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Effects of the equivalence ratio transient durations on self-excited combustion instability time scales in a single nozzle combustor

Xiaoling Chen, Wyatt Culler, Stephen Peluso, Domenic Santavicca, Jacqueline O'Connor[*]

Department of Mechanical and Nuclear Engineering, Pennsylvania State University, University Park, Pennsylvania, United States
[*]*Corresponding Author Email: jxo22@engr.psu.edu*

Abstract: Fuel staging is an effective way to attenuate combustion instability in lean, premixed combustion systems. Combustion instability occurs due to the coupling between heat release rate oscillations and combustor acoustics. In our experiments, we seek to understand how transient fuel staging affects the structure and dynamics of a single flame to help inform our previous studies of multi-flame systems. In the current experiments, fuel staging is achieved by changing the equivalence ratio in the nozzle. The equivalence ratio in the nozzle is varied over two different timescales, or transient durations, which are 1 ms and 4 s. For each duration, we also vary the percentage change in the equivalence ratio, with levels of ±3.57% and ±7.14% of the mean equivalence ratio, ϕ=0.7. Flame images recorded using CH* chemiluminescence imaging are analyzed to show the variations of the phase difference between pressure and heat release oscillations during transients. Phase difference transition behaves similarly in the flame base region but differently in flame/wall interaction region. More similarities between short and long duration transients are observed in combustion instability onset direction than decay direction.
Keywords: Combustion instability, Flame transient, Time scale

1. Introduction

Lean-premixed combustion is used to reduce the NO_x emissions in gas turbine combustors. However, lean flames sometimes suffer from combustion instability, which is caused by the coupling between the combustor acoustic field and heat release rate oscillations [1]. Both passive and active control methods have been used to suppress the combustion instabilities [2]. Fuel splitting, or when fuel is unevenly distributed between nozzles in a multi-nozzle system, is an effective way to attenuate the combustion instabilities [3]. Samarasinghe *et al.* [4] recently studied the mechanism behind longitudinal combustion instability suppression via fuel staging in a multi-nozzle can combustor, showing that fuel staging suppresses instabilities through variations in the heat release rate fluctuation phase between the staged nozzle and the other nozzles.. The transient behavior of the combustion instability suppression by the fuel staging in the multi-nozzle combustor was also recently studied [5]. Time scales of the combustion instability transition were found to be dependent on the fuel staging amount, transient timescale, and transient direction.

In this paper, we consider the effects of the transient timescales on the combustion instability transition characteristics in a single nozzle combustor (SNC), to better understand the processes in each individual flame in the fuel staging transient timescale variation studies in the multi-nozzle combustor.

2. Methods / Experimental

2.1 Experimental Setup

A single nozzle, lean, premixed swirling combustor is operated in a transient matter by increasing and decreasing the equivalence ratio over different time durations. A quartz liner with a diameter of 110 mm and length of 305 mm is installed to provide optical access to the flame. The geometric swirl number of the nozzle is 0.7 and the diameter of the nozzle is 55 mm. An illustration of the combustor is displayed in **Figure 1**. Perfectly premixed fuel and air flow to the system after a choke plate, which prevents fluctuations in the equivalence ratio in the main flow. Additional fuel is injected through holes on the swirler blades 0.1 m upstream the dump plane, and is controlled by a solenoid valve that varies the staging fuel quantity and delivery timescale. Previous mixing measurements show that the staging fuel is completely mixed by the exit of the nozzle [6].

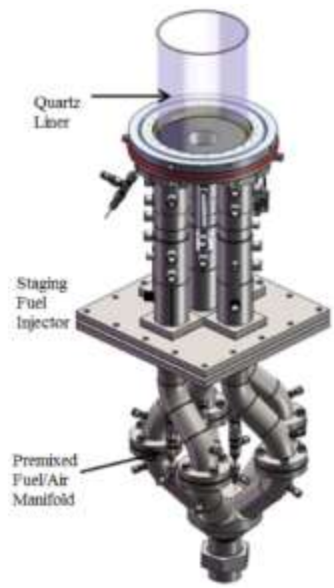


Figure 1. Geometry of the single nozzle combustor

2.2 Diagnostics Technique

An infrared (IR) absorption technique is applied to measure the temporal fuel concentration variation at the dump plane to obtain the fuel delivery characteristic timescale. Water-cooled, recess-mounted PCB dynamic pressure transducers mounted below the dump plate and on the center nozzle are used to record the pressure fluctuations within the combustor at a sampling rate of 16,000 Hz. A Photron SA4 high speed camera fitted with an Invisible Vision UVi 1850-10 intensifier, a Nikon AF Micro-Nikkor 60mm f/208 lens, and a 432±5nm bandpass filter is used to obtain high-speed CH* chemiluminescence images, a marker of heat release [7].

