23rd International Congress on Sound & Vibration
Athens, Greece 10-14 July 2016
ICSV23

EFFECT OF VARYING TURBULENCE INTENSITY ON THERMOACOUSTIC INSTABILITY IN A PARTIALLY PRE-MIXED COMBUSTOR

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An experimental study on a turbulent combustor with a swirl stabilized flame was conducted to understand the effect of the turbulence intensity on the dynamics of the combustor as it transitions from a low amplitude aperiodic (stable) state to high amplitude thermoacoustic instability. High speed imaging of the flame (representative of the field of heat release rate fluctuations) and simultaneous unsteady pressure measurements were performed. We observe that as the turbulence intensity at the inlet is increased, there is a decrease in the acoustic power generated by the interaction between the heat release rate fluctuations and the acoustic field. This is observed from the time averaged field of Rayleigh Index. Further, we also observe that the onset of the thermoacoustic instability is advanced as the turbulence intensity is increased. We also perform the study with a bluff body stabilized flame and observe that increase in turbulence intensities causes a different response compared to swirl stabilized flame. Increased turbulence intensities produce varied results across different flame stabilizing mechanisms.

1. Introduction

Thermoacoustic instability is a critical problem faced in practical combustors when they are operated at lean premixed conditions. This instability, caused by nonlinear coupling between unsteady heat release rate and acoustic perturbation, leads to large amplitude pressure oscillations inside a confined combustor. Suppressing, or controlling these thermoacoustic oscillations is of prime importance in propulsion and power generating systems as they cause structural failure to mechanical components of the combustor.

There have been a number of studies in the past that focused on the dynamics during instability and its characterization. However, the transition to thermoacoustic instability is by itself rich in dynamics and is worth investigating. Bifurcation related combustion dynamics have been reported in several experimental studies. Bifurcations of self-excited ducted laminar premixed flames were studied by Kabiraj et al. [1], who established the route to chaos through quasi-periodic and frequency locking routes in a laminar premixed combustor. Further, they showed that the thermoacoustic system exhibited intermittency, where the system switched from low amplitude aperiodic fluctuations to high amplitude periodic oscillations. However, this intermittency was observed prior to flame blow-off. Gotoda et al. [2] reported that thermoacoustic systems undertake a transition from stochastic fluctuations to periodic oscillations via low-dimensional chaotic oscillations, when the fuel equivalence ratio was varied. Further, in turbulent combustors that use swirler or bluff body as flame holding devices, Nair et al. [3] reported intermittency in a turbulent thermoacoustic system during the transition to instability. They observed that during this stable state called intermittency, the measured unsteady pressure signals acquired prior to thermoacoustic instability displayed bursts of high amplitude periodic oscillations.

Lieuwen [4] studied the limit cycle oscillations in a lean premixed gas turbine combustor. Both supercritical and subcritical Hopf bifurcations were observed in their combustor under different operating conditions. Subcritical bifurcation was observed when low inlet velocity and high pressure conditions were used while supercritical bifurcation was found when higher inlet velocity and lower mean combustor pressure was used. Nair et al. [5] noted that the statistical properties for pressure oscillations measured during the transition varied smoothly for the turbulent combustor with bluff body and swirl stabilized flames. They conjectured that the smoothness in the statistical properties was due to the presence of turbulence in the reactive flow and the resulting intermittent nature of the combustion dynamics. This was the motivation to investigate the effect of the turbulence intensity on the transition, which is the topic of this paper.

