Variation in Flame Surface Density in Acoustically Perturbed Flames

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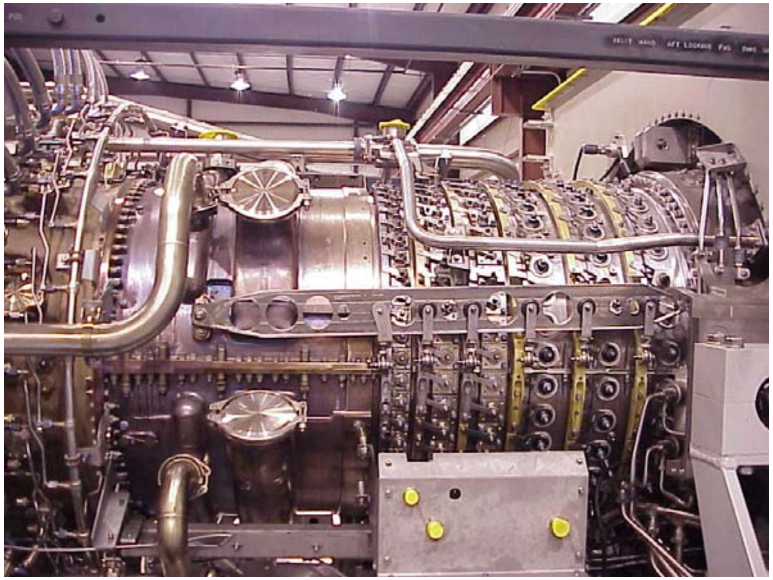
University of Iowa – Flood of June 2008

Outline

- Motivation – Why are we interested?
- Methodology – How is ours different?
- Experimental system
  - Chamber, burner, & imaging system
- Results and analysis
  - Flame Surface Density assessment
  - Analysis of physical mechanisms
- Conclusions

Motivation – Continuing Issues in Gas Turbine Power Systems

- Common problem: many combustion systems exhibit instabilities
- Instabilities may arise out of inadequate design or off-design operation
- Combustion instability is a result of interactions between system acoustics, system flow topology, and energy/heat release
- Instability can generate acoustic waves strong enough disturb the flow field, increase wall heat transfer, induce system vibration, and even catastrophic failure



Methodology

- Objective
  - *Examine the acoustics/combustion interaction for lean premixed low swirl stabilized flames*
  - Assess flame/flow coupling
  - Observe changes in the relative importance of various effects as scaling parameters are varied

- Technique
  - Chamber-based (downstream of flame) acoustic driving
    - Minimizes the effect of mass/turbulence intensity oscillations at the burner exit…
  - PLIF imaging:
    - Phase-resolved data acquisition followed by phase-dependent re-sorting…

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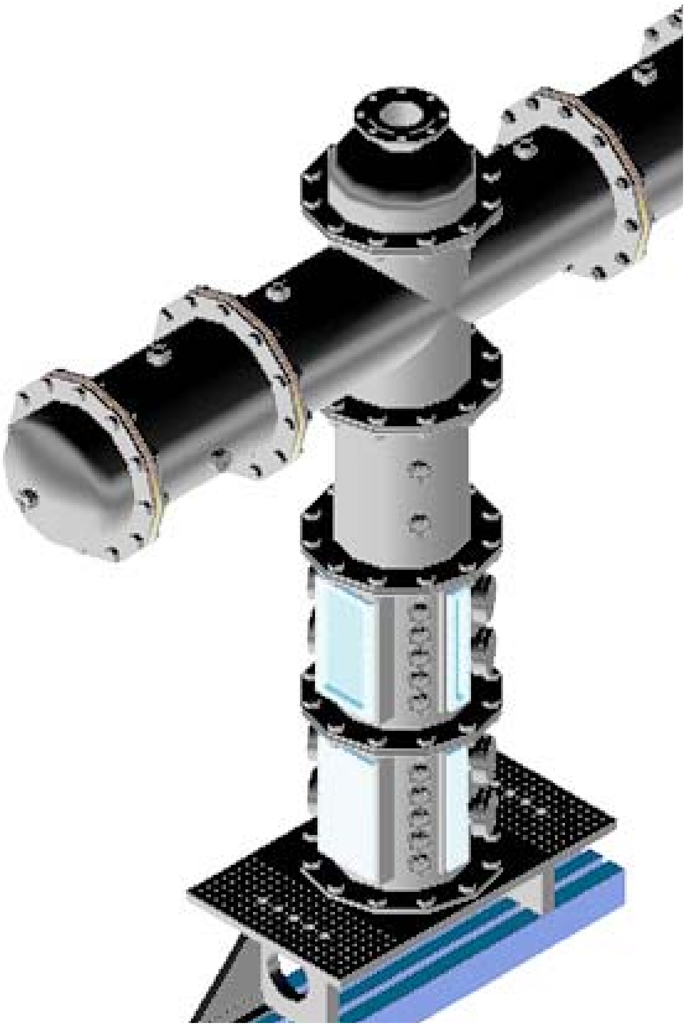
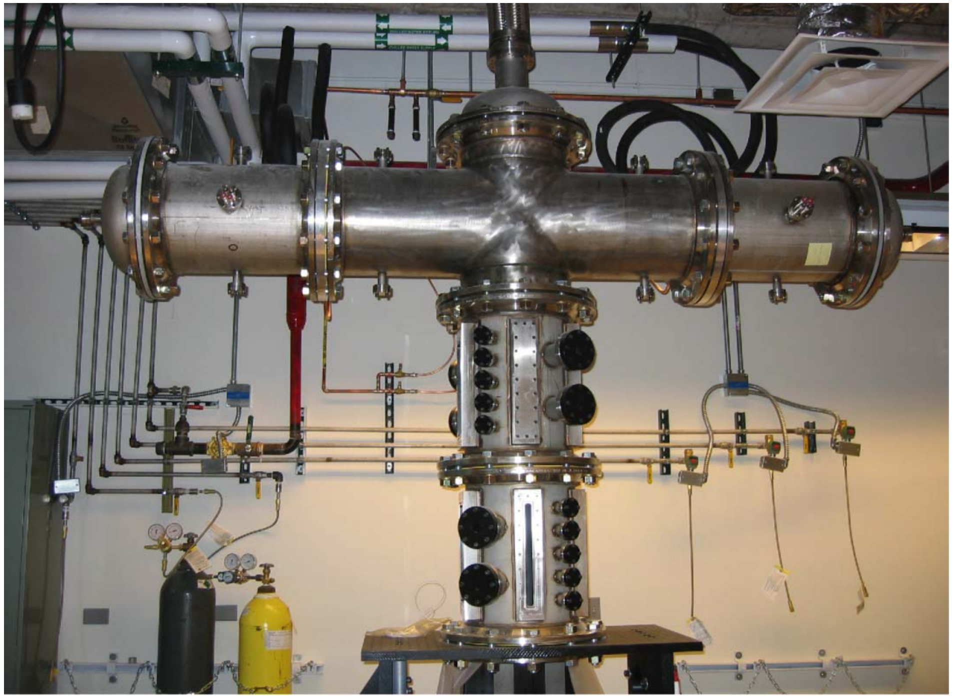
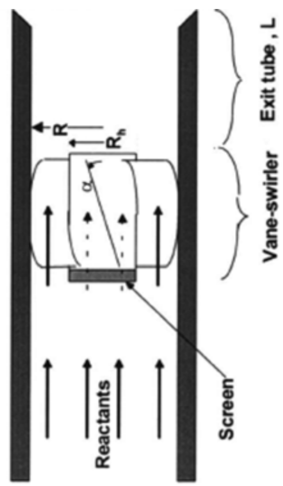
Experimental System - Chamber

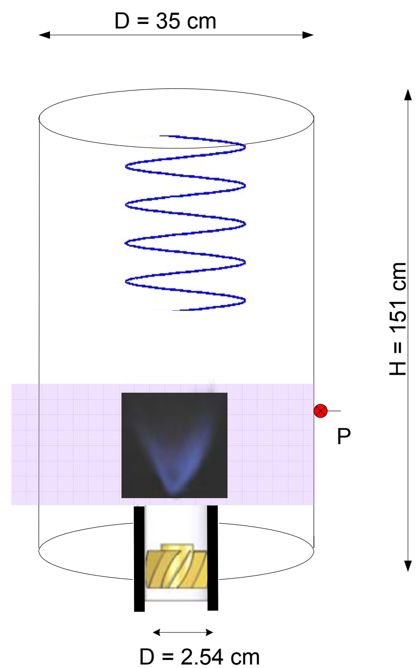


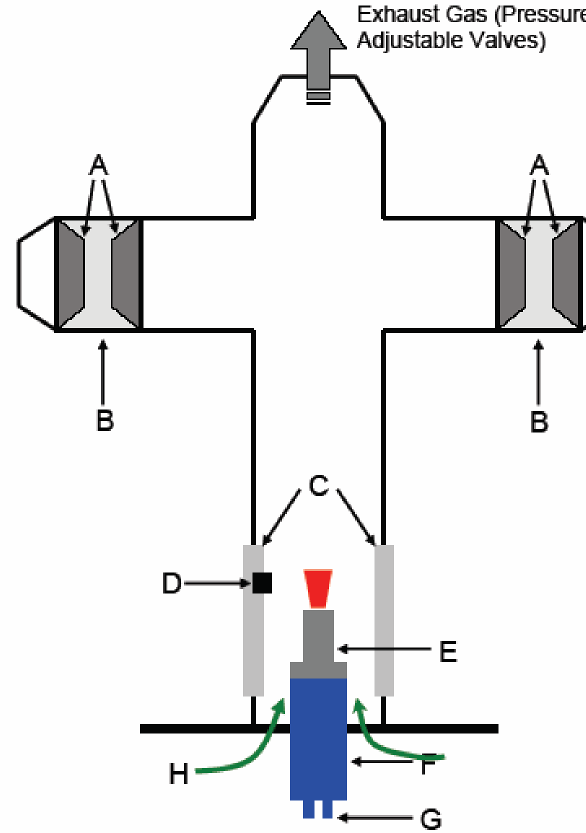


- Stainless Steel Chamber
  - Diameter 12”, height: 6’
- Optical imaging windows
- Side access ports