2.3 Data Processing Method

A logistic regression method is used to calculate the transient timescales, both the fuel delivery timescale as well as the instability growth and decay timescales. The transition median time, $t_{0,}$ and timescale, τ, are calculated in the logistic fit, as described in detail in Ref. [5]. To visualize the instantaneous phase between pressure and heat release rate fluctuations from chemiluminescence imaging, we use a Hilbert transform on both the pressure and image time series to calculate the relative instantaneous phase between the two. This process is described in detail in Ref.[5].

2.4 Test Matrix

Two fuel variation durations and two directions are selected for the transient tests with three amplitudes for the non-reacting (IR measurements) and in the reacting conditions, two amplitudes. The detailed test matrix is displayed in **Table 1** and **Table 2**.

Table 1: Main fuel/air flow characteristic parameters

Fuel flow rate (*g*/*s*)	1.16
Air flow rate (*g*/*s*)	28.52
Inlet mixture temperature (*K*)	473.15
Nozzle flow velocity (*m*/*s*)	26
Inlet Reynolds number Re_d	17,000

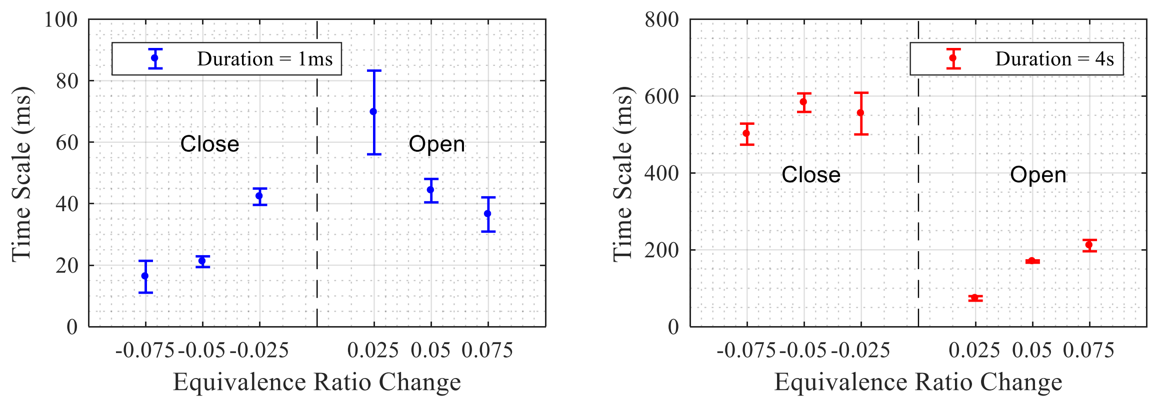
Table 2: Test matrix for the SNC transient tests

Transient duration	**Transient direction (Initial $\phi \rightarrow$ Final ϕ)**				
	Non-reacting			Reacting	
1 ms	0.625→0.7	0.65→0.7	0.675→0.7	0.65→0.7	0.675→0.7
	0.7→0.625	0.7→0.65	0.7→0.675	0.7→0.65	0.7→0.675
4 s	0.625→0.7	0.65→0.7	0.675→0.7	0.65→0.7	0.675→0.7
	0.7→0.625	0.7→0.65	0.7→0.675	0.7→0.65	0.7→0.675

3. Results and Discussion

3.1 Fuel delivery characteristics

To better understand the transition from stable to unstable, or unstable to stable, operation, we first characterize the rate at which fuel is delivered to the combustor at different commanded transient durations.



