NONLINEAR DYNAMICS OF A LAMINAR V-FLAME IN A COMBUSTOR

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This study investigates a laboratory-scale combustor consisting of a tube (a quarter-wavelength resonator with an open end at the top, and a closed end at the bottom) with a laminar V-flame inside it. The parameter of interest is the axial position of the flame relative to the tube. This position was varied in a step-by-step manner by moving the flame in small steps from the top end towards the bottom end of the tube. In each step, the pressure-time history was recorded and its frequency content was analysed. Nonlinear time series analysis was performed on the recorded pressure-time history to identify the dynamic states. As the flame got lowered, a range of dynamic states were observed. These include limit cycles at low and high amplitudes, but also highly irregular oscillations. The instability frequencies showed a continuously decreasing trend, as well. A set of thermal imaging with a large wavelength infra-red camera, was performed to understand the reason of this behaviour. Finally, the flame was filmed with a high-speed camera, and the images were used to explain the oscillation pattern during the limit cycle.

1. Introduction

Instability in modern day combustors is an issue of major concern. The modern day requirement asks for green combustion systems, which essentially means enhancing combustion efficiency and lowering emission products. Thus the concept of lean premixed pre-vaporised combustor came into reality. These combustors operate at lower temperature and hence, become susceptible to combustion instability. These self-sustained high-amplitude oscillations can lead to severe damage of the combustor walls. A common type of flame that gets utilised in modern day gas turbine combustor is a V-flame. The current set of discussion is going to be restricted to the instabilities related to V-flame only. In this regard, the following literatures have been identified. Vishnu et al[1] performed stability analysis on a laminar ducted V-flame combustor. They observed a period doubling route to chaos from their experiments. Karimi et al[2] determined experimentally the transfer function of a ducted laminar premixed flame by measuring the heat release modulation and also calculated the velocity perturbations at the tip of the flame holder. Further, Karimi et al[3] performed the experimental study of the dynamics of a conical, ducted, laminar, premixed flame subjected to acoustic excitation of various amplitudes. The flame transfer function was measured over a range of forcing frequencies and equivalence ratios. Kabiraj et al[4] identified a quasi-periodic route to chaos for combustion instability in a ducted laminar premixed conical flame. Schuller et al[5] prescribed a unified model for the prediction of laminar flame transfer functions and made comparisons between conical flame and V-flame dynamics.

Our objective in the present work is to develop a laboratory-scale model combustor consisting of a tube (a quarter-wavelength resonator with an open end at the top, and a closed end at the bottom) with a laminar V-flame inside it. The V-flame will be moved from the open end to the closed end of the combustor in a step by step manner and the alteration pattern of the flame dynamics will be duly noted. We are going to perform non-linear time series analysis on the experimental data to identify the dynamical states. To get a better understanding about the flame oscillation pattern, a set of high speed images is acquired during experiments. The damping of the setup is also measured with the help of a loudspeaker, a function generator and a power amplifier. Finally, a set of thermal imaging is performed on the set-up using a large wavelength infra-red (LWIR) camera.

2. Experimental setup

The experimental set-up consists of the following components: a borosilicate glass tube (a quartz glass tube has also been used for the flame imaging), a de-coupler, a mixing chamber, a mild steel rod (internally hollow), a brass rod, a mild steel flange, two flash-back arrestors, two rota-meters to control the flow velocity of air and fuel, some connecting pipelines for air and fuel supply line and a traverse mechanism developed to move the flame from one end of the glass tube to another.