Experimental System – Chamber & Burner



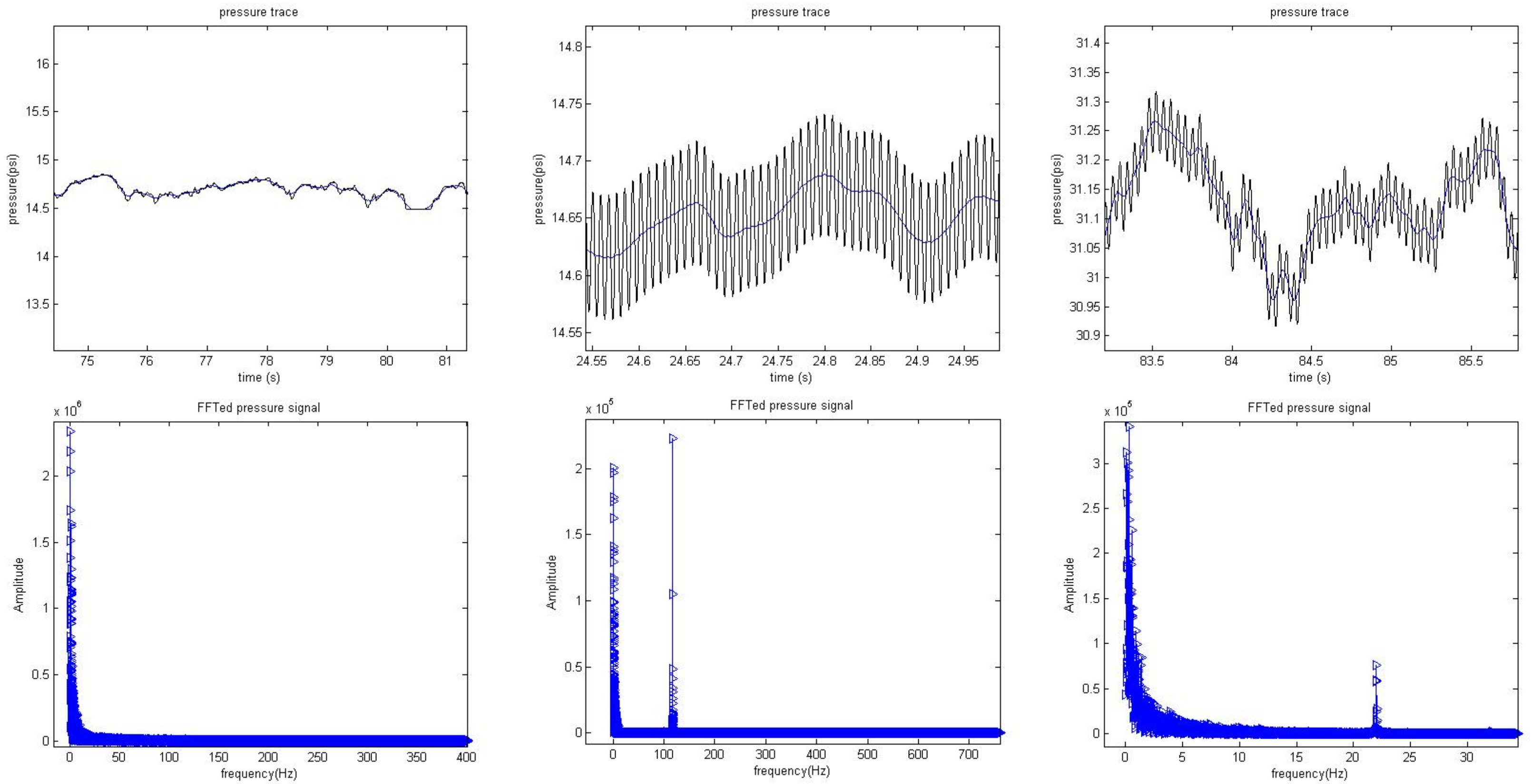




A: Loudspeakers B: Speaker Section C: Quartz Window
D: Pressure Transducer E: Swirl Burner F: Adjustable Premixer
G: Fuel/Air Inlets H: Nitrogen Co-flow

- Low swirl burner:
  - 2.54 cm diameter, 5 cm length
  - flow divergence for stabilization
  - provided by Dr. Robert Cheng of LBNL

Pressure fluctuations



No excitation

f=116 Hz

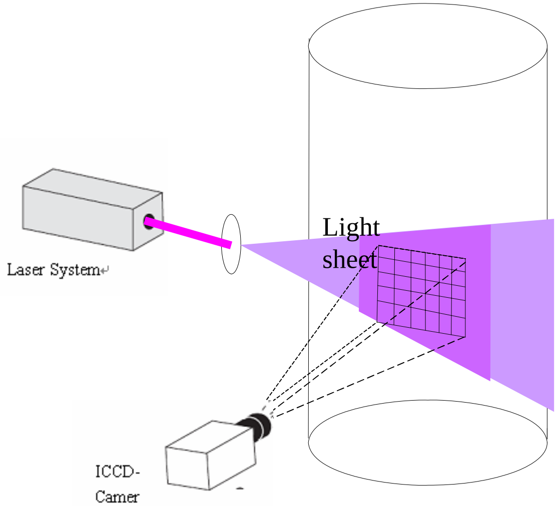
pressure fluctuation at 1 bar

pressure fluctuation at 2 bar

- In general, P_{rms} is about 0.05%. But it also depends on excitation frequency

Experimental System - Imaging

- Laser system
  - Nd:YAG pump laser, dye laser, frequency doubler
  - Sheet-forming optics
- Camera system
  - ICCD camera
  - View field: 8.9cm*8.9cm (512*512)
- Excitation – detection
  - 283 nm pump beam with 308-350 nm detection



Simplified schematic view of imaging system

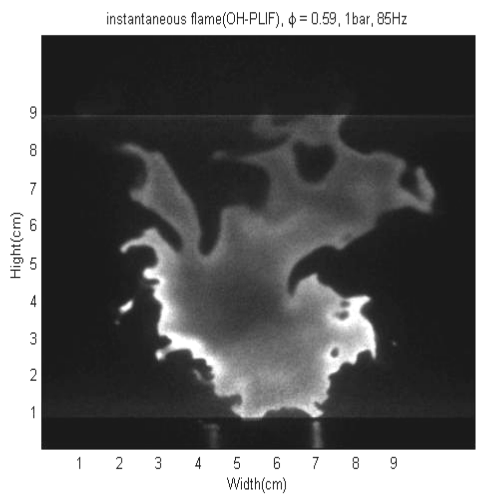
Experimental Conditions

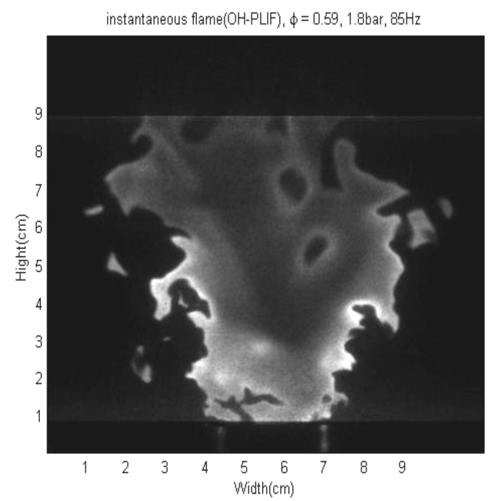
- Reactants
  - fuel: methane
  - oxidizer: air
  - equivalence ratio: $\Phi=0.5$
- Flow rates:
  - air: 100 slpm, methane: 5 slpm
  - reactants: 3.48m/s (outlet of the burner)
- Enforced acoustics
  - frequency: 22-370Hz
  - amplitude: ~0.05%
- Chamber bulk pressure:
  - P= 1 – 5 bar

