Prediction of Combustion Stability and Flashback in Turbines with High- Hydrogen Fuel

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Motivation

- ***Need:*** Gas turbines with sufficient flexibility to cleanly and efficiently combust high H_2 fuels.
- ***Need:*** Combustion systems that can stably operate over a wide turndown range.
- ***Problem*:** Combustion instabilities have posed one of most significant issues encountered in low NOx gas turbines.

→ **Fuel variability poses significant challenges in developing stable combustors**

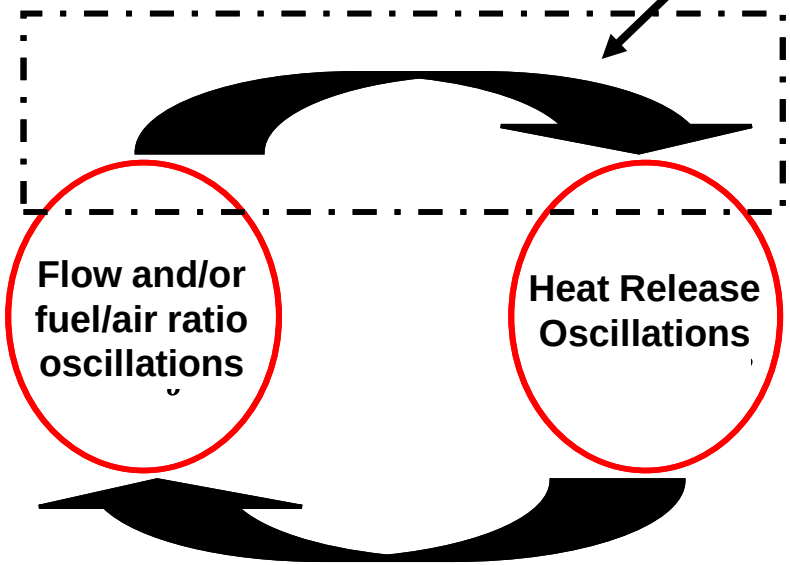
Objective and Approach

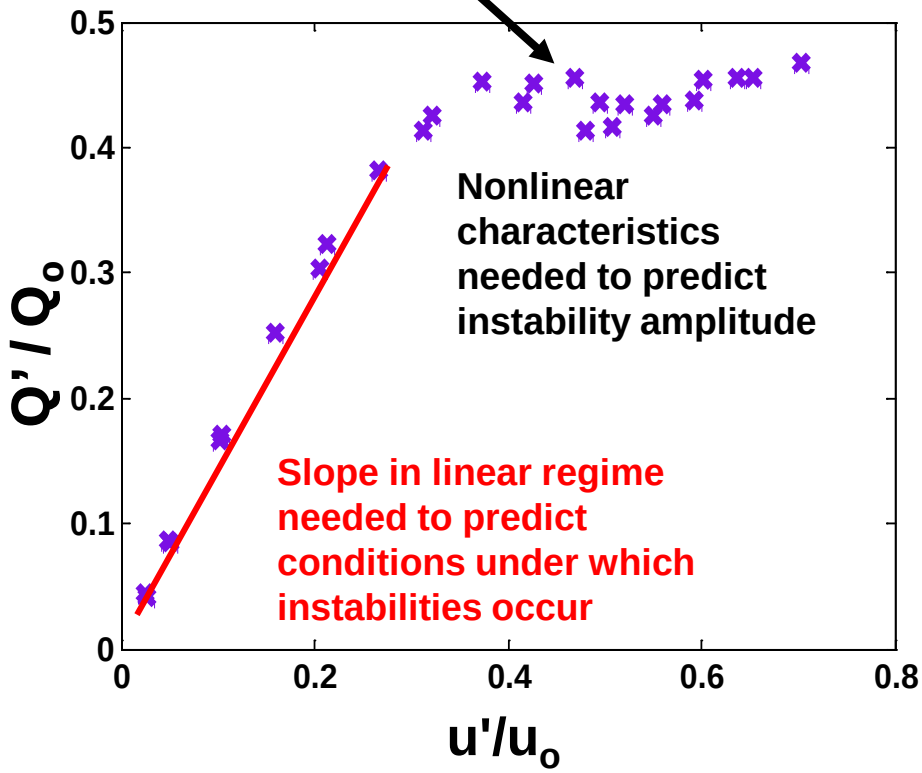
- **Objective:** Improve understanding of combustion dynamics in high H_2 fueled turbines

- **Approach:** Parallel theoretical, experimental and computational investigations of
  - Flame response to fuel/air ratio and velocity oscillations
  - Understand phenomenology and how it is influenced by fuel composition

Research Objective

Key unsolved problem;
Very nonlinear relationship





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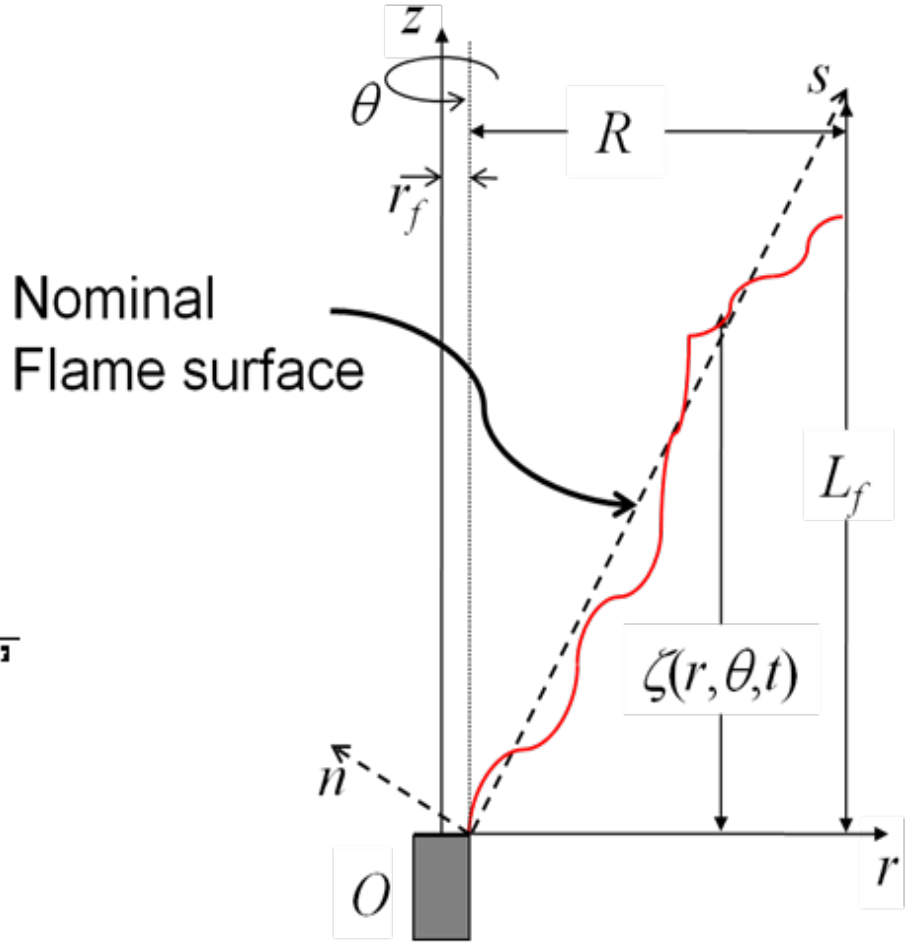
Turbulent Flame Response to Flow Perturbations