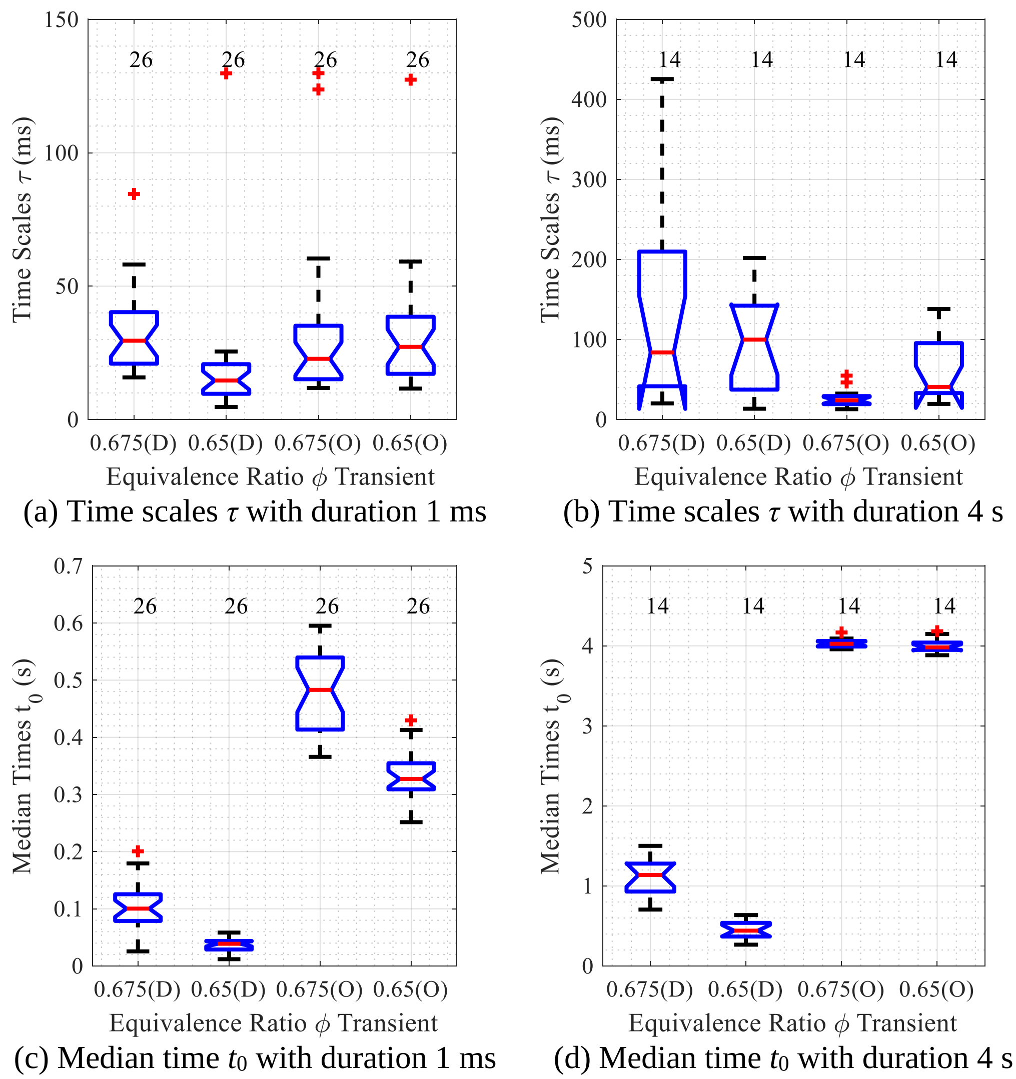
(a) Transient duration 1 ms (b) Transient duration 4 s

Figure 2: Dependence of fuel delivery time scales on ϕ change in two transient durations

In **Error! Reference source not found.**, the dependence of the fuel delivery timescales on equivalence ratio changes is illustrated, where the mean value is denoted by the red center and one standard deviation is denoted by the error bars. For the short-duration transients, the timescales associated with fuel delivery vary with equivalence ratio but not significantly with opening direction; the fuel delivery timescale is higher for larger equivalence ratio variations. For the long-duration transients, however, the equivalence ratio increase and decrease timescales are significantly different, where timescales associated with valve opening are much shorter than those of valve closing. These differences are likely due to both variations in the operation of the valve itself as well as the flow processes in the fuel circuit.

3.2 Pressure time scales

Similarly, logistic regression is also applied to combustor pressure fluctuation signals to obtain the timescales and median times of the pressure oscillation transition in both short and long duration transients. The dependence of the time scales/median times on the transient directions and amounts are plotted in boxplot [5] in Figure 3. In the boxplot, the red line indicates the median value of the ensemble and height of the box is determined by the first and third quartile of the data. Outliers of each case are denoted by the red crosses. The notch for the box represents the 95% confidence intervals, and the numbers above each box indicate the number of repeats in each ensemble at each condition.