OH-PLIF images

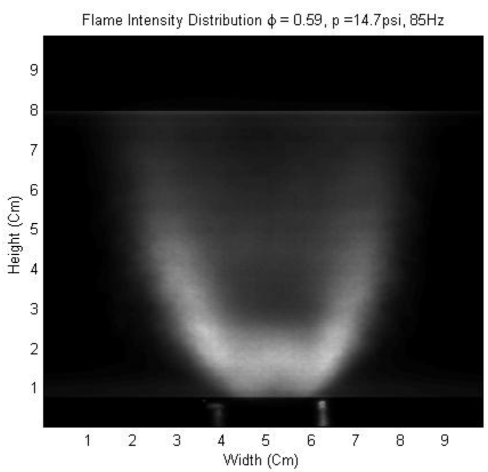
1 bar

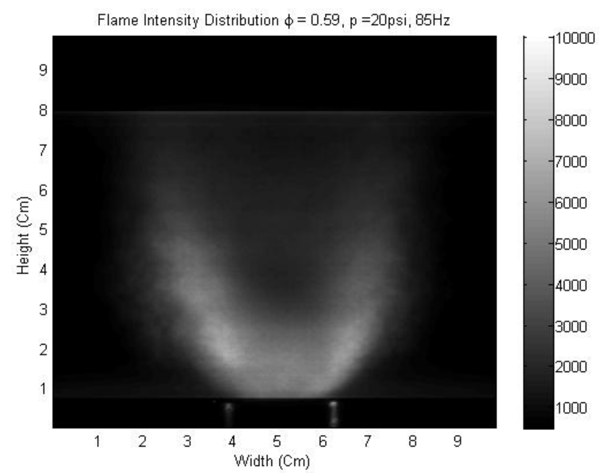
1.8 bar





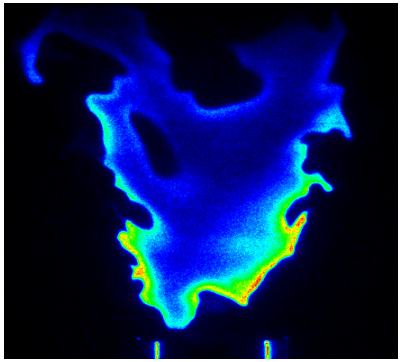
Instantaneous OH-PLIF images





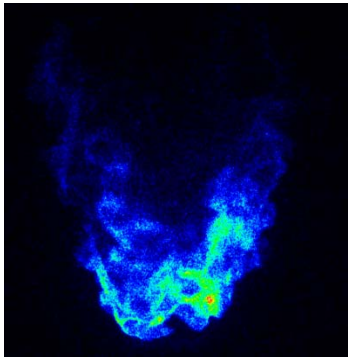
Mean OH-PLIF images

PLIF/Chemiluminescence Comparison



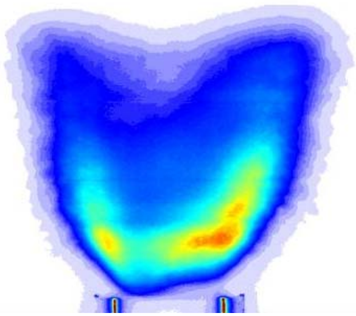
Instantaneous flame from OH-PLIF

Instantaneous flame from OH*

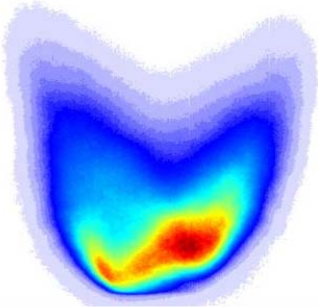


Visual image from ordinary camera

Averaged flame from OH-PLIF



Averaged flame from OH*



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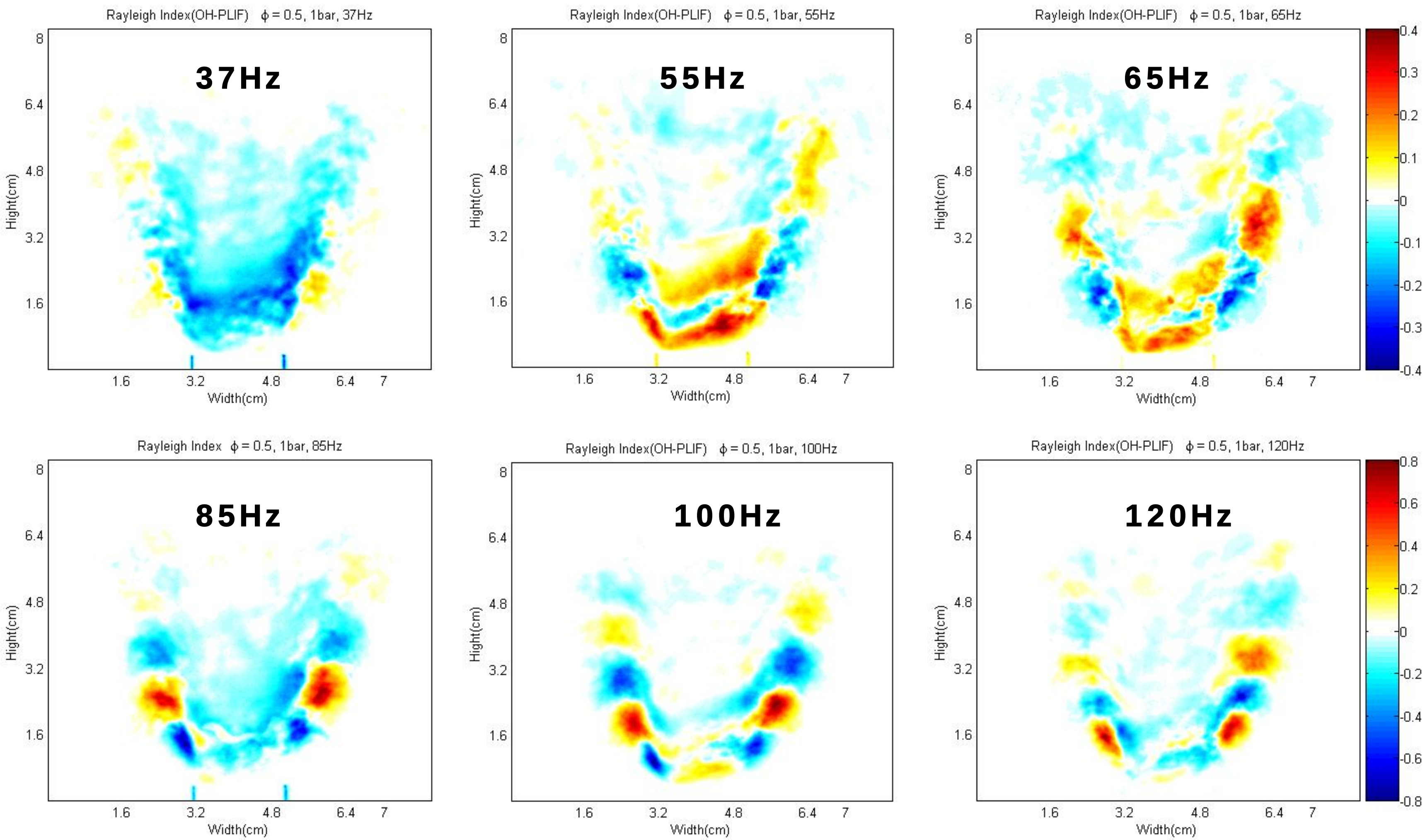
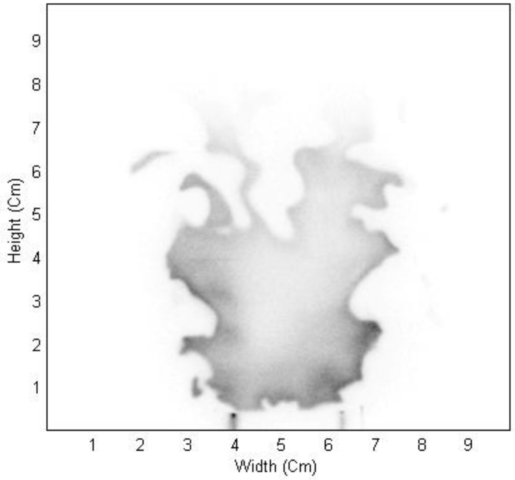
Rayleigh Index Distribution from OH-PLIF



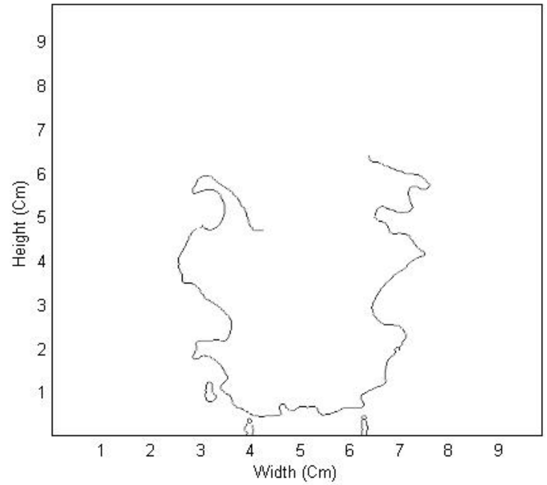
Rayleigh Index at the center plane of the flame

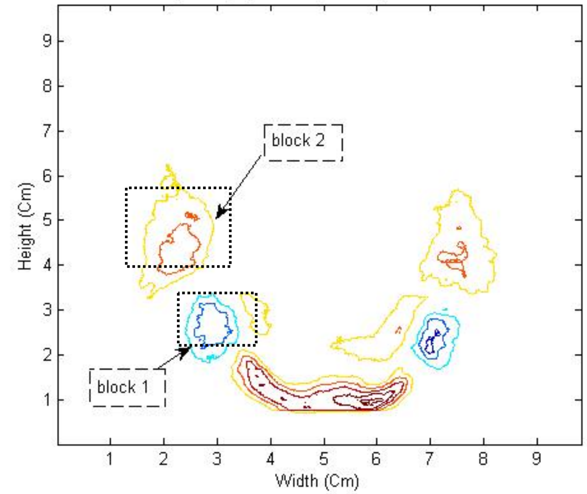
Flame Surface Density vs. Flame Intensity