Theoretical Framework

- Extensive prior work using level set based formulations to rigorously analyze laminar flame response to flow oscillations
  - Current implementations assume that this can be generalized to turbulent flames by replacing S_L by S_T
- Study objective: Perform perturbation analysis of turbulent flame response to flow oscillations
- Approach:
  - Consider flame response to superposition of broadband (turbulent) and narrowband flow oscillations

$$\frac{\partial \zeta}{\partial t} + \frac{u_\theta}{r}\frac{\partial \zeta}{\partial \theta} + u\frac{\partial \zeta}{\partial r} - v = -s_L\sqrt{1 + \frac{1}{r^2}\left(\frac{\partial \zeta}{\partial \theta}\right)^2 + \left(\frac{\partial \zeta}{\partial r}\right)^2}$$

- Using asymptotic expansions to find solutions
  - System of stochastic PDEs for the instantaneous flame shape.



Theoretical Framework

- Asymptotic expansion

$$\zeta(r,t)=\left[\zeta_o(r)+\varepsilon_T\zeta_{1t}(r,t)+\varepsilon_T^2\zeta_{2t}(r,t)+O\left(\varepsilon_T^3\right)\right]$$
$$+\varepsilon_a\left[\zeta_{1c}(r,t)+\varepsilon_T\zeta_{2ct}(r,t)+\varepsilon_T^2\zeta_{3ctt}(r,t)+O\left(\varepsilon_T^3\right)\right]+O\left(\varepsilon_a^2\right)$$

- Typical PDE for coefficients

$$\frac{\partial\zeta_{1t}}{\partial t}+\cos\gamma\sin\gamma\frac{\partial\zeta_{1t}}{\partial r}=\frac{f_n\left(r,\theta,z=\left(r-r_f\right)\cot\gamma,t\right)}{\sin\gamma}$$

Advection along flame

Local source (turbulence)

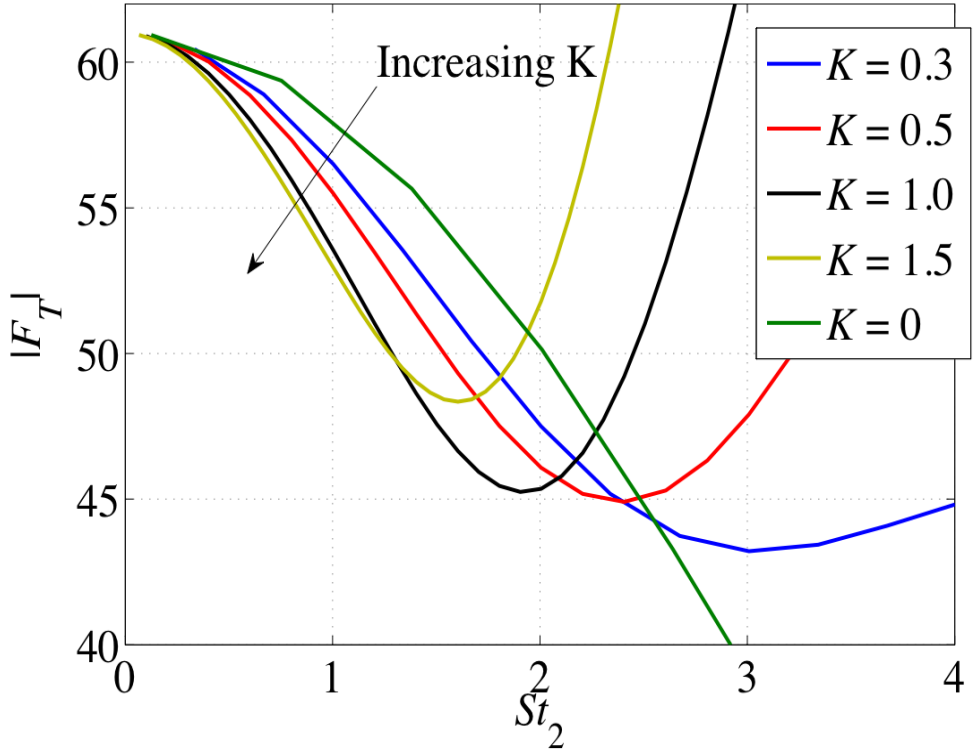
→ Flame surface response is non-local

Heat release response

- Transfer function

$$F(St) = F_L(St) + F_T(St)\,\varepsilon_T^2$$

- Turbulence correction
  - Non-zero
  - decreases with increasing frequency



Ensemble averaged flame response different from laminar response – “Kinematic coupling”

Analysis of Relationship Between Chemiluminescence and Heat Release in Oscillating Flames

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Relationship between Chemiluminescence and Heat Release

- Chemiluminescence routinely used as indirect indicator of unsteady heat release
  - However, also sensitive to strain, fuel/air ratio, etc.
  - Fuel/air ratio oscillations important mechanism for perturbing heat release

- Research question: What is relationship between chemiluminescence and heat release in flow with oscillating fuel/air ratio?