Prior work has been done in studying the effect of noise on the transition characteristics for various operating conditions in different thermoacoustic systems (mostly under the assumption that turbulence behaves as noise added to a laminar system). Waugh et al. [6] demonstrated that additive stochastic perturbations can cause triggering from low noise amplitudes to self-sustained oscillations in a Rijke tube. Further, Jegadeesan et al. [7] experimentally investigated the noise induced triggering of a non-premixed flame operating in a bistable region. Under the influence of noise as a result of equivalence ratio fluctuations, the system underwent transition from stable to oscillatory state. However, they observed that with an increase in the amplitude of the noise introduced into the system, the mean phase difference between the pressure fluctuations and the heat release rate fluctuations increased, resulting in reduced amplitude of the periodic oscillations. Further, Moeck et al. [8] investigated subcritical thermoacoustic instabilities in a premixed combustor. Using a nonlinear model, they observed that an increase in the noise level resulted in a narrower hysteresis region. They associated this behaviour to the modification of the domains of attraction of the respective equilibrium solutions. Gopalakrishnan et al. [9] reported that external noise added to a Rjike tube resulted in a reduction in the amplitude of the limit cycle oscillations. These previous studies show different ways in which the characteristics of the transition zone in different thermoacoustic systems have been altered under the influence of external perturbations (noise). On the other hand, we try to investigate the changes in the transition zone for a turbulent combustor by varying inherent fluctuations in the reactive flow (turbulence intensity).

Practical combustors used at an industrial scale are essentially turbulent. When thermoacoustic instability sets in, the flow field is dominated by coherent structures. This was investigated extensively by Coats [10]. The coupling between these coherent structures, the unsteady heat release rate and the acoustic sub-system in the confined space drives thermoacoustic instability. Paschereit et al. [11] succeeded in designing an active control system in a swirl stabilized combustor to suppress thermoacoustic oscillations. They reported that modulating the air flow resulted in varying the mixing process between fuel and air and the combustion products which reduced the coherence of the vortical structures. In our study, by increasing the strength of inherent fluctuations in the flow field, we change the characteristics of the coupling between the reactive flow and the acoustic field such that the energy given to the acoustic mode is reduced. The outline of this paper is as follows. A description of the experimental setup is presented in Section 2. Section 3 focuses on the results obtained. Finally, in Section 4, we will draw the important conclusions from this study.

2. Experimental Setup

The combustor used for the present study was adapted from Komarek et al. [12]. It is a turbulent combustor with a backward facing step. A fixed vane swirler was used as the flame stabilizing mechanism. In addition to the swirler, we used a turbulence generator that is described later. The combustion chamber has a cross-section of 90 × 90 mm^2. The length of combustor along with the extension ducts which was used in our case was 1100 mm. The fuel used here is LPG (60% Butane and 40% Propane). In this study we have represented the major results with respect to equivalence ratio (ø) of the combustion mixture. Equivalence ratio is estimated as

$$\phi = \dot{m}_f / \dot{m}_a \Big|_{actual} \Big/ \dot{m}_f / \dot{m}_a \Big|_{stoichiometric}$$

where, m_f and m_a correspond to the mass flow rates for fuel and air respectively. The uncertainty in the estimated equivalence ratio is ± 0.02. The fuel is injected 100 mm upstream of the swirler.

The mass flow rates of fuel and air were measured using mass flow controllers (Alicat Scientific, MCR Series) with an uncertainty of ± (0.8% of reading + 0.2% of full scale). Unsteady pressure fluctuations were measured using a piezoelectric (PCB103B02 uncertainty ± 0.15 Pa) transducer. Chemiluminescence images were acquired using a high speed camera capturing the filtered light intensity (narrow band, peak at 432 nm, 10 nm FWHM) corresponding to CH* chemiluminescence from the combustor at a sampling rate of 2 kHz. The signals from the pressure transducer were acquired using an A-D card (NI-6143, 16 bit) at a sampling frequency of 10 kHz.