Instantaneous image



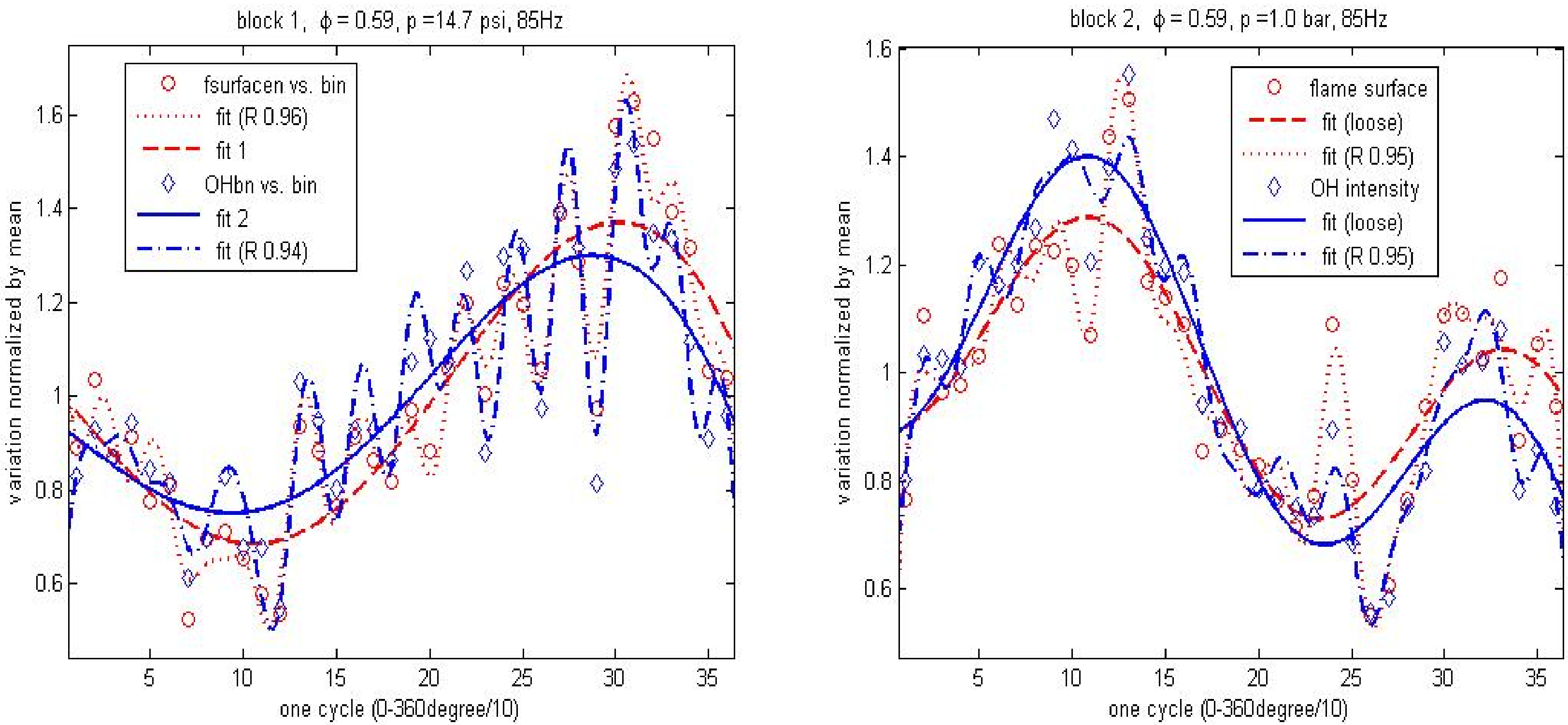
Flame front





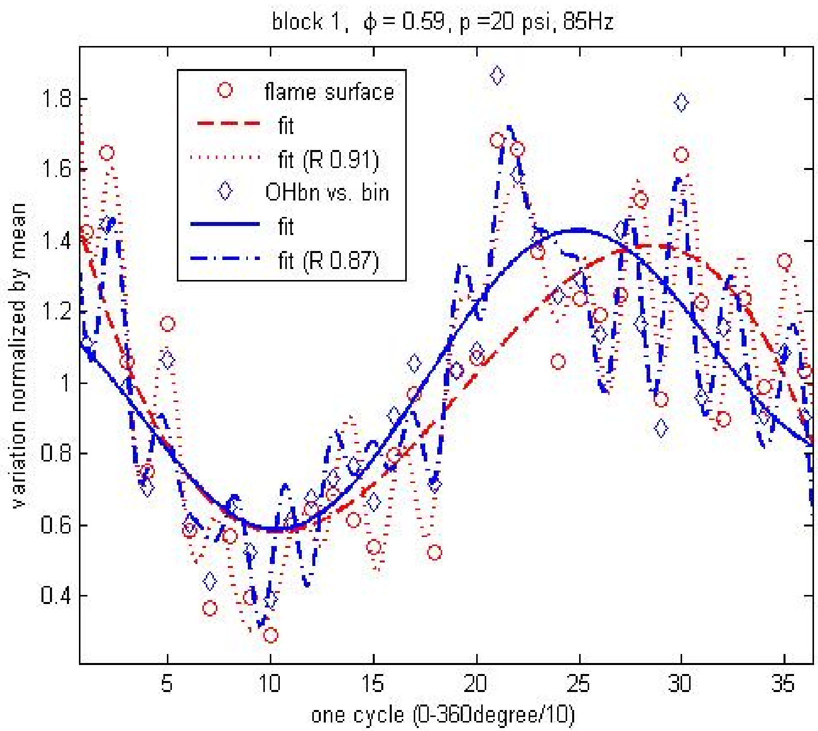
- Flame surface density is approximated as: *total flame length/ area*
- OH intensity is : *sum of OH/ area*
- Calculated in Matlab

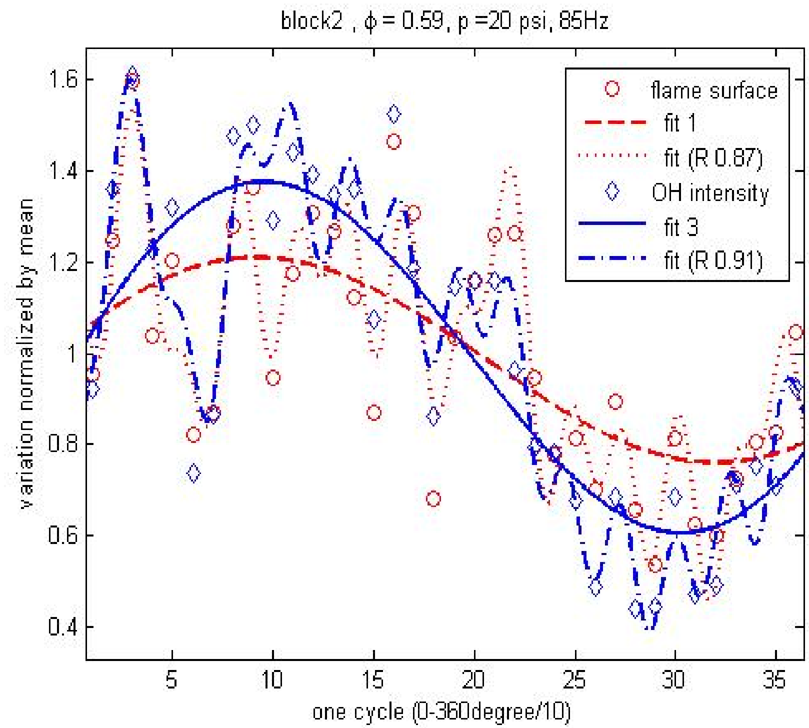
Flame Surface Density vs. Flame Intensity (1 bar)



- Correlation of FSD and OH at 1 bar
  - Block 1: 0.94
  - Block 2: 0.91

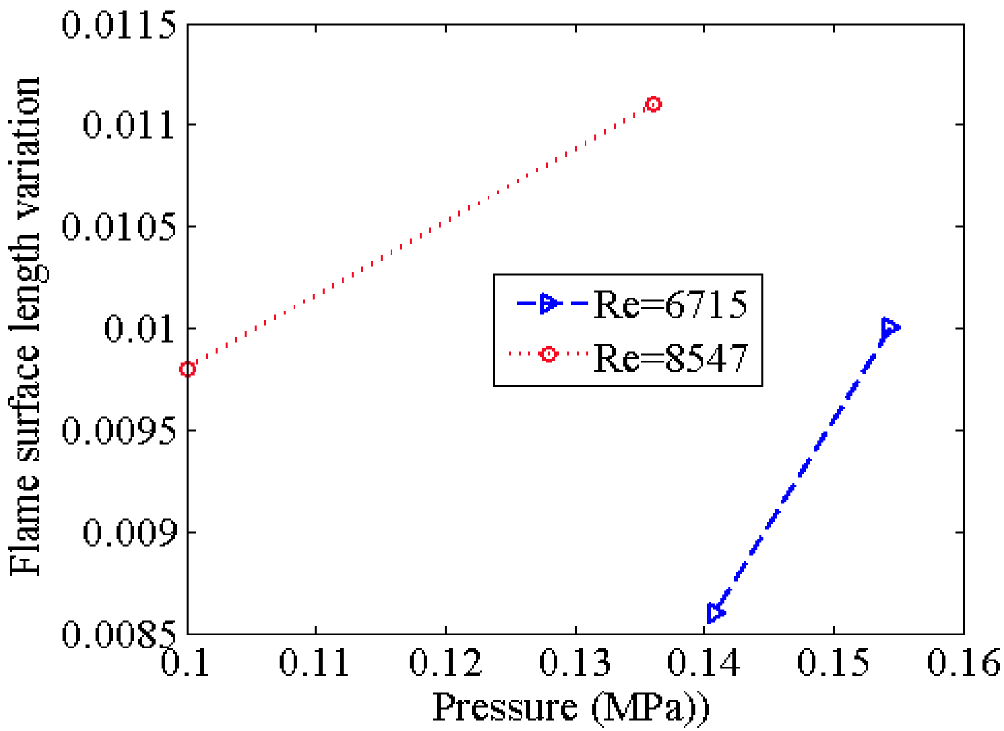
Flame Surface Density vs. Flame Intensity (1.5 bar)