Analysis Results

- Chemiluminescence transfer function

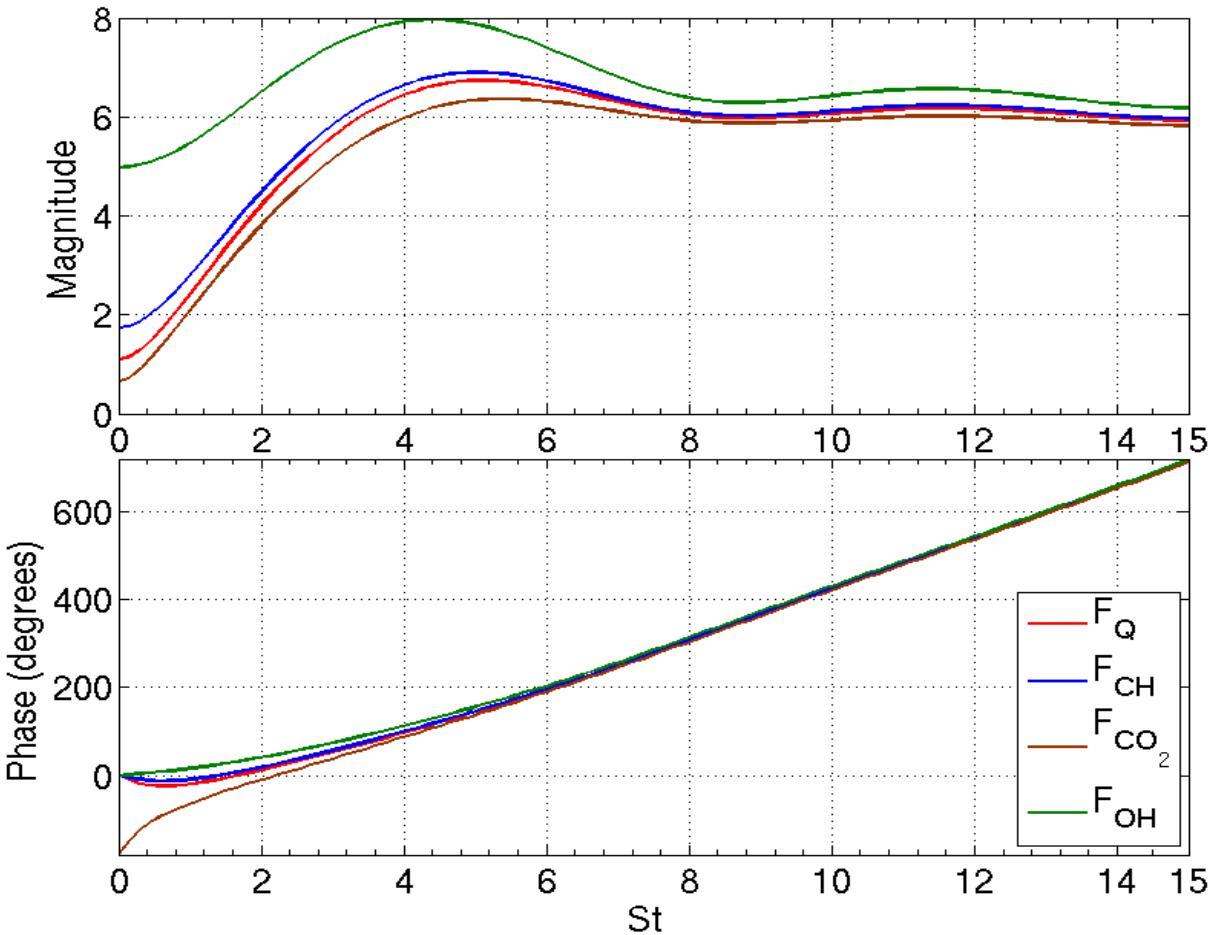
$$F_{CH*} = F_A + mF_{\phi_{eff}}$$

- Heat Release transfer function

$$F_Q = F_A + \left(s_{L1} + h_{R1}\right) F_{\phi,eff}$$

  - where
    - s_{L1} = normalized flame speed sensitivity to equivalence ratio fluctuations
    - h_{R1} = normalized heat of reaction sensitivity to equivalence ratio fluctuations

Comparisons between OH*, CH*, CO2*, and Heat Release



Axisymmetric V-Flame, half-angle = 14 deg., ϕ_o=0.6

- Heat release and chemiluminescence responses **very similar** at all but low Strouhal numbers
- Different species yield qualitatively similar trends, but there are differences

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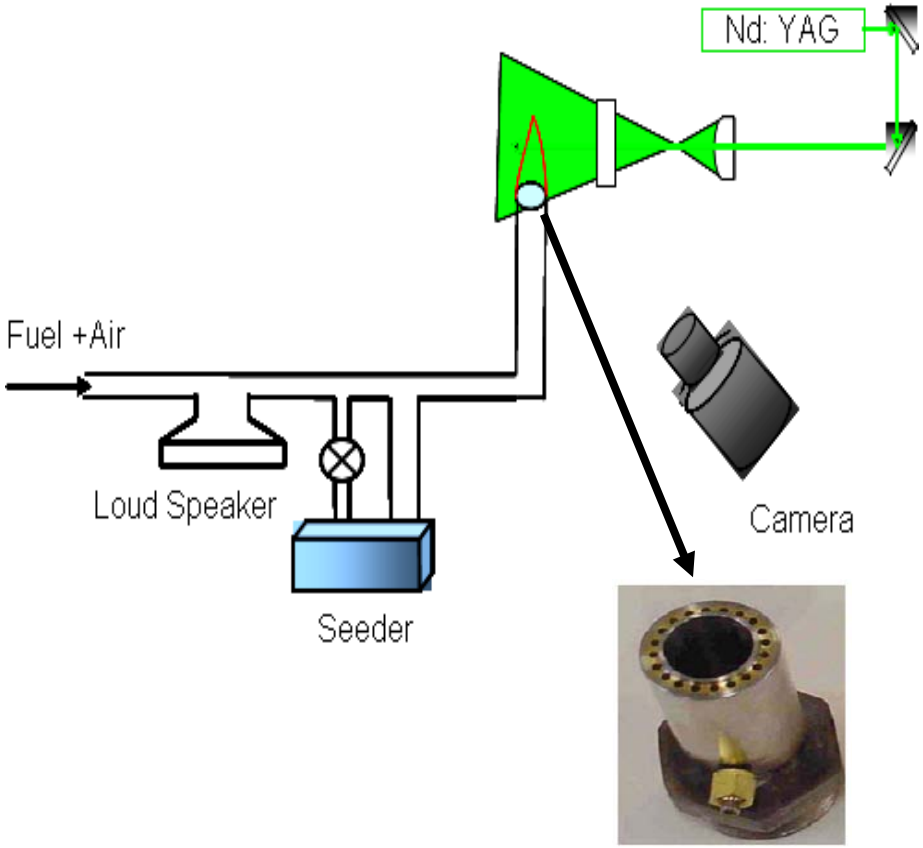
Interactions between Harmonic Excitation and Turbulence