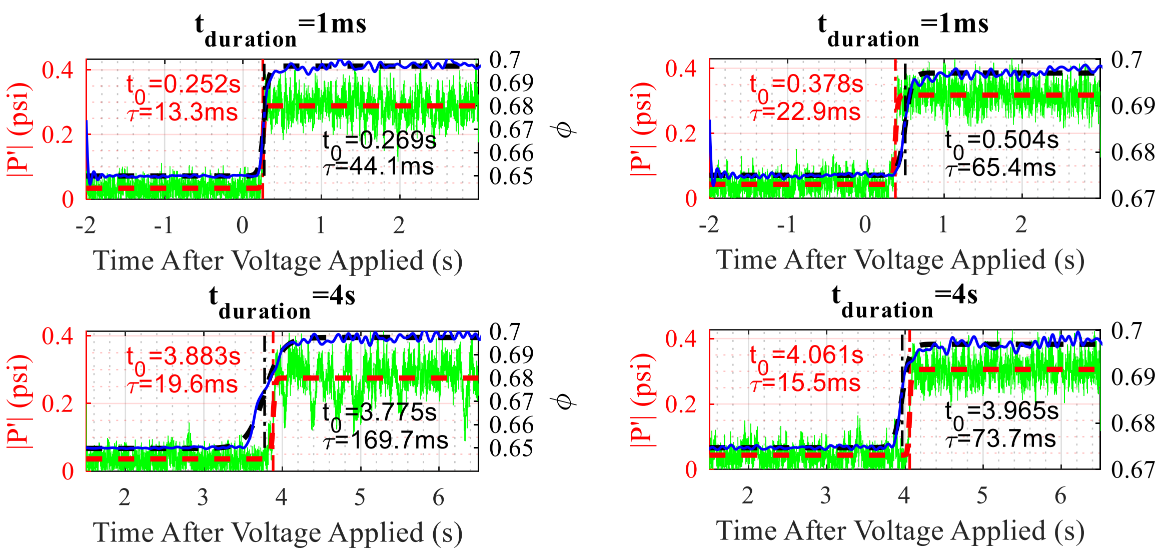
(a) Time scales τ with duration 1 ms (b) Time scales τ with duration 4 s

(c) Median time t_0 with duration 1 ms (d) Median time t_0 with duration 4 s

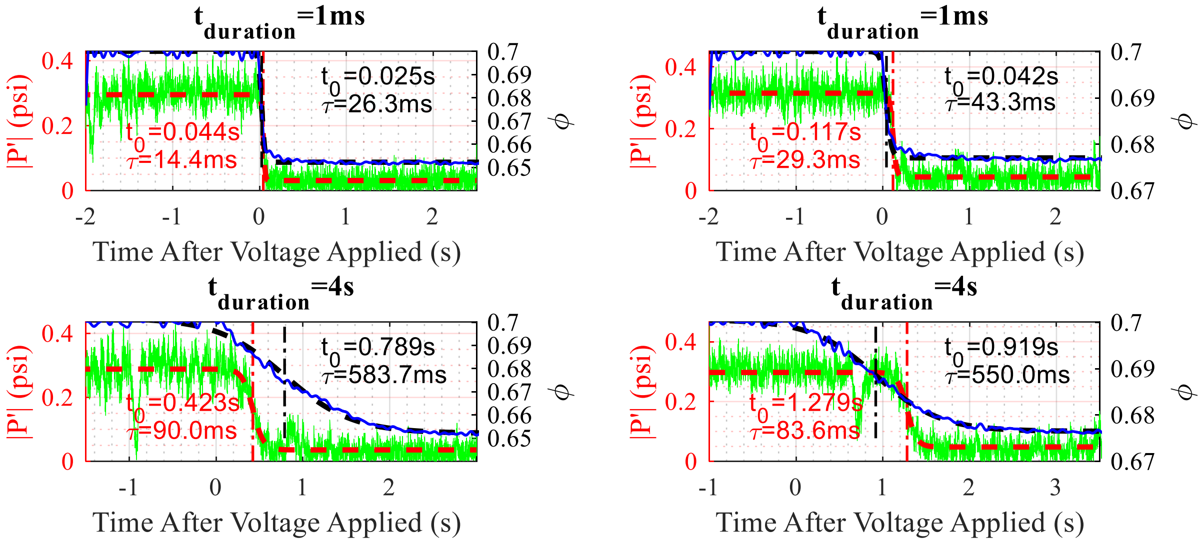
Figure 3: Pressure time scale and median time statistical distributions

The x-axis in the box plots shows the smaller equivalence ratio value during the transients and the capital letter inside the parenthesis indicates the direction of the transients. "D" represents combustion instability decay and "O" represents instability onset. For short duration transients, timescales of pressure oscillation transition are nearly independent of the ϕ change direction and amplitude, with the only exception that instability decay occurs more quickly with a smaller final ϕ. Differences between timescales for different ϕ change amplitudes for the long duration transients are not statistically significant. However, timescales for the long-duration transients are longer as compared with those of the short duration transients, which is congruent with the commanded transient duration. Instability onset occurs more repeatedly than instability decay, which is likely due to the differences in the fuel delivery characteristics for the long duration transient shown in **Error! Reference source not found.**. Dependence of the median times, t_0, on ϕ change directions and amplitudes are similar for the two transient durations; pressure onset occurs later than pressure decay and larger ϕ change amplitudes lead to an earlier transition of the pressure oscillation.