- Correlation of FSD and OH at 1.5 bar
  - Block 1: 0.92
  - Block 2: 0.91

Flame Surface Density with Increasing Pressure



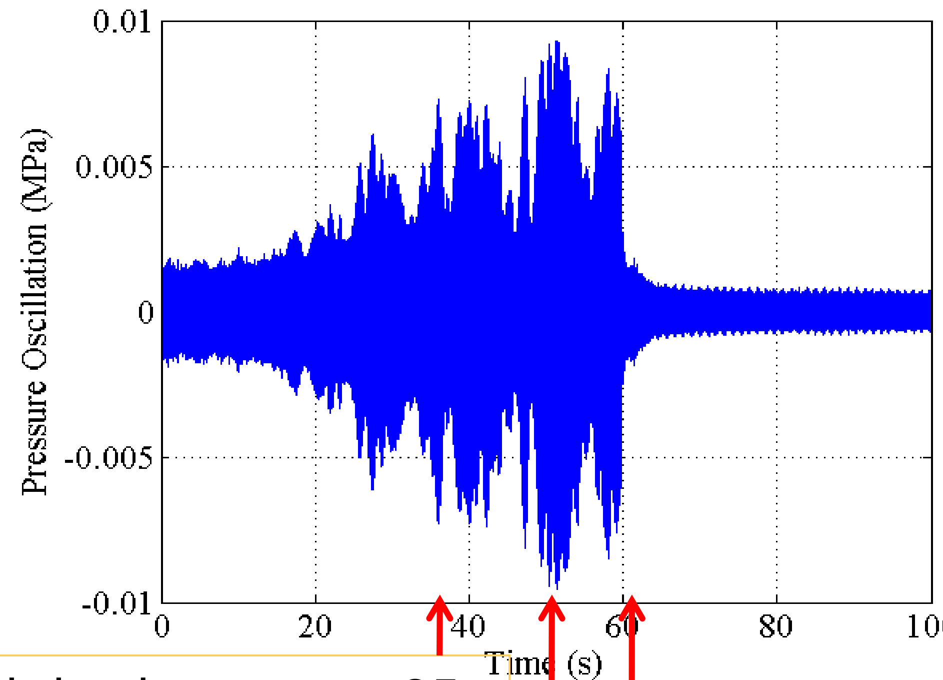
- Flame Surface Density increases with increasing pressure even while Reynolds number is held constant
- Increases are most likely due to increases in turbulence intensity

Natural Instability Growth

- Normal operation involves controlling the pressure amplitude by increasing or decreasing the driving power to hold the amplitude constant
- As a test, constant power was applied at various frequencies
- At 125 Hz, the system slowly developed an unstable mode that grew the pressure amplitude, caused the flame to move upstream, and the flame to extinguish after some time
- It was found that there is a minimum driving pressure to establish the shear-layer vortex street that then can lead to this unstable mode

Effect of Pressure Oscillation Amplitude

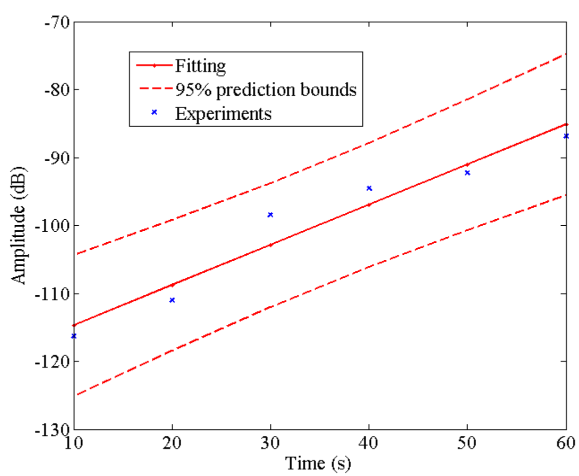
- The pressure variation p'/P has to be more than 0.04% to trigger coupling
- Between 0.04% to 0.7% perturbation, the distribution of the vortex structure remains unchanged
- Above 5%, flash back occurs



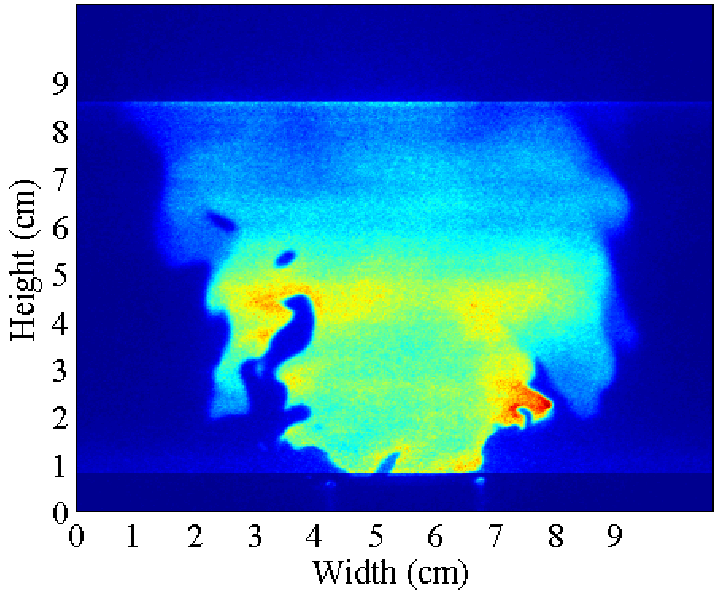
Flash back starts at 35s

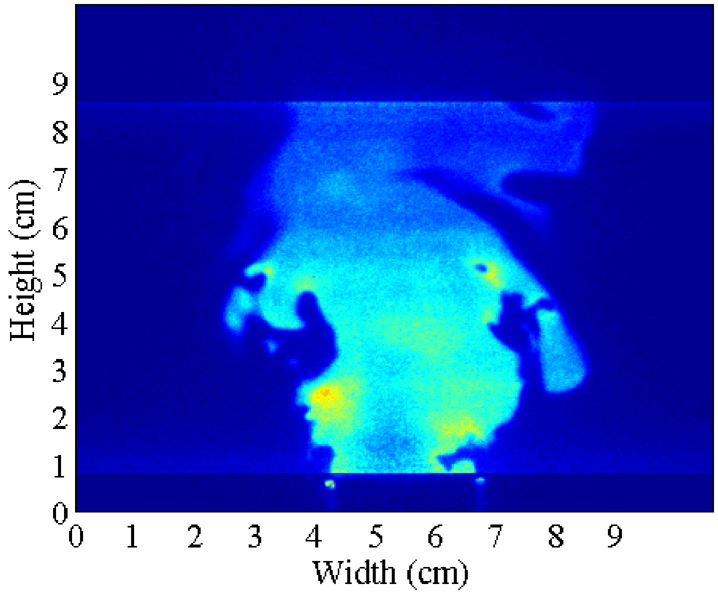
Jet flame behavior starts 49s

Flame extinction at 59s

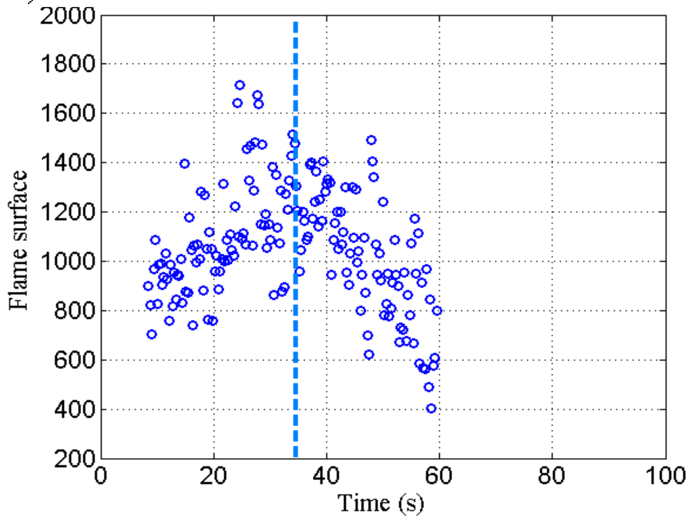


Flame Transition





Occasional Flash-back



Flame Anchored Upstream

Summary

- Flame Surface Density is constant across frequencies
- Guessing that the instability is driven by burner heating
- Increase in heat release appears to be driven by an increase in FSD
- If that is true, is the FSD increase driven by increasing turbulence intensity coming off of the swirler?
- Flash-back is probably driven by flow reversal driven by velocity oscillations at the burner exit
- Why does blowout occur?

Thanks for Listening!

Any Questions?

Analysis

- Wave equation

$$\nabla^2 \boldsymbol{p}' - \frac{1}{\boldsymbol{a}^2}\frac{\partial^2 \boldsymbol{p}'}{\partial \boldsymbol{t}^2} = -\frac{1}{\boldsymbol{a}^2}\frac{\boldsymbol{R}}{\boldsymbol{C}_v}\frac{\partial \boldsymbol{q}'}{\partial \boldsymbol{t}} + \boldsymbol{g}$$

  - Superscript ()' denotes deviations from mean value, *a* is the speed of sound, and the term *g* contains all influences other than that of heat addition.