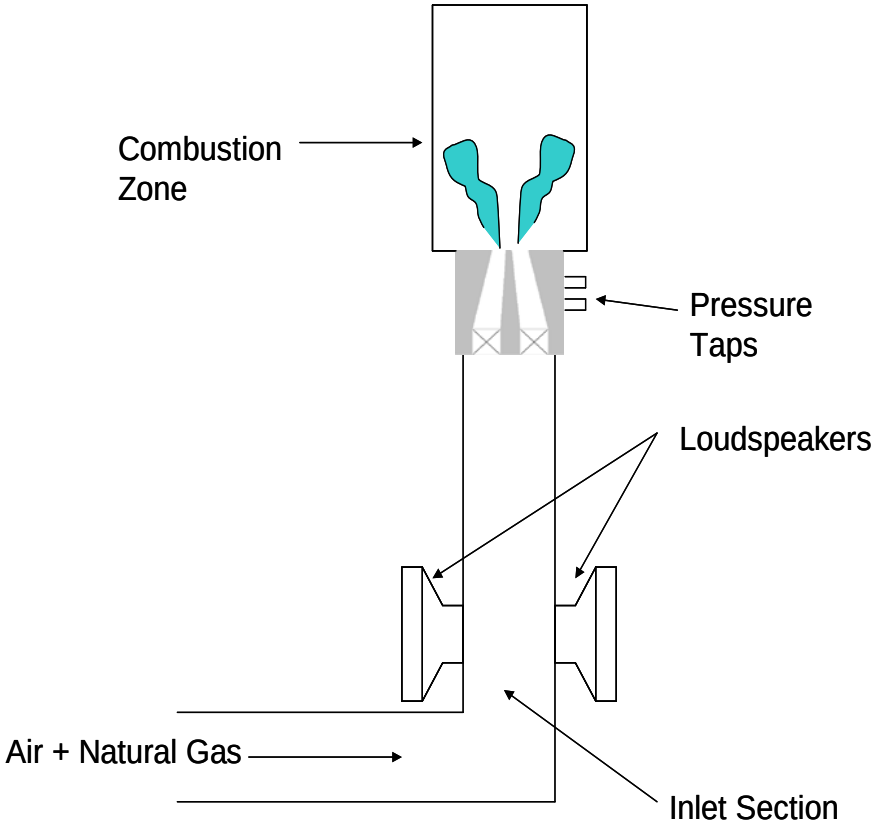
Background

- Flames being simultaneously disturbed by narrowband harmonic excitation, and broadband turbulent fluctuations

- Research Question: Do baseline turbulence characteristics (e.g., S_T, flame brush thickness, u') change in the presence of harmonic excitation?

EXPERIMENTAL FACILITIES





- **Pilot stabilized axisymmetric Bunsen flame**
- **Mie scattering**

- **Swirl stabilized burner with centerbody**
- **OH PLIF**

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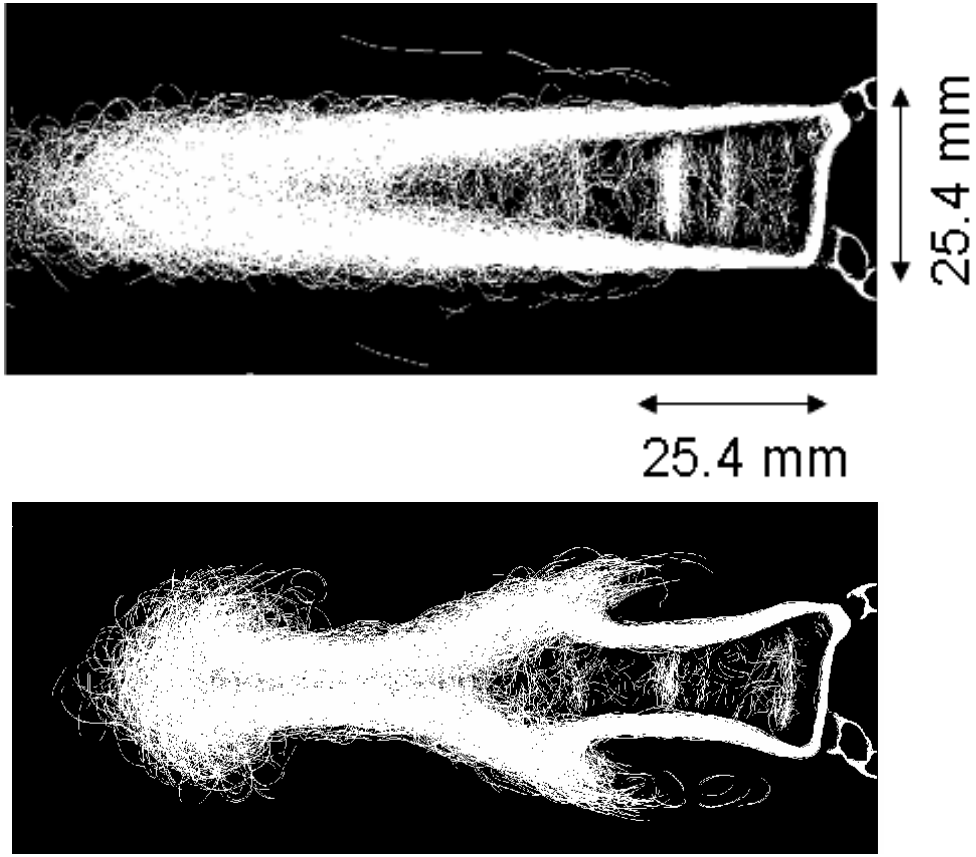
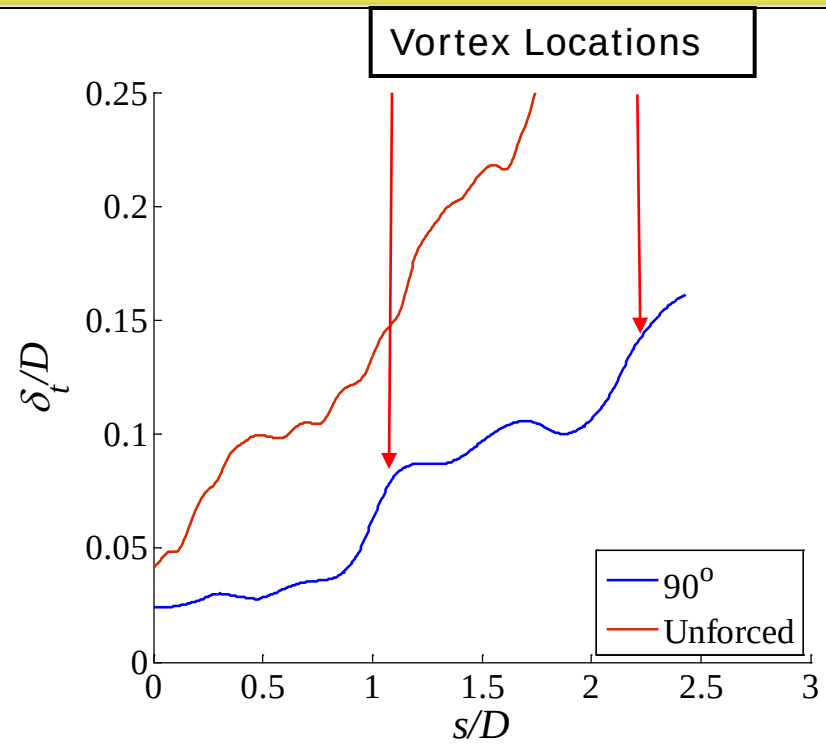
Results -Acoustically forced Bunsen flame