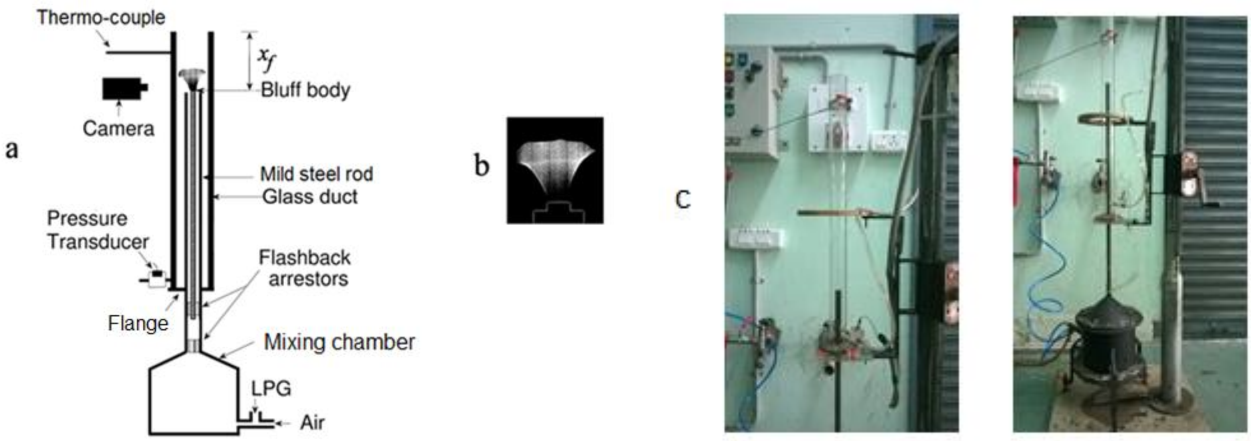

Fig 1: (a) Schematic of the experimental setup, (b) schematic of the V-flame and (c) the setup as installed in the laboratory (showing the glass tube with the traverse mechanism)

The V-flame is supported on the tip of a brass rod of 6.4 mm diameter, kept concentrically inside a mild steel rod of 12.6 mm inner diameter. Two flashback arrestors are installed at the bottom of the mild steel rod. This whole assembly is kept inside a borosilicate/quartz glass tube for flame visualization from outside. The glass tube has got 45 mm inner diameter, 2.5 mm thickness and 750 mm in length. A mild steel flange is connected to the lower end of the glass tube to simulate a closed end. The upper end of the glass tube is kept open for experiments. The mild steel rod and brass rod assembly is connected to a mixing chamber for air and fuel. In the upstream side of this assembly there are a couple of rota-meters to control the air flow rate from the compressor line and fuel flow rate from the LPG cylinder line. The rota-meter for fuel flow line is calibrated from 43.97 ccm to 439.7 ccm and the air flow line is calibrated from 1.13 lpm to 11.3 lpm. There are a couple of pressure gauges and pressure regulators installed for the fuel and air supply line. During our experiments we have supplied 200 ccm of LPG at 1 bar gauge pressure and 10 lpm of air at 1 bar gauge pressure to the mixing chamber. This corresponds to an equivalence ratio of 0.59. There is a traverse mechanism developed that will guide the flame to travel from one end of the glass tube to another (refer fig 1-c). During this operation the glass tube moves and the flame remains stationery on the tip of brass rod. At the start of the experiment, the flame is ignited with the help of a butane torch, keeping the air flow rate below 10 lpm and fuel flow at 200 ccm. Once the flame is ignited, the air flow rate is increased gradually for the flame to settle down in stages. Finally, the flame attains a proper V-structure. There is a pressure transducer connected at 5 cm away from the closed end flange. The pressure transducer has got the following specification: PCB piezotronics 103B02, voltage sensitivity 223.4 mV/kPa and resolution 0.142 Pa. Acoustic pressure data is acquired at 10 kHz sampling rate. The transducer gets connected to a signal conditioner (PCB480E09), which gets connected to a data acquisition card (NI PCI-6221). During the experiment, as the flame is moved from the open end to the closed, pressure data is recorded and analyzed. There is a thermo-couple fitted 10 cm away from the open end of the tube to show the glass temperature during experiment.