The pressure and ϕ time series with their logistic fits are plotted in one plot in Figure 4. Original data are plotted on top of the logistic curve in green (pressure) and blue (equivalence ratio). The median time, t_0, of the pressure transition occurs a little bit earlier than the equivalence ratio in direction of instability onset and opposite in direction of instability decay for short transient duration. For the long transient duration, the pressure transition always occurs earlier than the ϕ in the instability onset direction no matter the amplitude of ϕ change. In direction of the instability decay, t_0 of pressure is smaller that of ϕ for $\Delta\phi$=0.05 but larger for $\Delta\phi$=0.025. This is because the instability decays at a critical ϕ around 0.68 and it takes shorter time for the equivalence ratio to become this critical value in larger change of decreasing ϕ. A summary of the critical equivalence ratio in instability onset and decay with long transient duration is plotted in Figure 5.



(a) 0.65 → 0.70 Direction (b) 0.675 → 0.70 Direction



(c) 0.70 → 0.65 Direction (b) 0.70 → 0.675 Direction

Figure 4: Equivalence ratio and pressure oscillation variations

The critical equivalence ratio ϕ_{cr} is the equivalence ratio at the median time, t_0, of the pressure transition curve. The different ϕ_{cr} are plotted in Figure 5 for different transient directions and amplitudes, where the error bars show one standard deviation in the data from all the ensembles. The ϕ_{cr} is between 0.68 and 0.69 for all cases. No strong difference in the critical equivalence ratio is observed amongst all the cases, which supports the conclusion that a critical equivalence ratio indeed exists.