- Energy per cycle

$$\Delta\varepsilon_n(t) = (\gamma - 1)\frac{\omega_n^2}{E_n^2}\int dV \int_t^{t+\tau_n} \frac{p_n'}{\bar{p}}\frac{q'}{\bar{q}}\,dt$$

  - *n* denotes different modes of the acoustic oscillation

- Rayleigh Index

$$R_f = \int_0^1 \frac{p'q'}{p_{rms}\bar{q}}\,d\xi$$

  - Positive R_f means that pressure oscillation and heat release are in phase and hence the oscillation is enhanced
  - In reality, a flame could be stable while exhibiting a positive Rayleigh Index since dissipation is not included in this equation

Data Reduction

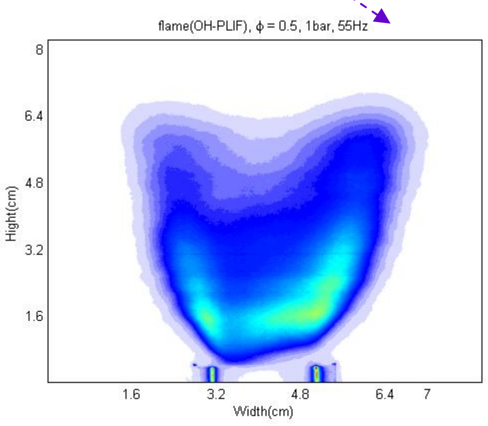
Instant Image [OH]

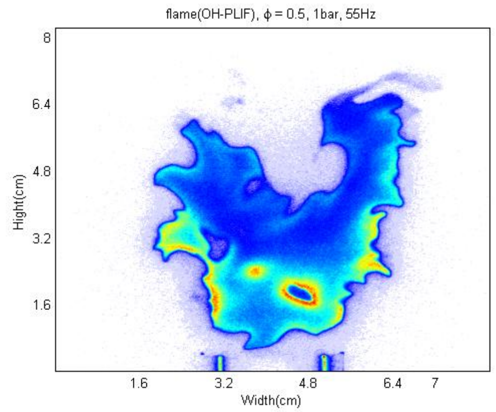
Averaged Image $\overline{[OH]}$

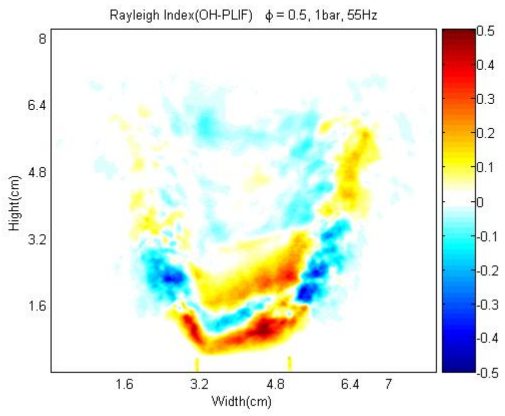
Instant p'

Instant Image [OH]'

Rayleigh Index

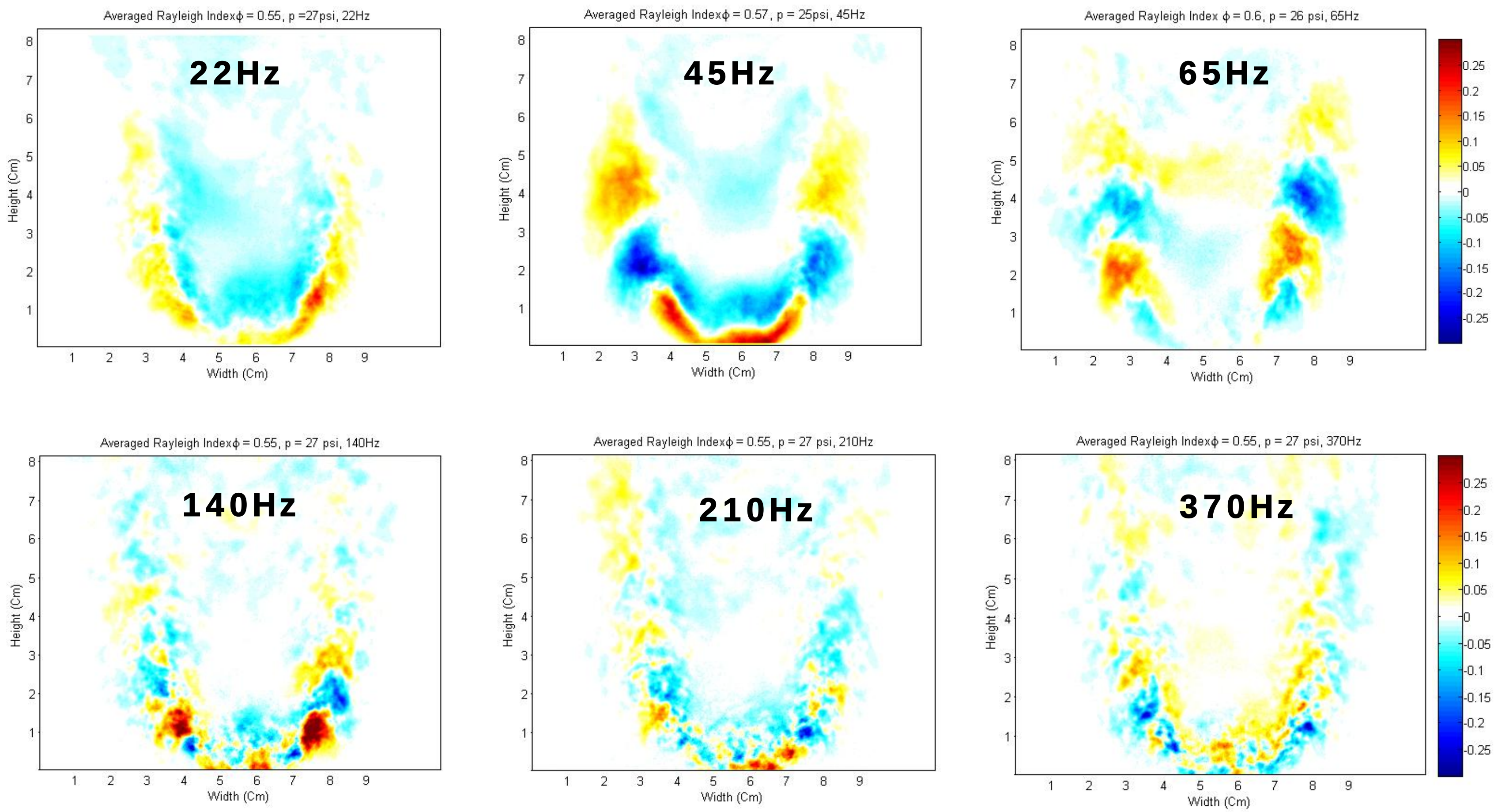






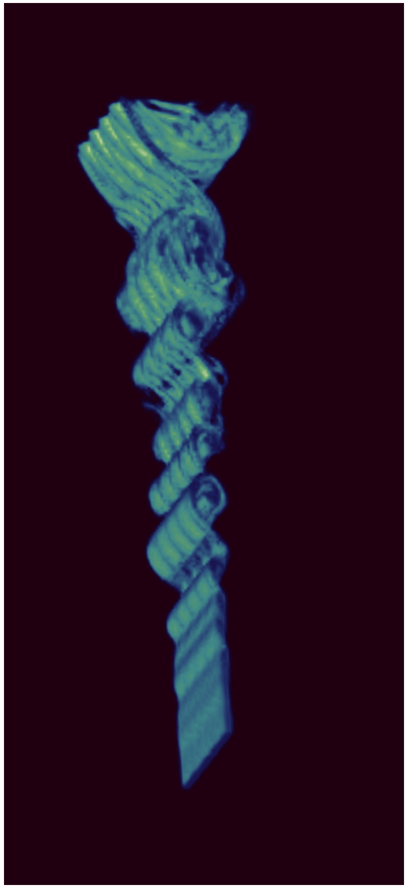
- No clear structure seen from OH concentration
- Pattern appears in Rayleigh Index

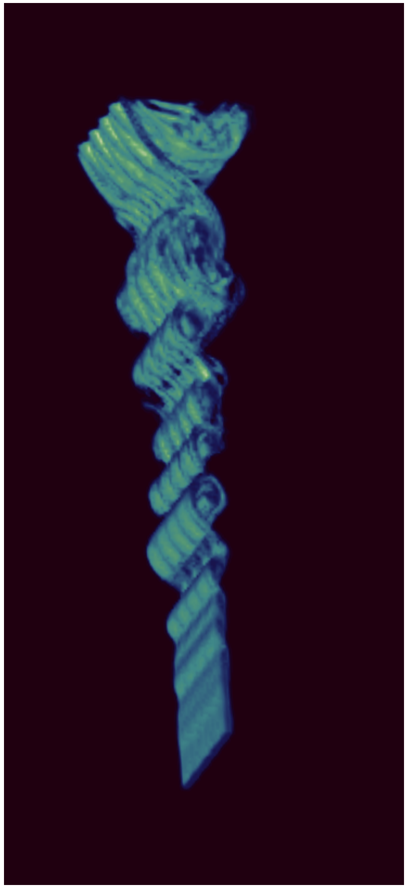
Rayleigh Index (1.8bar)