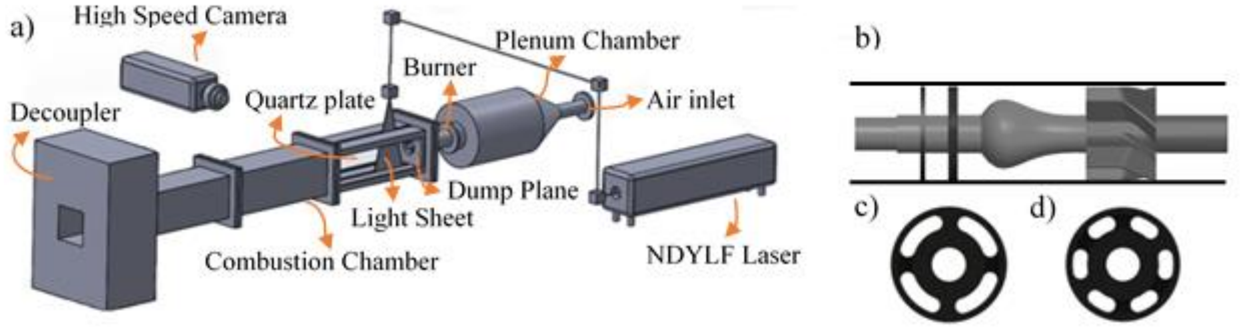

Figure 1: a) The schematic of the experimental setup. b) The burner assembly. c) Flow restrictor configuration corresponding to case A. d) Flow restrictor configuration corresponding to case B.

Chemiluminescence images and PIV images are acquired at an optically accessible section of the duct using a Phantom high speed camera V 12.1. We obtained velocity field measurements near the dump plane through Particle image velocimetry (PIV). A single cavity double pulsed NDYLF laser (Photonics) of operating wavelength 527 nm was used at a repetition rate of 4 kHz. The light sheet used for illuminating the seeding particles was produced using different lens configurations. For PIV in the absence of combustion, olive oil of 10 micron droplet size (approximate value) was used. A high speed camera (Phantom V 12.1) in sync with the laser exploiting frame straddling was used to capture the single frame single exposed PIV images. The time delay between the pulses was kept fixed at 30 microseconds. The PIV images were processed using PIVview software from PIVtech GmBh.

The burner assembly comprises of flow restrictors located upstream of a contoured nozzle followed by the swirler and a central body. Vortices are produced by flow restrictors, creating blockage in the flow. The key idea behind the design is that a vortex that impinges on the contoured nozzle disintegrates into smaller vortices through turbulent cascade producing fine scale turbulence. The intensity of the impinging vortex can be changed either by varying the blockage ratio or varying the mean flow velocity. The design of the turbulence generator shown in the figure was inspired from the works of Marshall et al. [13]. Using this arrangement, the turbulence intensity can be varied without changing the mean flow velocity.

Three cases are investigated in this experimental study. The first study, referred to as the base case uses only the swirler in the burner housing. The second case, referred to as case A, uses the turbulence generator arrangement as shown in Fig. 1.b. with the configuration of the flow restrictor as shown in Fig. 1.c. Case B, uses turbulence generator arrangement with the flow restrictor configuration shown in Fig. 1.d.

3. Results

Previously, in a study by Waugh et al. [6] reported that a thermoacoustic system will dislodge itself from the oscillatory solution if the noise amplitude is sufficiently high. There have been studies in the past that considered turbulence as noise as the base state is characterized by aperiodic oscillations. This is not the first time however that effect of turbulence has been studied as the effect of noise. A theoretical study was done by Clavin et al. [14] on turbulence induced noise effects on high frequency combustion instabilities in liquid propellant rocket motors. Their theoretical work contributed to the theory of combustion instability that turbulence leads to multiplicative noise in the thermoacoustic system. We try to verify experimentally the effect of increased turbulence intensity on the thermoacoustic system.

As the blockage ratio of the flow restrictors in the turbulence generator is increased, there is an increase in the turbulence intensity. Hence, the base case, which is without the flow restrictors has a lower turbulence intensity in the region of the shear layer when compared to cases A and B. Further, case B has the highest turbulence intensity when all three cases are compared.

This is because the blockage ratio is maximum in the configuration of case B. In Fig. 1, the time averaged turbulence intensity fields (a, c and e) and the corresponding vorticity fields (b, d and f) are shown. These measurements were performed in the absence of combustion. The xy plane shown here corresponds to a window of 126 mm x 90 mm in size and the left side matches with the dump plane. The bulk flow is from the left to the right. Fig. 1.a. and Fig. 1.b show the time averaged turbulence intensity field and corresponding time averaged vorticity field for the base case with only the swirler. Fig. 1.c and Fig. 1.d correspond to the results with case A configuration with the flow restrictors while Fig. 1.d. and Fig. 1.e. refer to case B configuration. Turbulence intensity fields show higher intensities near the dump plane in the shear layer as the blockage ratio is increased. A higher vorticity strength can be observed in the shear layer regions for cases A and B when compared to the base case.