The initial time for the flame to settle down has been kept as 20 minutes during experiments. It has been shown through detailed temperature study, using a thermo-couple that the steady state is attained within 20 min. The following graph represents the rise in glass tube temperature with respect to time as measured by the thermo-couple. Clearly, an initial settling time of 20 minutes is sufficient to attain steady state of the setup.

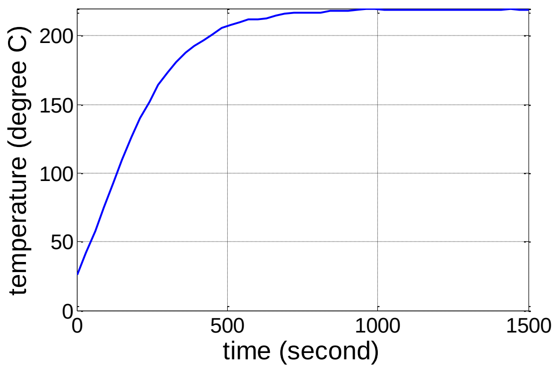

Fig 2: Temperature of the glass tube (measured at x_f=10 cm) vs time

A similar investigation has been carried out to identify the interim settling time while moving the flame by 1 cm at a time. It has been observed through detailed study that it takes maximum 2 minutes for the system to regain steady state once x_f (the distance between flame and open tube end) is changed.

3. Results and discussion

The flame has been moved 1cm at a time from the open end to the closed end of the glass tube. Initially the flame is steady. However, as the flame travels towards the closed end, it tends to grow more and more unsteady. Figure 3 shows three different states, both in terms of pressure time history and corresponding frequency spectrum, as x_f is increased. At x_f=33 cm, first set of oscillation comes into picture. From the Fast Fourier transform of the pressure-time history, the dynamic state is identified as a pure limit cycle. As the flame moves further downwards, at x_f= 38 cm, new dynamic state appears, with increase in acoustic pressure amplitude. Finally, at x_f=44 cm, the pressure attains really high amplitude and a new limit cycle comes into picture. Further increase of x_f, increases the acoustic pressure significantly. It can also be observed from fig 3 that the instability frequencies come down, as x_f is increased. Thus from FFT analysis, three major states are observed

i. Low amplitude limit cycle
ii. Transition from low to high amplitude limit cycle
iii. High amplitude limit cycle