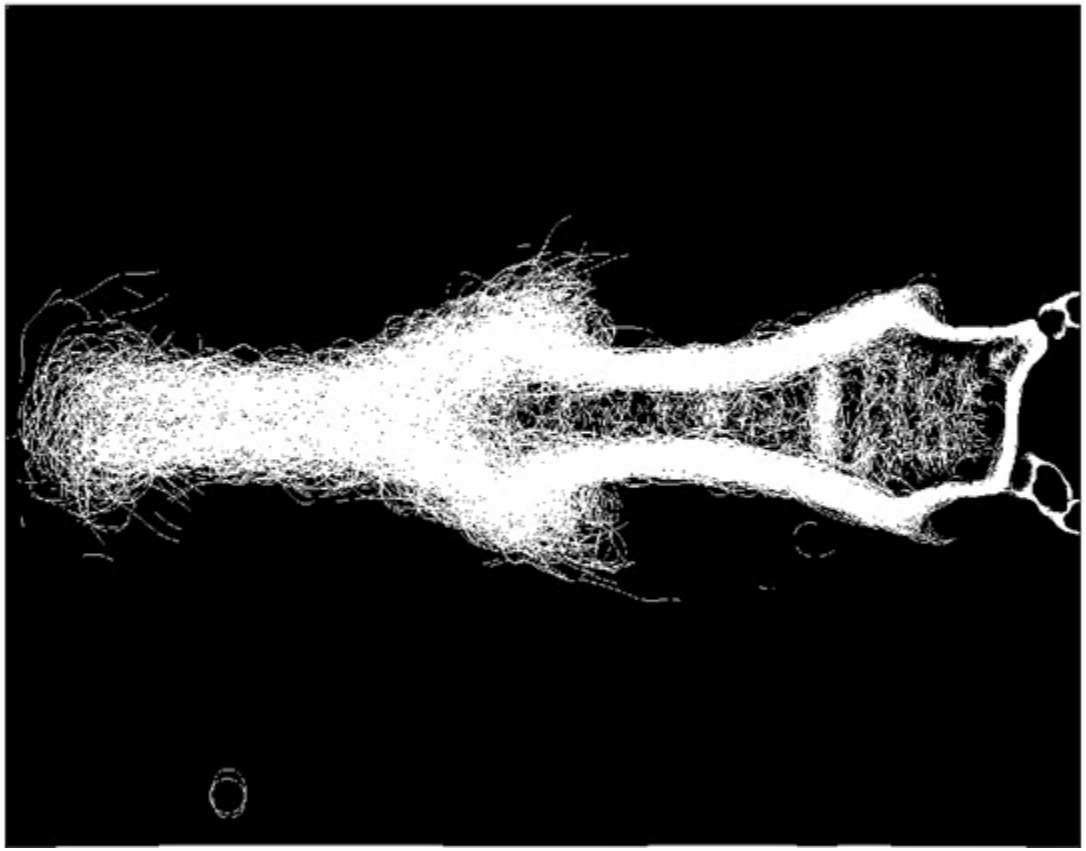


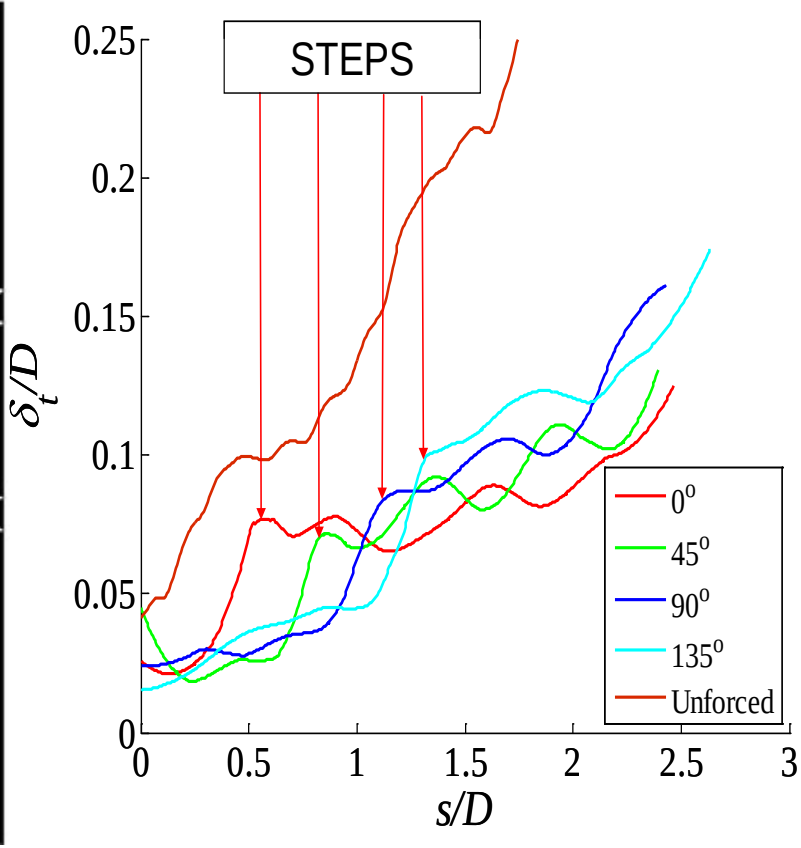


Re =10,200, u'/uo =0.2

- Two behaviors exhibited by flame brush:
  - Slow growth relative to unforced case
  - Rapid growth across convecting vortex

Results - Acoustically forced Bunsen flame





Re =10,200, u'/u_o= 0.2

- Very slow growth relative to unforced case
- Step like increases across vortical structures