Rayleigh Index at elevated pressures

Shear Layer Forming Vortices

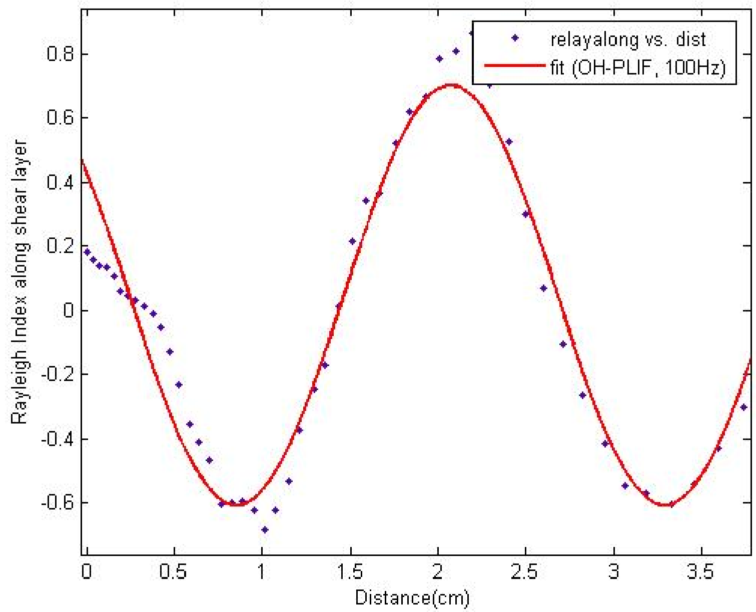




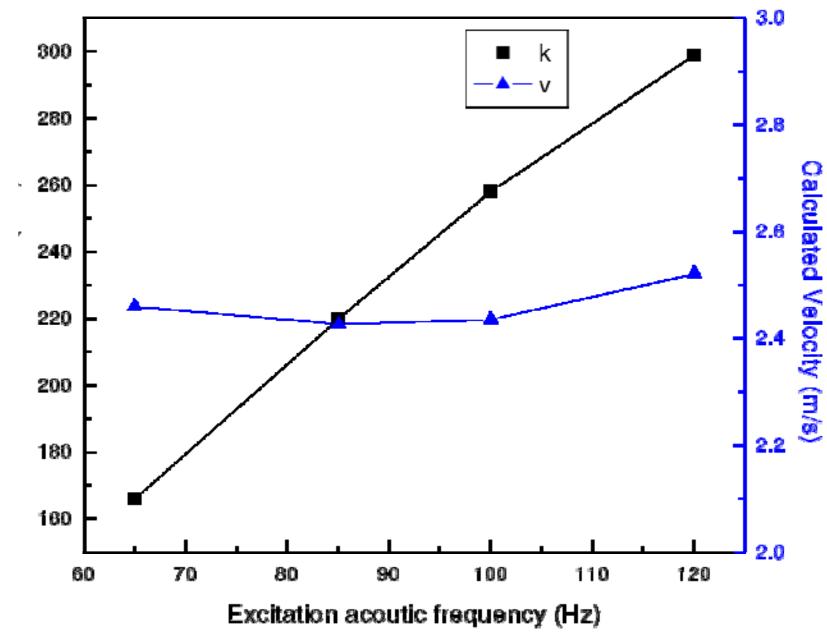
- A. S. Almgren, J. B. Bell, P. Colella, L. H. Howell, and M. L. Welcome, **``A Conservative Adaptive Projection Method for the Variable Density Incompressible Navier-Stokes Equations,''**, *J. Comp. Phys.*, **142**, pp. 1-46, 1998.

Vortex Behavior

- The Rayleigh Index through a line running between the vortex cores is extracted and a curve fit is applied



Rayleigh Index along the structure, 100Hz

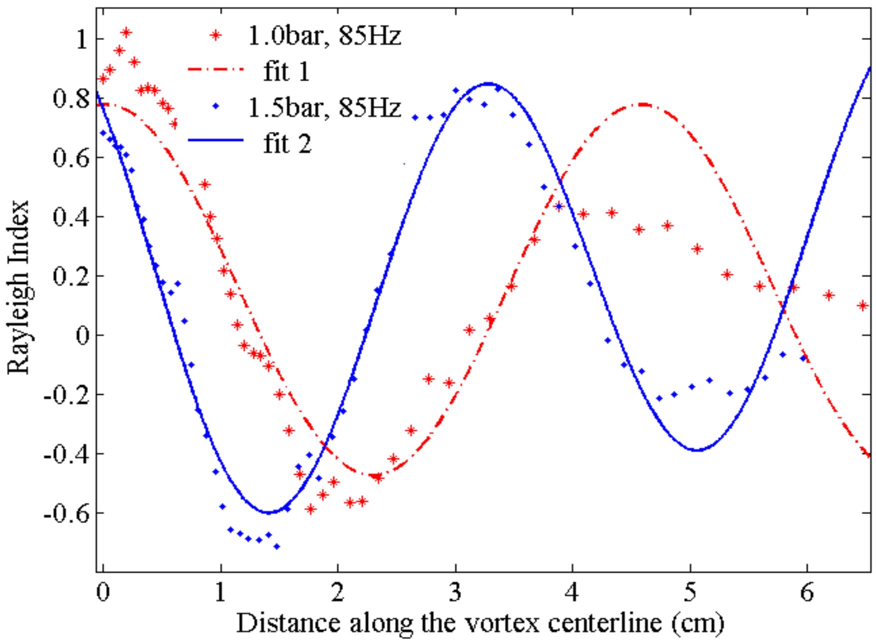


Wave number and calculated velocity

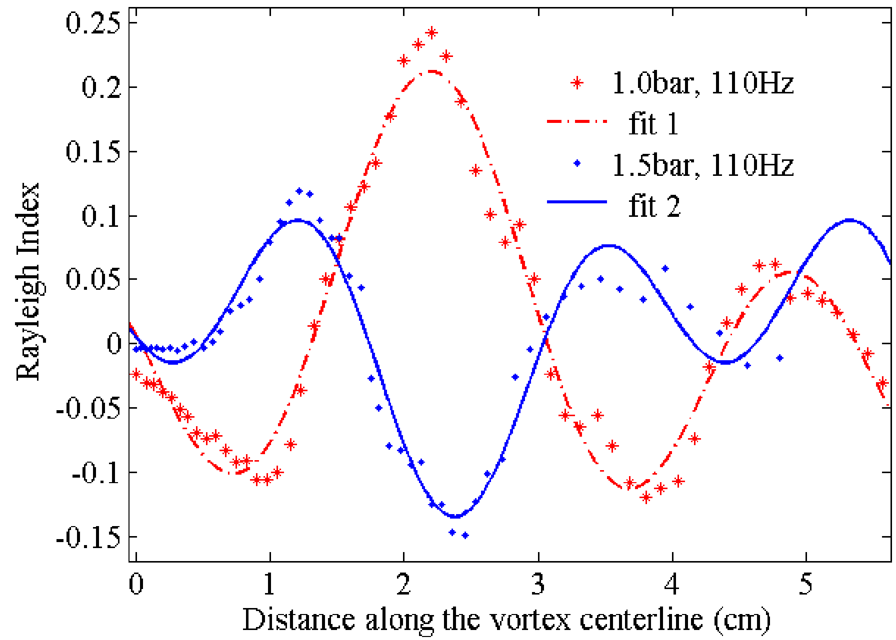
$$\boldsymbol{k} = {2\pi}/{\lambda} = 258$$ ---Wave number

$$v = {2\pi f}/{k} = 2.43 m/s$$ ---comparable with the fluid velocity

Sensitivity to Swirl Number



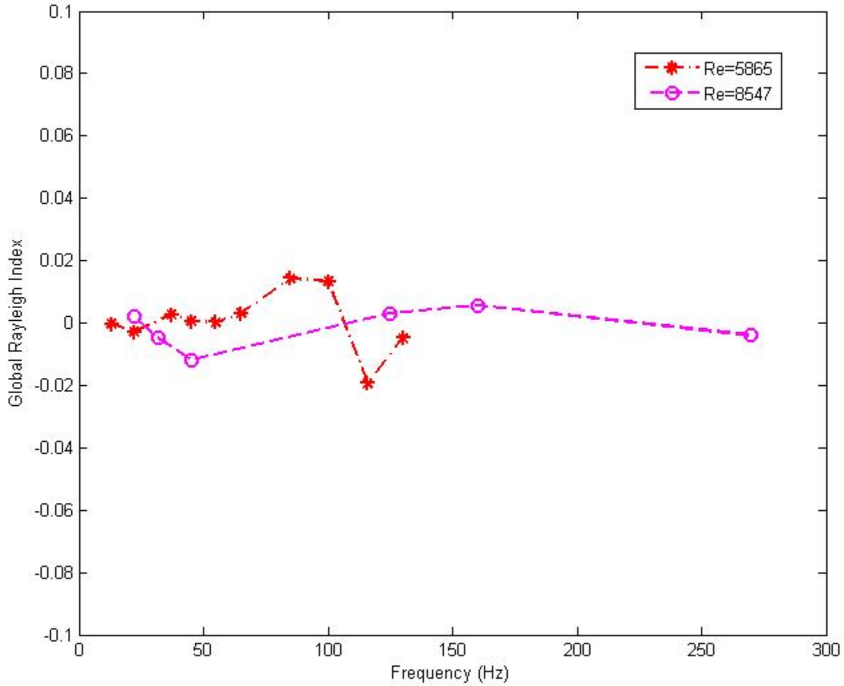
Flame with swirl number of 0.5



Flame with swirl number of 0.2

Neither swirl number nor pressure change have a significant impact on the coupling evident in these low swirl flames

Net Global Rayleigh Index



- Although there are local negative positive regions, the global Rayleigh index is close to zero
- Similar phenomena is observed for the other pressures tested
- The increase of pressure does affect the coupling but not significant difference observed yet

Coupling Range

- How to predict the coupling?
  - Can you easily tie the shear layer instability to jet instability or behavior?
- Are Reynolds number and Strouhal number analyses useful?