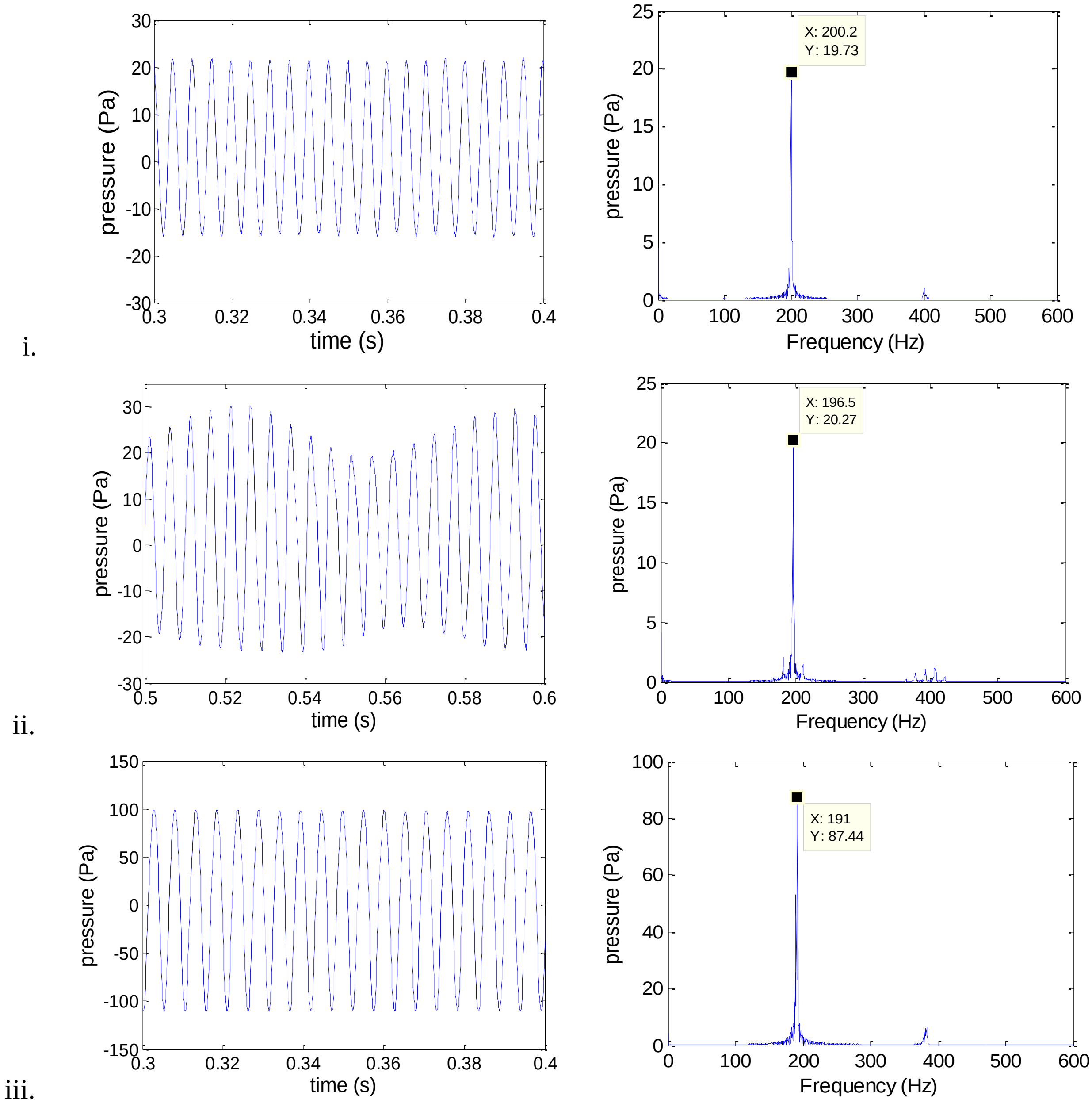

Fig 3: pressure-time series and FFT of the signal at (i) x_f=33 cm, (ii) x_f=38 cm and (iii) x_f=44 cm

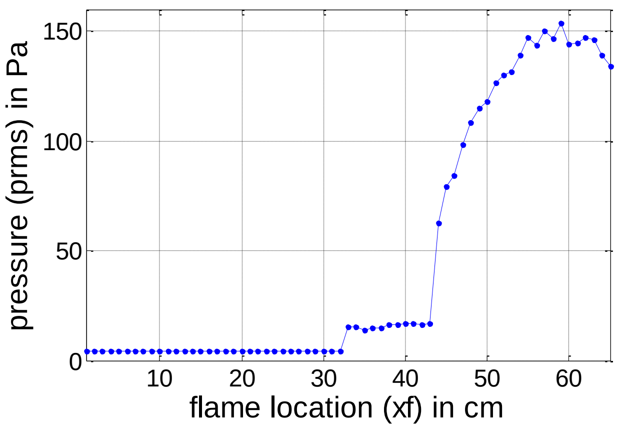

Fig 4: Bifurcation diagram (effect of flame location, $_f$ on r.m.s. pressure amplitude)

Fig 4 represents a bifurcation diagram, explaining the effect of increase in x_f on pressure amplitude. Clearly, the figure represents transitions from steady state to low amplitude limit cycle (at x_f=33 cm) and from low to high amplitude limit cycle, thereafter (at x_f=44 cm). This kind of secondary bifurcations have been observed by Ananthakrishnan et al[6] in a pair of resonantly coupled oscillators.