Combustion experiments were conducted to observe the effect of the modified flow field in the combustion chamber. The fuel flow rate was maintained constant and the air flow rate was used as the control parameter for all the experiments. The experiments are started with the air-fuel mixture at stoichiometric ratios and equivalence ratio is lowered to lean limits. The amplitude of the unsteady pressure fluctuations are plotted against the equivalence ratio for the three cases which were studied in Fig. 2. We can observe three zones in this figure.

In zone III, where the equivalence ratio is close to the stoichiometric ratios, we can observe that the Prms rises initially for the base case with respect to case A and B. As the equivalence ratio is reduced further, we find a region (zone II) where the Prms increases faster for case A and B with respect to the base case (near ø = 0.6). With a further reduction of the equivalence ratio, (less than ø = 0.5), we can observe that there is a reduction in the amplitude of the acoustic pressure oscillations for the cases with the flow restrictors at low equivalence ratios (zone I). Our results are similar with those obtained by Gopalakrishnan et al. [9] in a Rijke tube where they studied the effects of noise on the bistable regime. In their case, the added noise into a laminar system led to a reduction in the Prms values when the control parameter was changed. From Fig. 2, we can understand that the stability region of the operating conditions of the combustor is modified significantly due to the varying turbulence intensities. Even though the amplitude of the pressure oscillations are reduced relatively with the presence of flow restrictors, there seems to be a possibility of an advanced onset of large amplitude pressure oscillations. In our study with the base case, there appears to be sudden increase in the amplitude of oscillations at an equivalence ratio of 0.48 resembling a subcritical Hopf bifurcation. However, with the inclusion of the flow restrictors, the transition from low amplitude aperiodic fluctuations to large amplitude periodic oscillations is more gradual, although this appearance may be due to the reduction in the amplitude of periodic oscillations.

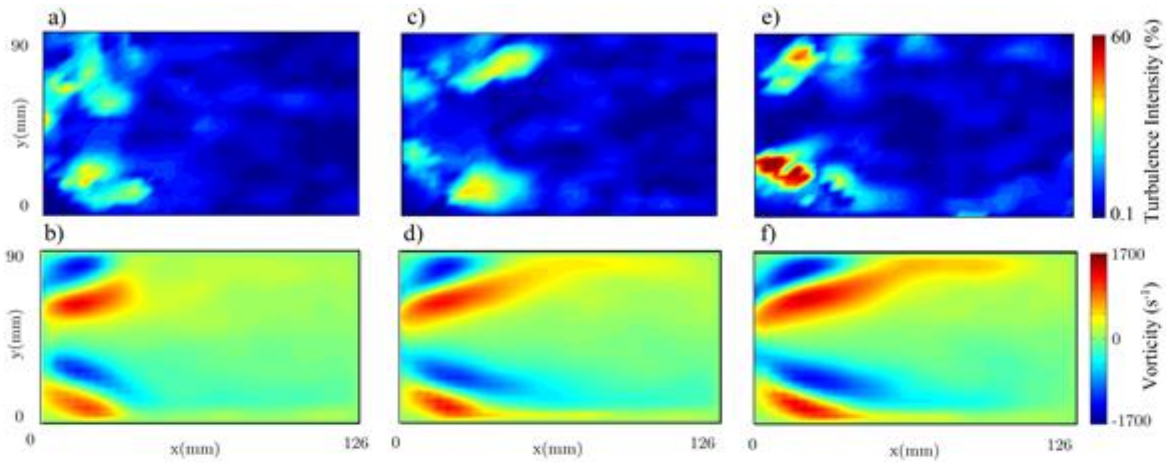

Figure 2: Time averaged turbulence intensity fields (a, c and e) and the corresponding time averaged vorticity fields (b, d and f) downstream of the dump plane where x refers to the distance from the dump plane and y refers to the position in the vertical plane.

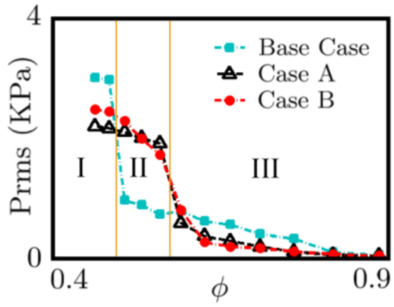

Figure 3: Variation of amplitude of unsteady pressure fluctuations (Prms) with respect to equivalence ratio (ø).