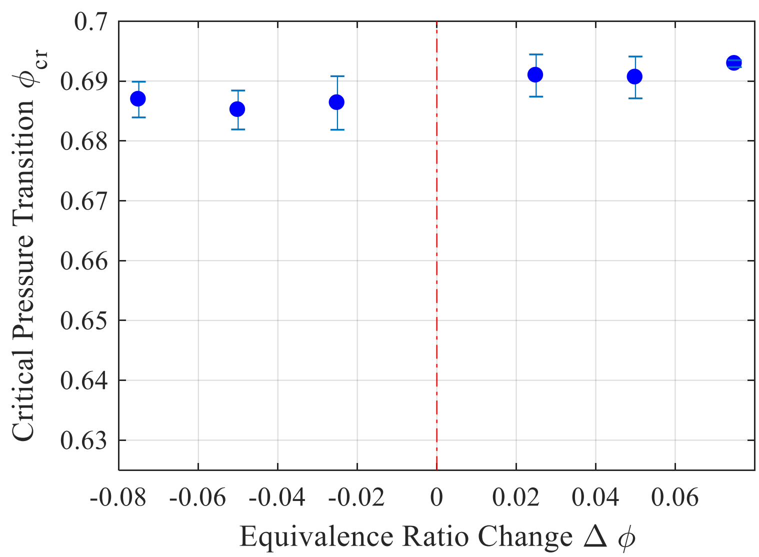
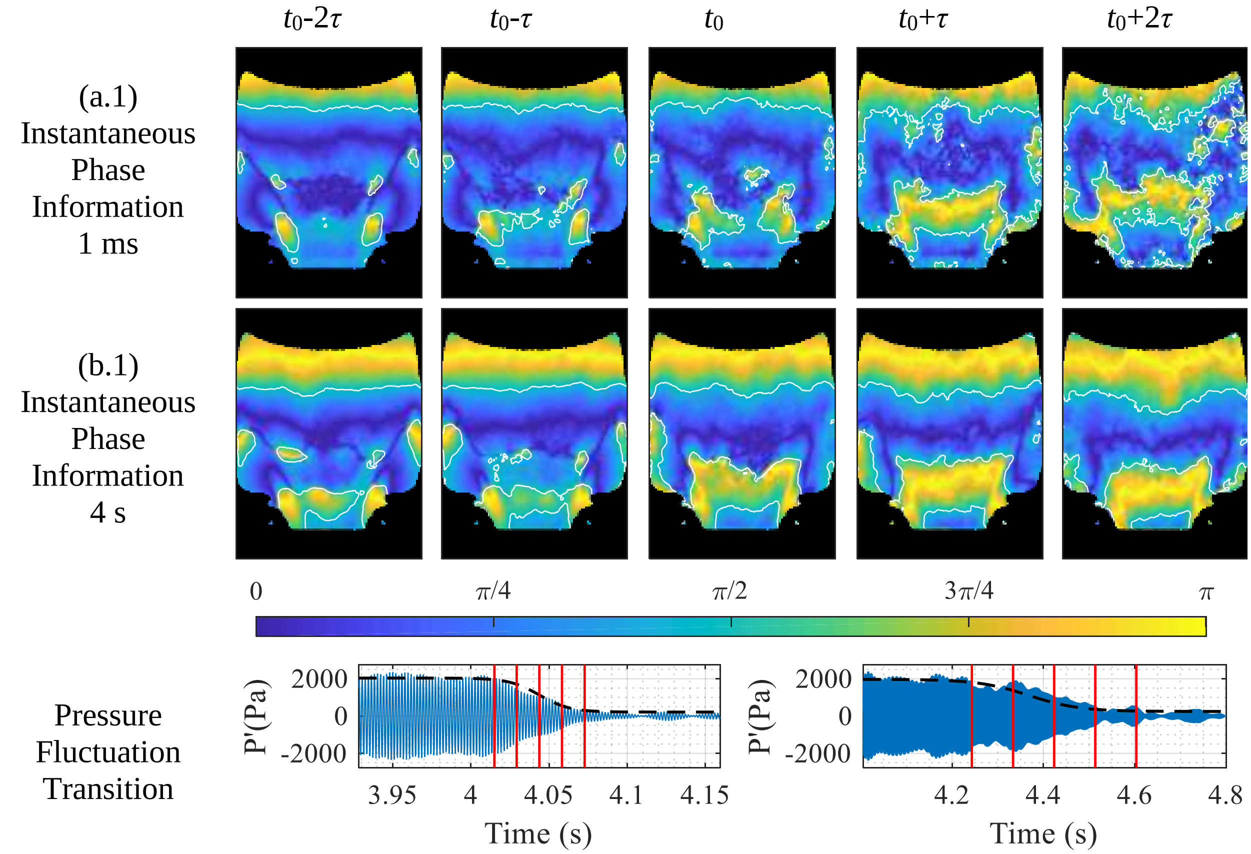


Figure 5: Critical equivalence ratio ϕ_{cr} for long duration transient

3.3 Phase image analysis

Instantaneous phase differences between pressure and heat release rate oscillations captured by CH* chemiluminescence intensity for both short and long duration transients are displayed in Figure 6. The white line is the $\pi/2$ iso-contour, which shows the delineation between regions that drive and those that damp the instability. The corresponding pressure time series is at the bottom of the phase images with left for short duration transients and right for long duration transients.



(a.2) 0.70 → 0.65 (1 ms duration) (b.2) 0.70 → 0.65 (4 s duration)

Figure 6: Instantaneous phase difference images transition during instability decay

There is little difference in the instantaneous phase distribution between the short duration and long duration transients in both the decay and onset directions, although only one (instability decay direction) is shown. This is different than the multi-nozzle combustor, where the onset and decay processes are quite different, especially for the intermediate steps during short duration transients. In the multi-nozzle combustor, the instability onset shows the entire center region of the combustor shifts in-phase very quickly, while the center region shifts first followed by the rest of the flame in instability decay direction. In long duration decay transient, out-of-phase appears mostly in both the flame/wall interaction and flame base regions. However, in short transient duration, the region slightly above the flame base transits to out-of-phase mostly and the originally in-phase region tends to have a more random distribution of phase difference. The short and long duration transients do show differences in the instantaneous phase transitions.

4. Conclusions

We compared the dependence of instability transition timescales on transient directions, timescales, and amplitudes in a lean, premixed single nozzle combustor. In both short and long duration transients, there is nearly no difference in timescales when the transient amplitudes doubles in both two directions. Comparison of the combustor pressure and equivalence ratio data shows that combustion instability transition strongly depends on the equivalence ratio and the critical equivalence ratio is approximately 0.68 for all cases regardless of instability transient duration or direction.

5. Acknowledgements

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6. References

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