To verify the identity of the dynamic states, non-linear time series has been applied on the pressure-time history. This has been performed in the following steps:

First of all, information about time-lag has to be obtained for the pressure time history[7]. In the next step, we need to identify the minimum number of embedding dimension required to plot the state-space diagram[8] (refer fig 5). Finally, the state space plotting is performed and the corresponding Poincare section is obtained. Following this procedure on dynamic state i and iii, we can find the time lag=12 ms. Minimum number of embedding dimension has been identified as 5. Fig 6 represents the state space diagrams and the Poincare sections for dynamic state i and iii. Clearly, the dynamic states are limit cycles.

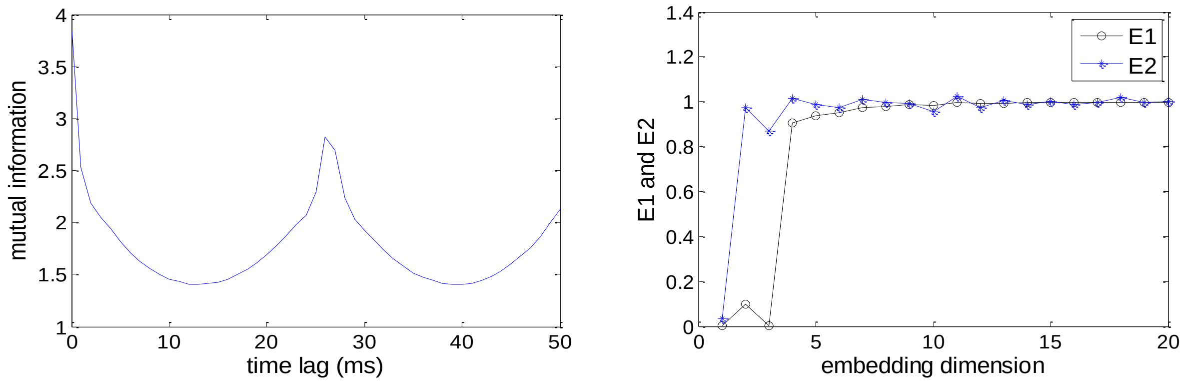

Fig 5: Plots to calculate the time lag and the minimum embedding dimension needed for state-space diagram