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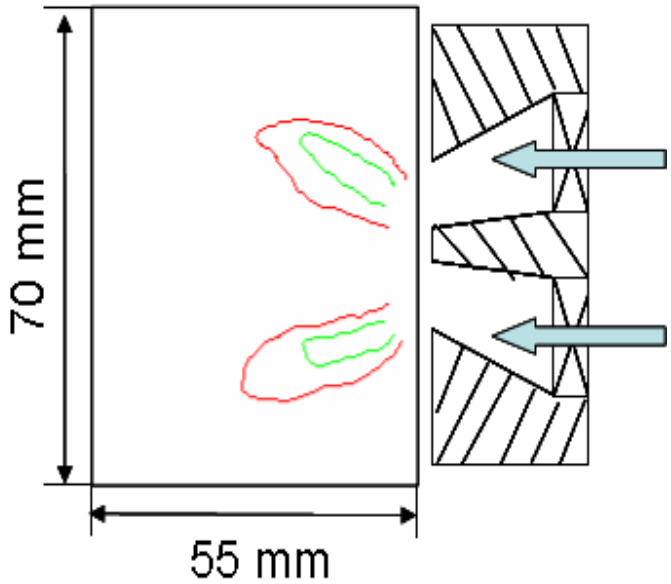
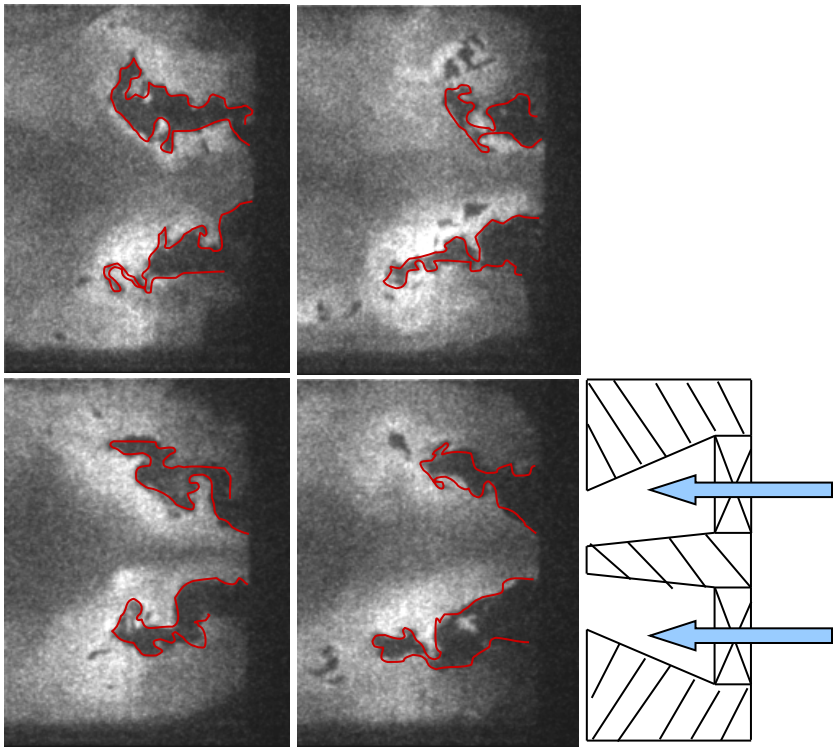
Results – Swirl flames

Re =21,000 (Unforced)



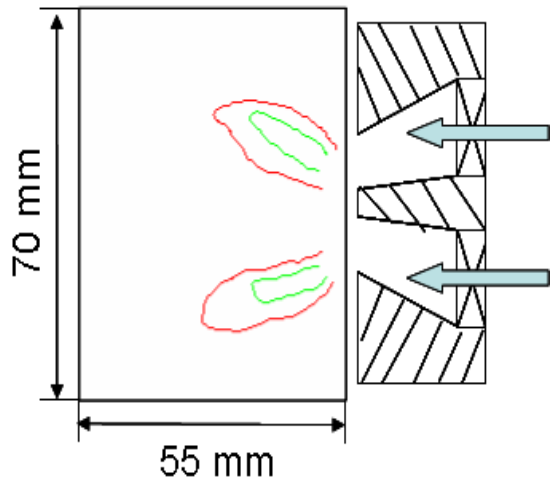


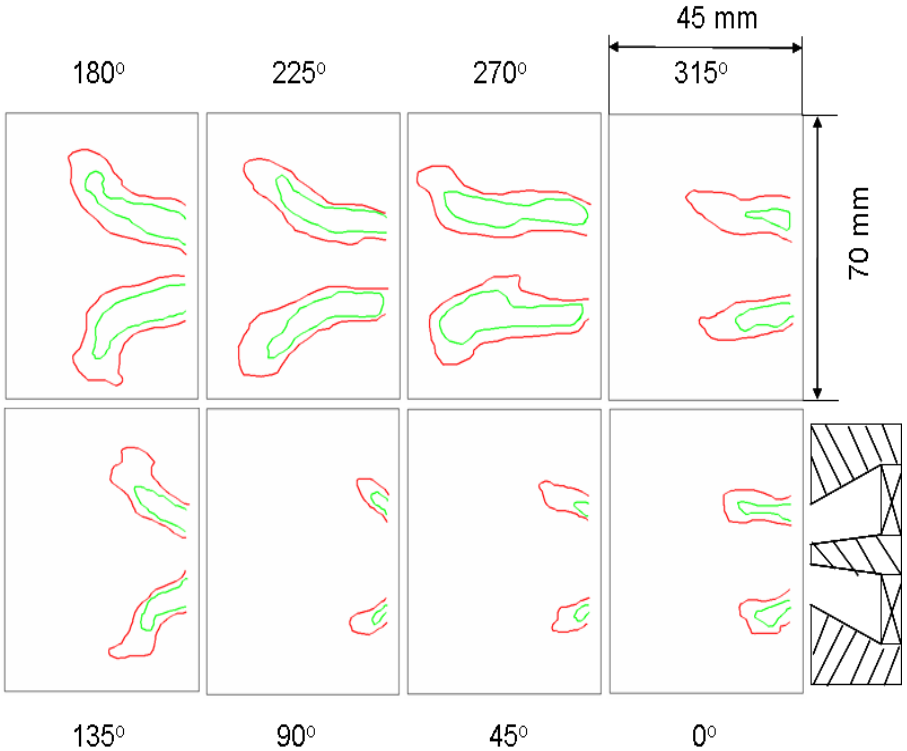
Progress variable contours

Instantaneous OH PLIF images

- Gradual growth in flame brush thickness

Results –Swirl flames





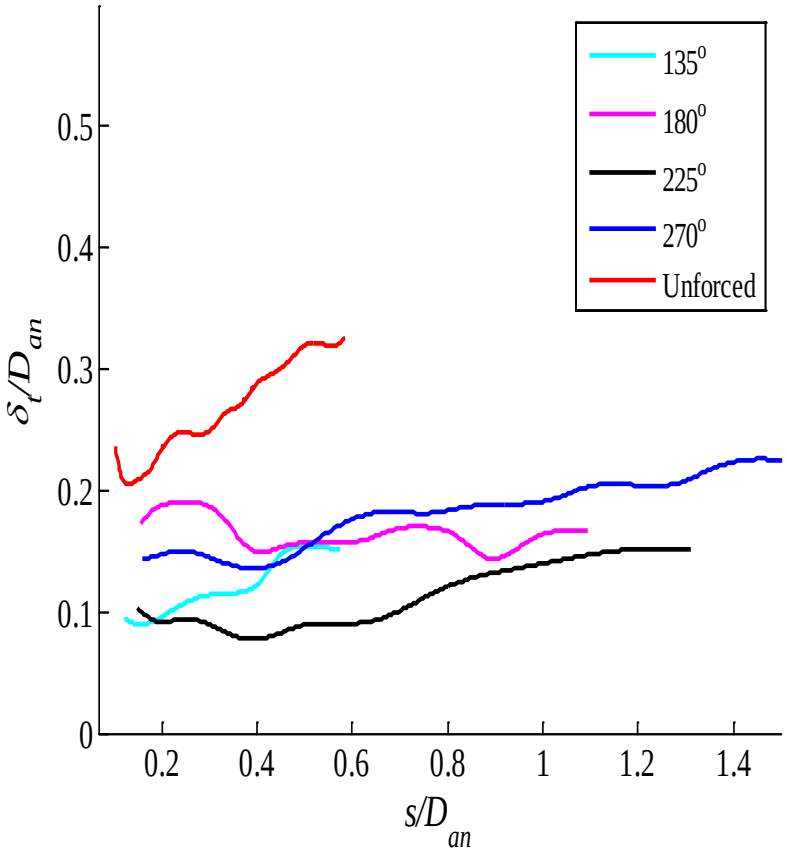
Re =21,000 (Unforced)

