearly flat without any discernible trend over the entire range of the total mass flow rate, nonetheless, the boundaries shift with increasing amount of heat supplied along with the change in mode. It shows that one acoustically unstable region for burner position of 0.25 and two acoustically unstable regions for burner positions 0.2 and 0.1. Figure 6(a) shows large stable region compared to unstable region for burner position x/L = 0.25. Carvalho et al. (1989) and Matveev and Culick (2003) have discussed how the position of the heat source in the Rijke tube dictates the mode of the thermo-acoustic instability and derived the exact locations, on the basis of energy input, where heat source can produce the fundamental and different higher modes of the thermo-acoustic instability. For electrically heated Rijke tube stability region for third mode of instabilities is up to 0.33. In premixed gas burner heated Rijke tube, the flame length depends on presence of oxidizer in premixer. The flame length is reduces with higher oxidizer at lower equivalence ratio and this will alter the stability boundaries. In Figure 6(c) area of first unstable region is larger than Figure 6(b), whereas it disappears in Figure 6(a). At the entry of Rijke tube the local pressure and velocity fluctuations are more than downstream part of Rijke tube which result in instability as per the Equation 1.

4.2. Radial air injection
4.2.1. Pointed air injection
Figure 7 shows the frequency spectrum for different test conditions. Figure 7((a) and (b)) are for burner location, x/L = 0.25 with different total flow rate, where second mode of instability occur. The pointed injection at g/L = 0.006 (5 mm from burner) amplifies SPL of about 5 dB and 12 dB, respectively, for total flow rate of 70 LPM and 30 LPM. The frequency of instability does not affect much with pointed injection. A complete suppression of instability was achieved by shifting the plane of injection close to burner position. To compare the effect location of plane of pointed injection, the frequency spectra are plotted for different plane. The complete suppression of instability is achieved with radial pointed air injection at g/L = 0.033.

Figure 8 demonstrates effect of pointed effect on wall pressure at the burner plane. The wall pressure registered at the burner plane inside the Rijke tube for the total mean flow rate of 70 LPM, in the
presence of instability and then after pointed injection is switched on. It shows amplitude variation within a band of about 58 Pa. When the air injection is switched on at around 350 ms from the time of acquiring the data as seen in Figure 8, quickly within about 250 ms the instability is seen to disappear resulting in significant attenuation of the amplitude of the pressure variation within a band of about 5 Pa. The amplitude of pressure is higher than the measured with microphone. The variation in amplitude is mainly due to two reasons, one is microphone is placed at a distance of 60 cm from Rijke tube and it measures only pure acoustic part. Whereas, the measured wall pressure is a hydrodynamic pressure combination of fluid and acoustic.
The peak SPL data obtained at various total air flow rates and quantity of radial pointed air injection from spectra similar to those shown in Figure 7 are compiled and shown in Figure 9. The SPL value for the case of complete suppression of the thermos-acoustics is determined from the spectrum at the frequency corresponding to the peak without any air injection. For lower total flow rate with pointed air injection of 2.6 LPM peak SPL increases from 88 dB to 102 dB for \( x/L = 0.25 \) and \( g/L = 0.006 \). The study carried out for burner position 0.2 shows slight variation in peak SPL at lower flow rate and burner location 0.1 shows no variation in peak SPL for same \( g/L \) positions. Figure 9(b) indicates that pointed injection with higher flow rate and high total flow rate suppression of instability is take place. The ring positions from the burner at \( g/L = 0.006 \) no suppression is observed, whereas ring positions \( g/L = 0.02 \) show suppression at 2.6 LPM flow rate is possible. Figure 9(c) shows that for lower total flow rates acoustic oscillations grow with pointed injection. The peak SPL is in the
range of 80 dB–90 dB for all flow rates. The ring positions \( g/L = 0.02 \) and \( g/L = 0.033 \) also show similar kind of trend. Figure 9(d) shows that \( g/L = 0.033 \) suppression is possible. In burner positions 0.25 and 0.1 not much change in peak SPL is observed.
4.2.2. Diffused injection

The experiments of diffused air injection over the burner were carried out with outward ring and inward ring with deflector. It is noticed that there is no significant change in peak SPL. Figure 10 shows the frequency spectrum for without air injection and diffused injection from wall and deflector at 2.6 LPM flow rate through ring at $g/L = 0.02$, equivalence ratio 0.7 and burner position $x/L = 0.2$. The other burner positions and rig positions also shows the same kind of trend.

The result of experiments for diffused injection shows that burner location 0.2 shows amplification of sound for all the positions of ring. Figure 11(a) shows that peak dB variation with different diffused air injection flow rate through ring, equivalence ratio 0.7, $x/L = 0.2$, and $g/L = 0.02$. The ring positions 0.0066 and 0.033 also show the same kind of trends. Whereas, at burner locations 0.25 and 0.1 no much effect on peak SPL with diffused air injection was observed. Figure 11(b) shows peak dB variation with different diffused air injection flow rate through ring, equivalence ratio 0.7 and 70 LPM total flow rate at $x/L = 0.2$ and different ring positions. It shows that for burner location 0.2 with diffused injection at all ring position increase in peak SPL. In burner positions 0.25 and 0.1 no considerable change in peak SPL was observed.

Figure 12(a) shows the frequency spectrum for different diffused air injection flow rate through ring at ring position $g/L = 0.033$, equivalence ratio 0.7 and $x/L = 0.2$. It is found that with less amount of diffused air injection will grow the acoustic oscillations. Figure 12(b) shows the frequency spectrum for no diffused air injection and with diffused air injection of 2.6 LPM for different ring positions, equivalence ratio of 0.7 and 70 LPM total flow rate at $x/L = 0.2$. It is clear from the figure that with high diffused air injection at all locations acoustic oscillations growth is possible.
The experimental result shows that with insertion of ring for different burner position with ring inside the tube there is amplification of sound at burner location 0.25 and 0.2, whereas suppression of sound at burner location 0.1. Figure 13(a) shows increase in SPL from 87 dB to 92 dB due to insertion of ring at burner location 0.25 for different position of ring. Figure 13(b) shows increase in SPL from 84 dB to 92 dB due to insertion of ring at burner location 0.2 for different position of ring. Figure 13(c) shows decrease in SPL from 83 to 73 dB due to insertion of ring at burner location 0.1 for different position of ring. This indicates that insertion of ring with burner changes the pressure field near the burner plane.

5. Conclusions
This study concludes that the stability regions are depend on burner location and mode of instability depends on flow rate through the burner and not much with total flow rate through Rijke tube. The instability of lower mode can be obtained with increasing flow rate through the burner, but very high flow rate leads to flame blow out at lower equivalence ratios. This study further concludes that pressure and velocity fluctuation near the heat source location are accountable for instability. The presence of ring over the burner increases the instability. The pointed injection near the burner plane at higher total flow rate and radial injection flow rate can bring the system to stable condition from unstable. With diffused air injection over the flame from wall of Rijke tube as well as deflector alter the pressure field and help to increase the SPL level. The plane of pointed air injection needs to be optimized to achieve the stability inside the Rijke tube. Whereas, the diffused air injection can be effectively used where increase in heat transfer rate is essential to grow the instability inside the system.

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