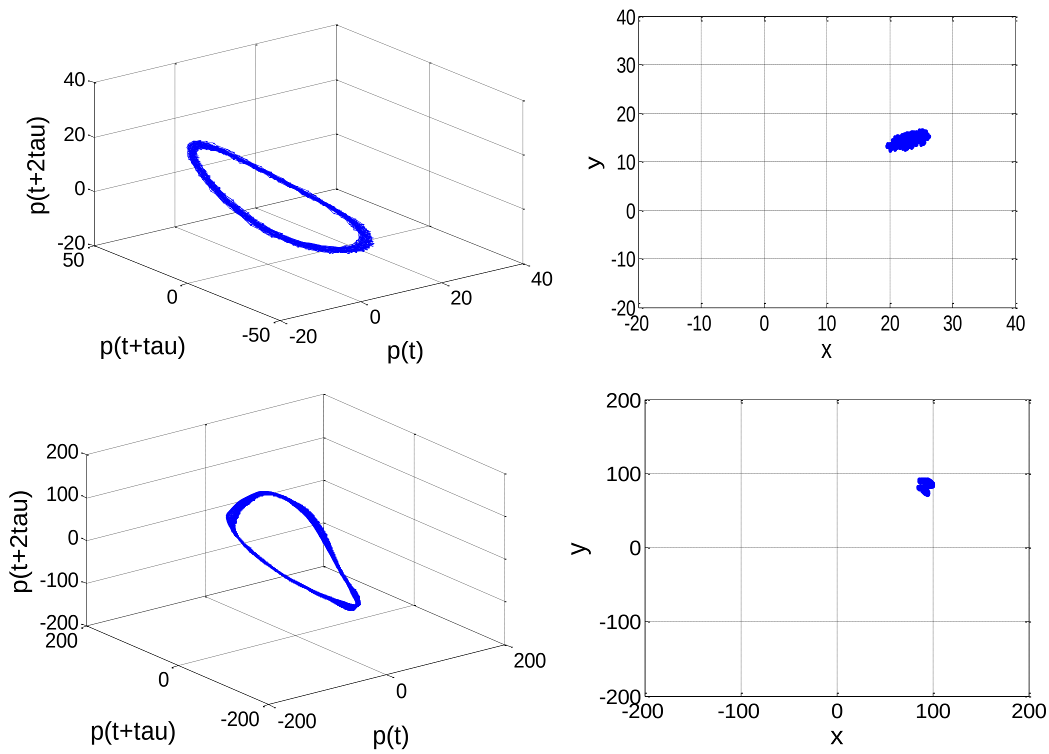

Fig 6: State-space diagram and the Poincare section for x_f=33 cm and 44 cm

4. High speed imaging of the V-flame

The oscillation patterns of different states of the V-flame have been captured with the help of a high speed camera (Phantom V12.1). The images have been taken at 4000 frames per second without CH filters on the lens.

i. Low amplitude limit cycle

As mentioned in section 3, the low amplitude limit cycle comes into existence from x_f=33 cm. Figure 7 demonstrates a set of pictures to represent one cycle of the flame oscillation, during this dynamic state. A wave travels from the bottom to the tip of the V-flame.

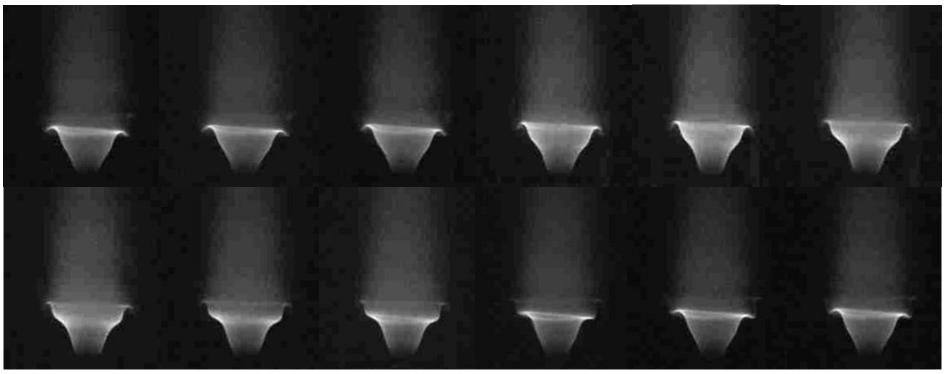

Fig 7: Flame oscillation pattern within a cycle for the low amplitude limit cycle

ii. Transition from low to high amplitude limit cycle

This transition phase comes into picture from x_f=38 cm. Just like the low amplitude limit cycle state, a wave travels from bottom to tip of the V-flame, but with a higher speed. In real time visual image, the flame is found to show some flapping oscillation pattern. The acoustic pressure amplitude is higher than in the previous state, as well.