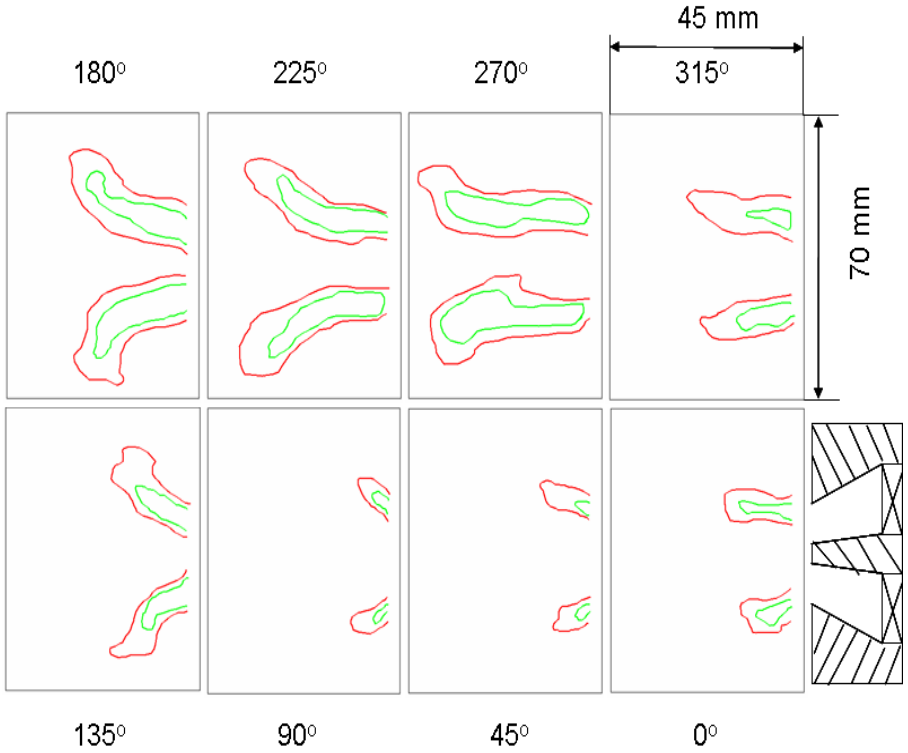
Re =21,000, f= 130 Hz, u'/u_o = 0.6

- Gradual growth in flame brush thickness

- Modulations in flame length.

Results – Acoustically Forced Swirl flame





- Re =21,000, f= 130 Hz, u'/u_o = 0.6

- Flame brush growth suppressed/inhibited in forced case

- Modulations in flame length.

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Comments

- Turbulent flame dynamics clearly altered by harmonic forcing
  - Flame brush growth suppressed, exhibits “step like” behavior
  - Believed to be associated with oscillating, coherent flame stretching associated with convecting vortical structures.

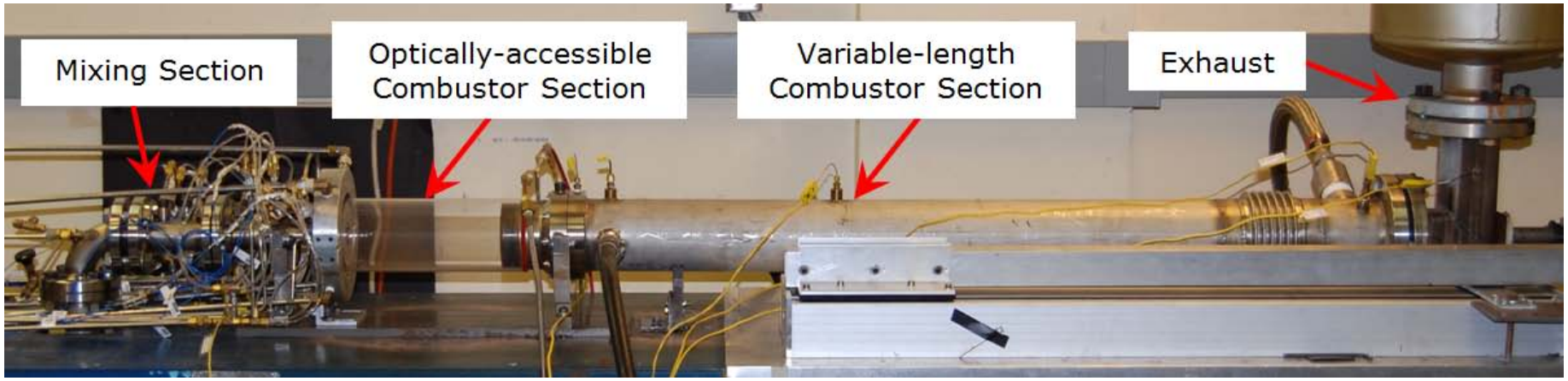
Flame Transfer Function Measurements

- **Forced response to velocity perturbations: premixed flame response**
  - Steady-state flame structures
  - Linear and nonlinear dynamics
  - Effects of hydrogen enrichment

- **Forced response to equivalence ratio perturbations: partially premixed flame response with fuel modulation**