$$Re = UD\rho/\mu$$

$$St = fD/U$$

U is the inlet velocity

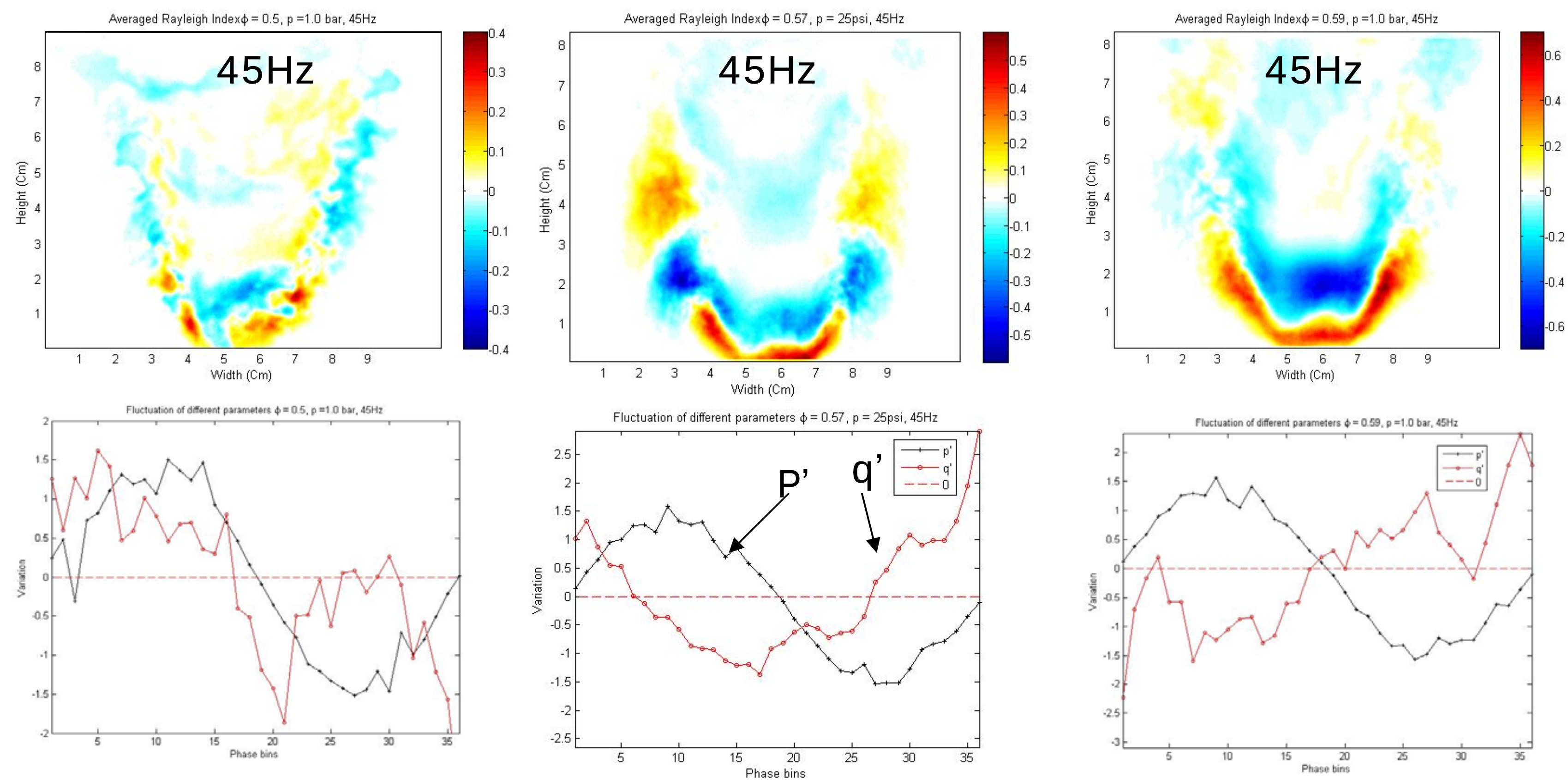
D is the burner diameter

f is excitation frequency

μ is the dynamic viscosity of the reactants

- Re = 5562 (1bar), *f*: 55-120Hz, St: 0.27-0.87
- Re =7376 (1.8bar), *f*:22-140Hz, St: 0.23-1.49
- Re = 8547 (1bar), *f*: 22(tested), St: 0.11

Coupling range study

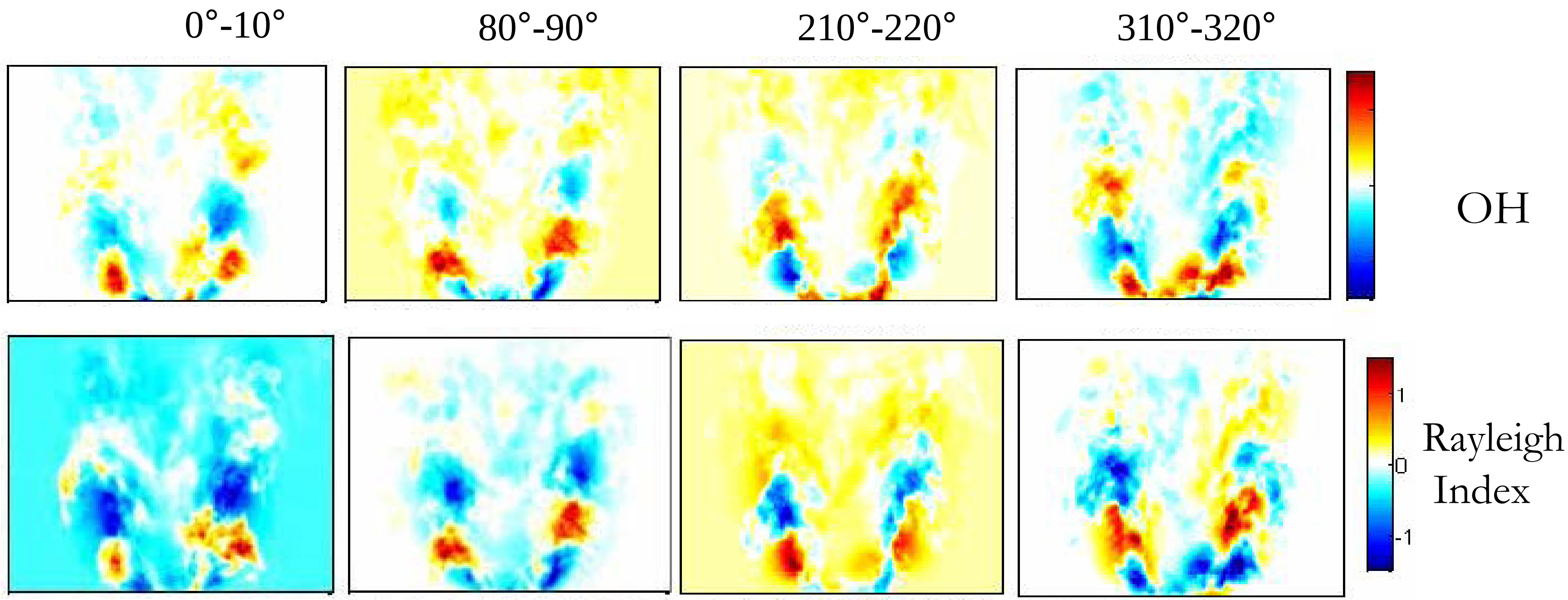


Re=5865
U=3.5 m/s
St= 0.32

Re=7040
U= 2.05 m/s (4.18 m/s at 1 bar)
St=0.50

Re=8547
U=5.18 m/s
St= 0.20

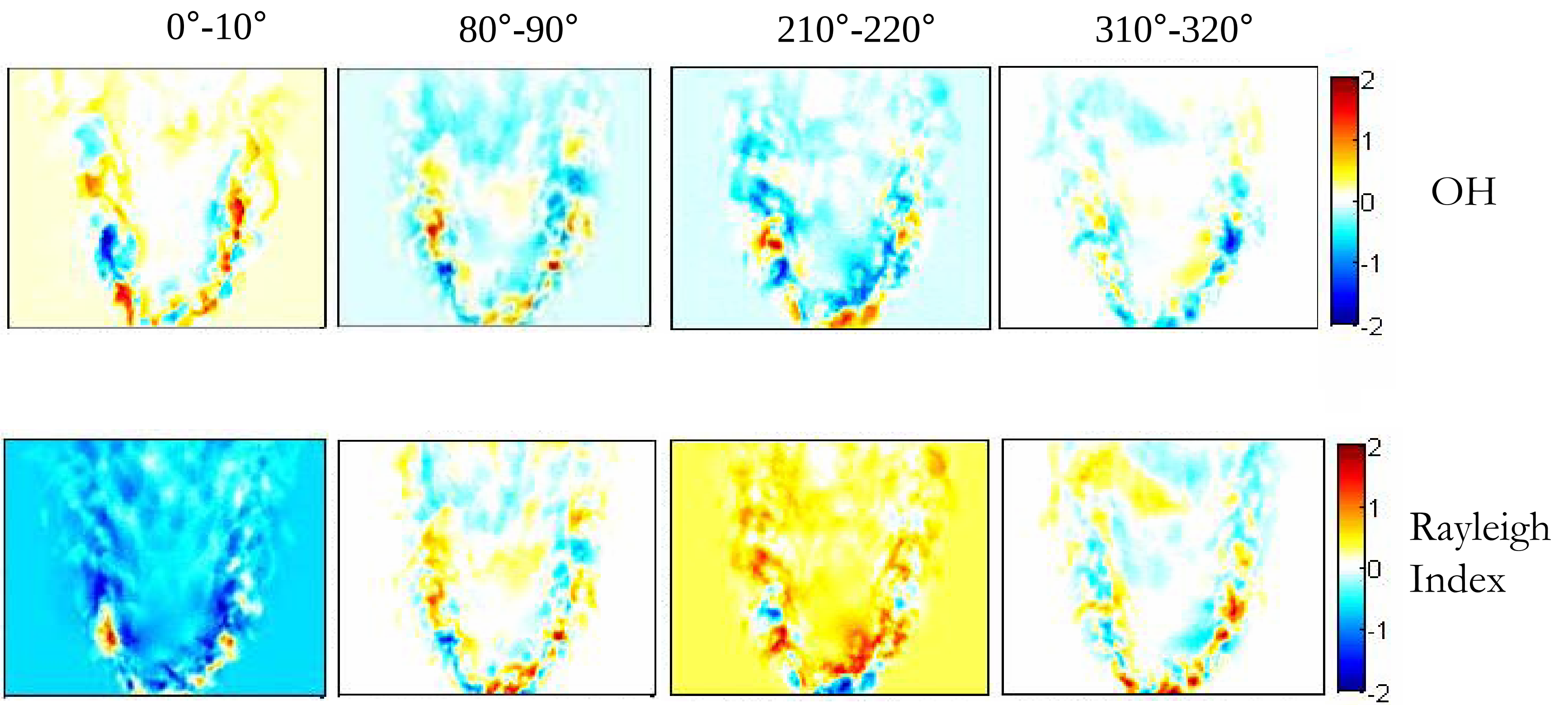
Rayleigh Index Exploration



f=116Hz, Re=7040

- OH concentration changes in a cycle
- Raleigh Index distribution doesn't change much in a cycle.

Comparison of Unstructured Flow



f=22Hz, Re=7040

- When the acoustics perturbation and the shear layer are not coupled, there is no clear structures from OH and Rayleigh index.