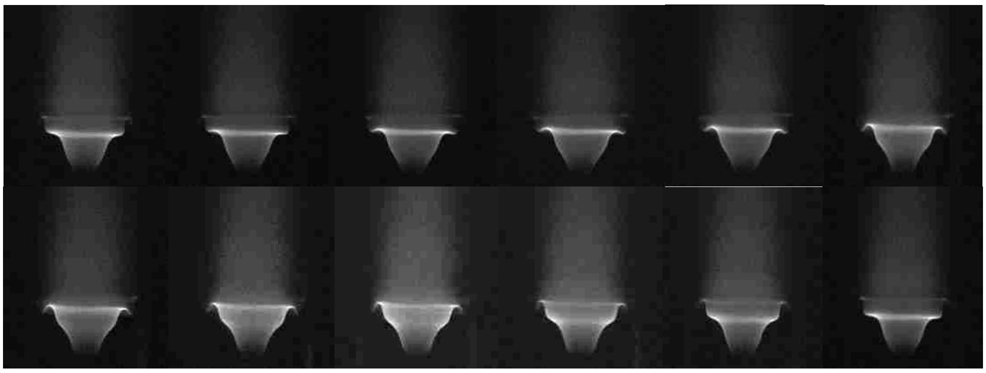

Fig 8: Flame oscillation pattern within a cycle for the transition phase

iii. High amplitude limit cycle

The high amplitude limit cycle comes into picture at x_f=44 cm. Figure 9 is self-evident that the wave that travels from bottom to top of the flame is of much higher amplitude than the previous two dynamic states. The oscillation frequency and the acoustic pressure are enhanced to a greater degree, as well. Also, it has been observed that during each cycle a section from the top part of the flame isolates from the main flame and gets annihilated. During the end part of this limit cycle (x_f=60 cm), this annihilation pattern is more prominent. Moreover, the light intensity from the bottom of the V-flame is reduced subsequently, indicating that the flame root might be slightly lifted off the flame holder.

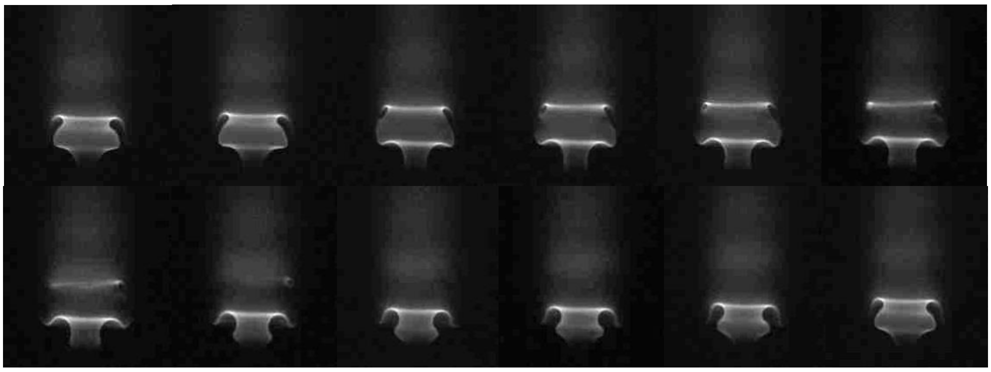

Fig 9: Flame oscillation pattern within a cycle for the high amplitude limit cycle

5. Measurement of the damping of the setup

For measurement of the damping of the setup, following set of equipment has been used: a loudspeaker, a function generator and a power amplifier. The function generator helps to generate sinusoidal signal at fundamental frequency (115 Hz for our setup) that goes as an input to the loudspeaker via the power amplifier. A 3 second window is selected for measurement (refer fig 10). The loudspeaker is switched on and switched off within this 3 second window and the pressure time history is recorded using the data acquisition system. The decay of pressure amplitude, as observed from the figure 10 is a measure of the damping of the setup. The damping value comes out to be 10 s^{-1}.