The unsteady pressure fluctuations are shown in Fig. 4 for all the three cases for equivalence ratios 0.89 to 0.63. It can be observed that the pressure fluctuations increase in amplitude as the equivalence ratio is reduced for all the three cases. Further, the increase in the amplitude of the pressure fluctuations is faster for the base case with respect to case A and case B. This corresponds to the first region shown in the plot of the rms value of the pressure fluctuations vs the equivalence ratio. The periodic regions of the intermittent state are larger in amplitude for the base case when compared to the other two cases. At ø = 0.63, it appears that the unsteady pressure fluctuations are already periodic. However, the amplitudes are relatively low at this value of equivalence ratio compared to ø = 0.48. Further, with the flow restrictors, the pressure fluctuations seem more aperiodic and intermittent rather than self-sustained periodic pressure oscillations. This gives the appearance of a wider range of stable operation compared to the base case.

We observed from Fig. 3 that the transition characteristics are different as the turbulence intensity is varied. In Fig. 5, we show the unsteady pressure fluctuations for lower equivalence ratios (ø = 0.89 to ø = 0.46) corresponding to the areas where the amplitude of the pressure fluctuations was relatively higher. The advanced onset of thermoacoustic instability (with large amplitude periodic oscillations) is clearly observed for the cases with flow restrictors. However, at ø = 0.48, the amplitude of the pressure oscillations are maximum for the base case, which is with the swirler alone. There is indeed a suppression of the amplitude of the large amplitude oscillations with increase in turbulence intensity. However, self-sustained large amplitude oscillations are still observed. The frequency of the pressure oscillations obtained from FFT at ø = 0.48 (not shown here) for all the three cases studied is approximately 125 Hz.

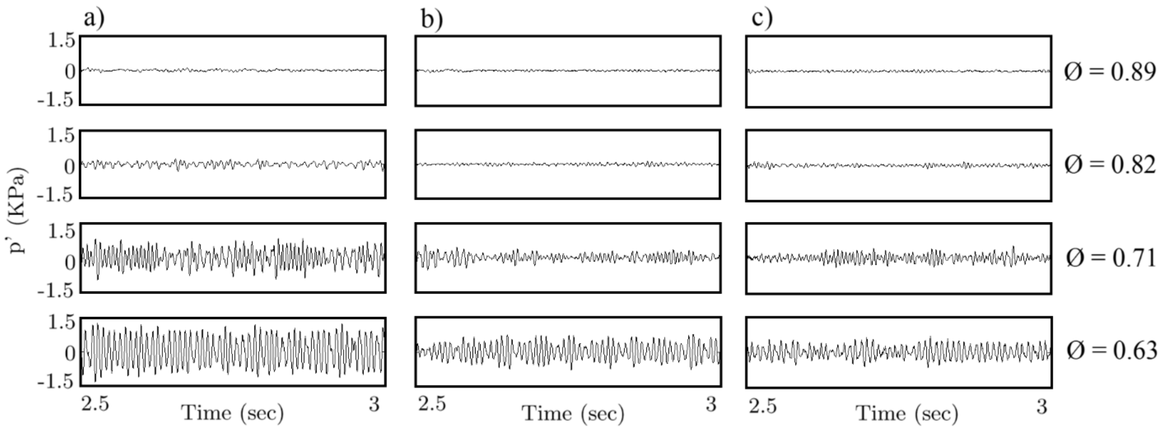

Figure 4: Unsteady pressure fluctuations a) Base case, b) Case A and c) Case B for ø = 0.89 to 0.63 for swirl stabilized flame.