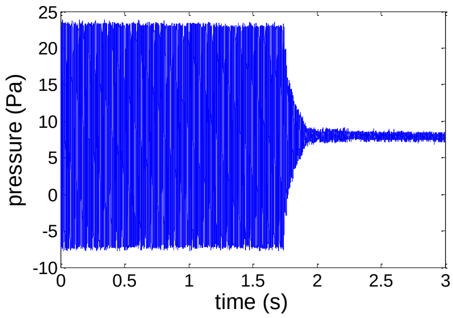

Fig 10: pressure-time history plot for damping measurement of the set-up

6. Temperature data from the combustor

In this section, we will describe the thermal imaging of the V-flame using a Jade Large Wavelength Infra-Red camera. The images have been captured at every 5 cm interval, starting from x_f=13 cm. The camera has been able to measure the glass tube temperature profile, with respect to the change in x_f. The measurement of the air column temperature is beyond the capacity of the LWIR camera. Figure 11 is a sample image, demonstrating the temperature field across the glass tube for x_f=33 cm. The temperature of the glass tube is 234 degree C adjacent to the flame and it gradually reduces up to 137 degree C, at the top end. The mean temperature of the hot region (starting from the flame location to the open end) has been measured to be 165 degree C. It has also been observed from the thermal images that the maximum, as well as, the mean temperature keeps on going down, as the flame is lowered. The reduction in temperature could be one possible reason for the reduction of instability frequencies with increase of x_f, as observed in section 3. However, detail investigation need to be done to establish this fact.

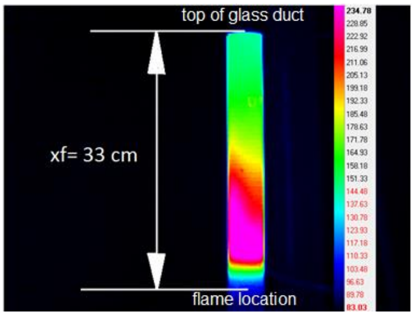

Fig 11: Thermal image of the glass tube with the V-flame inside it, for x_f= 33 cm

7. Conclusions and the scope of future work

From this paper, we can conclude that we have identified the existence of low amplitude and high amplitude limit cycle in a laminar ducted V-flame setup. We have also identified the transition phase between two limit cycles. The frequency data clearly shows that instability frequencies go down as the flame is moved from open-end to closed-end of the glass tube.

The detailed calculation of the resonance frequencies from the temperature data lies within the scope of our future work. These frequencies need to be compared with the instability frequencies observed from the experiment. The calculation of the heat release rate vs. time history from the flame images lies within the scope of future work. The presence of hysteresis in the combustor set-up can also be treated as a content of investigation.

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REFERENCES

1 Vishnu, R., Sujith, R. I., Aghalayam, P. Role of flame dynamics on the bifurcation characteristics of a ducted V-flame, *Combustion Science and Technology*, **187**, 894-905, (2015).

2 Karimi, N., Jin, S.H., Brear, M.J. An experimental study of the transfer function of a ducted, laminar premixed flame, *16th Australasian Fluid mechanics conference*, Gold coast, Australia, 2-7 December, (2007).

3 Karimi, N., Brear, M. J., Jin, S.H., Monty, J.P. Linear and non-linear forced response of a conical, ducted, laminar premixed flame, *Combustion and Flame*, **156**, 2201-2212, (2009).

4 Kabiraj, L., Saurabh, A., Wahi, P., Sujith, R. I. Route to chaos for combustion instability in ducted laminar premixed flames, *Chaos*, **22**, 023129, (2012).

5 Schuller, T., Durox, D., Candel, S. A unified model for the prediction of laminar flame transfer functions: comparisons between conical and V-flame dynamics, *Combustion and Flame*, **134**, pages 21-34, (2003).

6 Ananthakrishnan, N., Sudershan, S., Sudhakar, K., Verma, A. Large amplitude limit cycles in resonantly coupled oscillators, *Journal of Sound and Vibration*, **231**(5), 1377-1382, (2000).

7 Abarbanel, H. D. I., Brown, R., Sidorowich, J. J. , Tsimring, L. S. The analysis of observed chaotic data in physical systems, *Reviews of modern physics*, Vol **65**, No 4, October (1993).

8 Cao, L. Practical method for determining the minimum embedding dimension of a scalar time series, *Physica D*, **110,** pages 43-50, (1997).