To understand the cause of the reduction in amplitude of the periodic oscillations during thermoacoustic instability with the inclusion the flow restrictors, we plotted the field of Rayleigh index obtained using the instantaneous pressure fluctuations and the instantaneous heat release rate images (Chemiluminescence images). In Fig. 6, the time averaged p'q' images are shown for the three cases we have studied at ø = 0.48 where the amplitude of the periodic oscillations was maximum. The Rayleigh index is obtained as the product of the heat release rate at each pixel and the value of the pressure fluctuation at the particular time instant. The heat release rate field is obtained from the chemiluminescence images acquired during the experiment. Higher amplitude of the pressure oscillations without the flow restrictors can be associated to a higher strength of the Rayleigh index near the dump plane compared to case A and case B. The higher strength of the Rayleigh index drives the thermoacoustic instability. With the inclusion of the flow restrictors, we can observe that there is a reduction in the Rayleigh index at higher turbulence intensities. We conjecture that coherent vortices, which are characteristic of thermoacoustic instability are suppressed due to the higher turbulence intensities, leading to a suppression of the large amplitude pressure oscillations. The increased turbulence intensity has caused the spatial heat release rate to go out of phase with hydrodynamics.

To check if the effect of the increase in turbulence intensity in a swirl stabilized burner can be generalized to other flame holding mechanisms, we performed experiments with a bluff body as well. The turbulence intensity was increased in the same manner, by including the flow restrictors upstream of the bluff body. The circular bluff body was kept 5 cm downstream of the dump plane.

In Fig. 7, the unsteady pressure fluctuations are plotted against the equivalence ratio for the cases with bluff body stabilized flame. At ø = 0.86 amplitude rises first for the base case when compared to the cases with the flow restrictors. At lower equivalence ratios, close to ø = 0.55, we observe that the amplitude of the fluctuations is higher for the cases with flow restrictors when compared to the base case. With the base case, the oscillations were of smaller amplitude but periodic.

The increase in turbulence intensity with the bluff body stabilized flame resulted in large amplitude pressure fluctuations. However, the fluctuations were not periodic for case A and B at these low equivalence ratios. The dynamics remained intermittent. The periodic regions of intermittency displayed large amplitude oscillations. These oscillations were larger in magnitude than the periodic oscillations observed with the base case. Thus, we have observed a very different response with the bluff body stabilized flame when the flow restrictors were included. Here, we observe that the increase in turbulence intensity has resulted in a significantly different response with the bluff body stabilized flame.

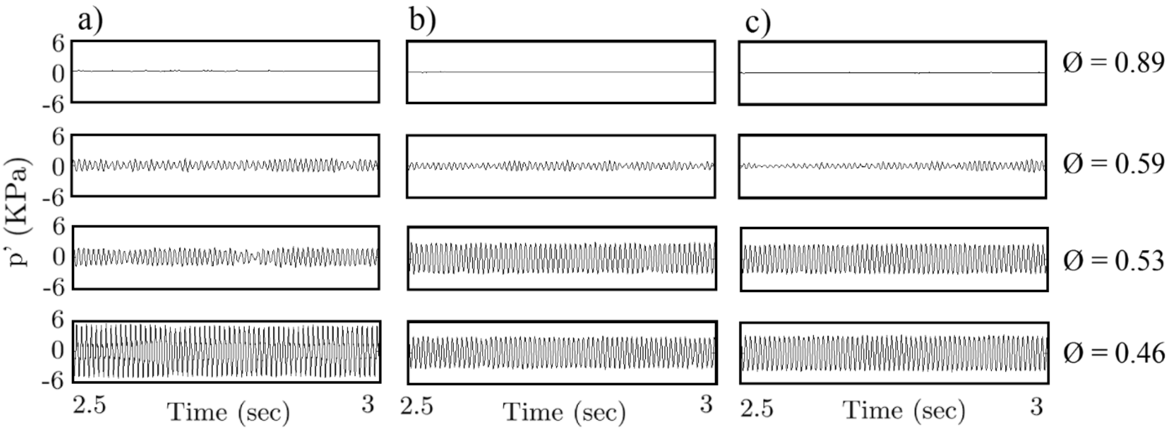

Figure 5: Unsteady pressure fluctuations a) Base case, b) Case A and c) Case B for lower equivalence ratios (ø = 0.89 to 0.46) for swirl stabilized flame.

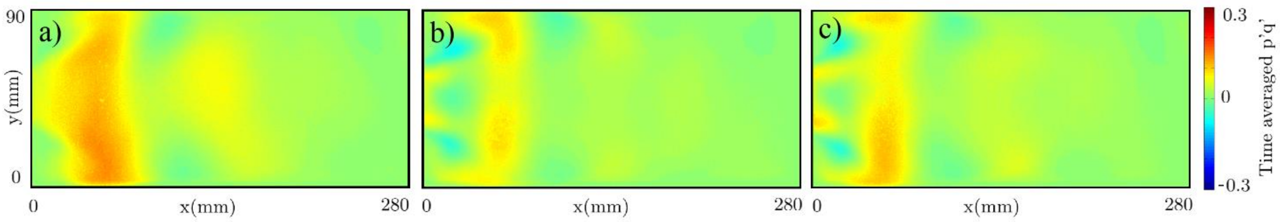

Figure 6: Time averaged Rayleigh index field a) Base case, b) Case A and c) Case B for swirl stabilized flame at ø = 0.46.

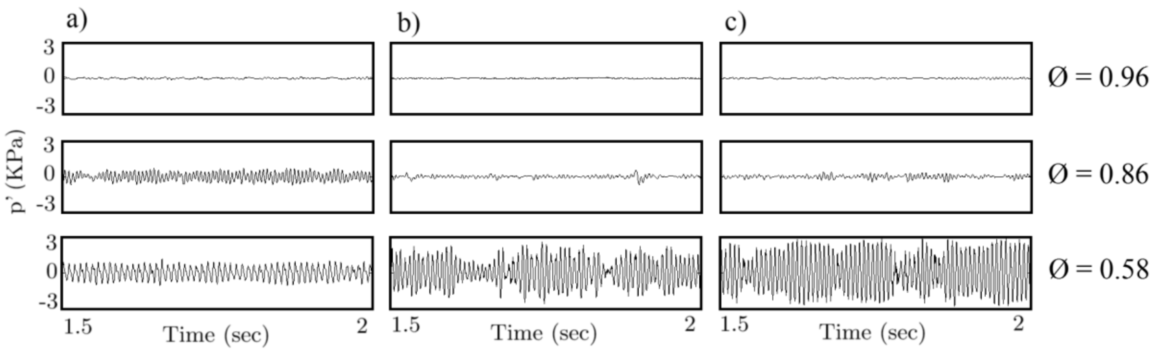

Figure 7: Unsteady pressure fluctuations a) Base case, b) Case A and c) Case B with bluff body stabilized flame.

4. Conclusion

In our experimental study, we tried to understand the transition regime from combustion noise to thermoacoustic instability by varying the turbulence intensities of the flow field using flow restrictors. In the case of a swirl stabilized flame, we saw that the small amplitude periodic oscillations set in early for the base case when compared to the cases with flow restrictors. However, at low equivalence ratios, we saw a reduction in the amplitude of the periodic oscillations when the turbulence intensity was increased. We related the reduction in the amplitude when the turbulence intensity was increased to the lower strength of the Rayleigh index. We also saw an advanced onset of thermoacoustic instability with increase in turbulence intensity. Further, we also saw that case B, which had the highest turbulence intensity gave higher amplitude of pressure oscillations at low equivalence ratios when compared to case A. With the bluff body stabilized flame, we observed that the response of the system is not similar to what was seen with the swirler. With increase in turbulence intensity, we observed an increase in the amplitude of the pressure fluctuations. However, at low equivalence ratios, the dynamics remained intermittent with large amplitude oscillations during the periodic regime. From these findings, we can understand that the effect of varying turbulence intensity gives different responses. These results show that there is a definite need to understand the transition from stable combustion to thermoacoustic instability using spatial analysis with PIV and flame imaging within the nonlinear dynamics framework.

Acknowledgement
The authors would like to acknowledge the European Commission under call FP7-PEOPLE-ITN-2012 within the Marie Curie Initial Training Network Thermo-acoustic and aero-acoustic nonlinearities in green combustors with orifice structures (TANGO) as well as the Gas Turbine Technology Enabling Initiative (GATET), India for financially supporting the study. We would also like to acknowledge Komarek & Polifke for the combustor design.

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