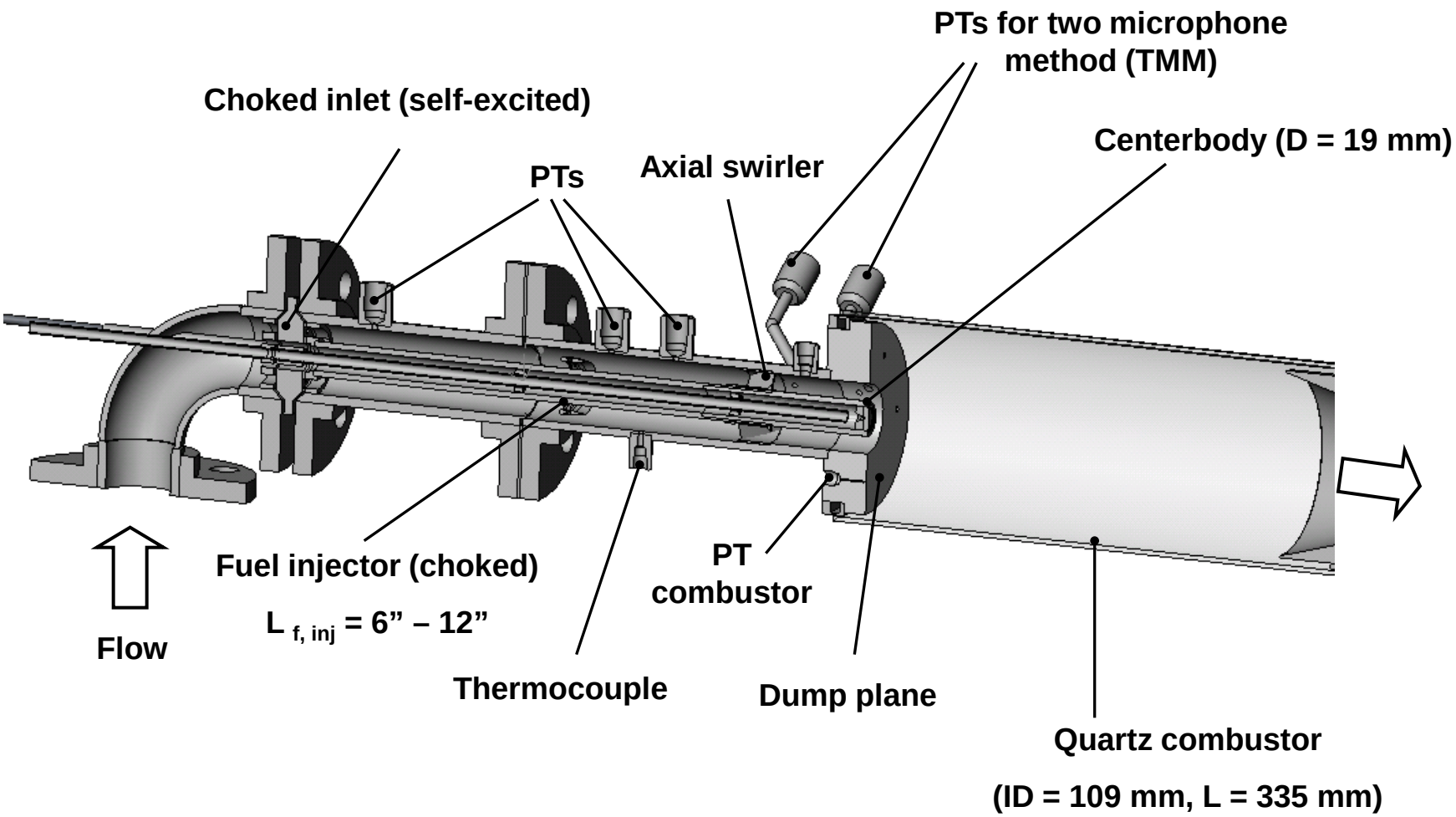
- **Forced response to V' and Φ': partially premixed flame response with air modulation**

Swirl Stabilized Lean Premixed Dump Combustor



- **Variable location fuel-injection**
- **Optically-accessible combustor**
- **Variable-length combustor**

Variable Location Fuel Injection



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Measurements

- **Dynamic pressure measurements**
  - Several locations in the mixing section and the combustor section
- **Two-microphone method**
  - Inlet velocity fluctuation
  - Calibration by a hot wire anemometer
- **OH*, CH*, CO_2* chemiluminescence intensity measurements**
  - To characterize the temporal fluctuation of the heat release
- **Global CH* (OH*) chemiluminescence imaging**
  - Two dimensional imaging to characterize flame structures
  - 3-point Abel inversion
- **Infrared absorption measurements**
  - Temporal fluctuation of the equivalence ratio at the entrance to the combustor

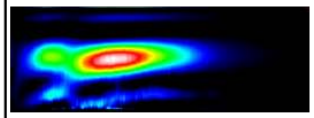
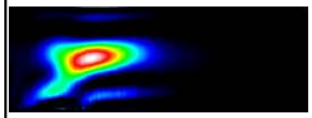
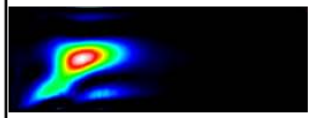
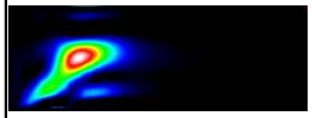
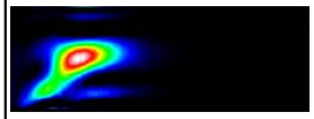
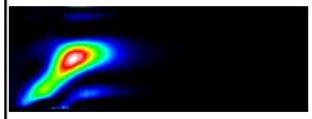
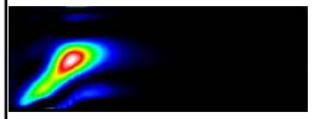
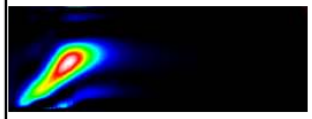
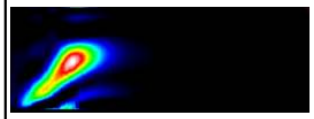
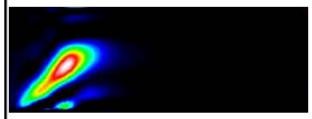
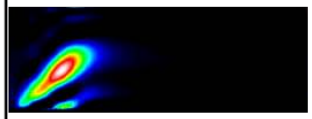
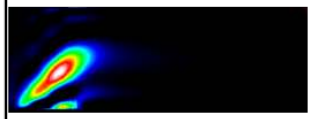
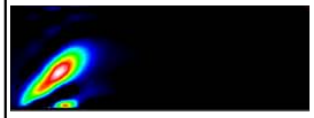
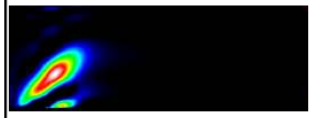
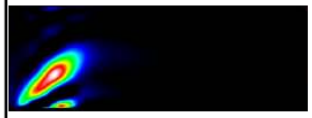
Test Conditions for FTF Measurements

Parameters	Test conditions
pressure	1 atm
inlet temperature	200 °C
nozzle velocity	60, 70, 80, 90, 100 m/s
nozzle fuel split	premixed (PM) and partially premixed (PPM)
equivalence ratio	0.55, 0.60, 0.65, 0.70
fuel composition	8 cases
forcing frequency	100 ~ 400 Hz
forcing amplitude	~ 60%

#	Natural Gas	Hydrogen
1	100%	0%
2	85%	15%
3	70%	30%
4	55%	45%
5	40%	60%
6	25%	75%
7	10%	90%
8	0%	100%

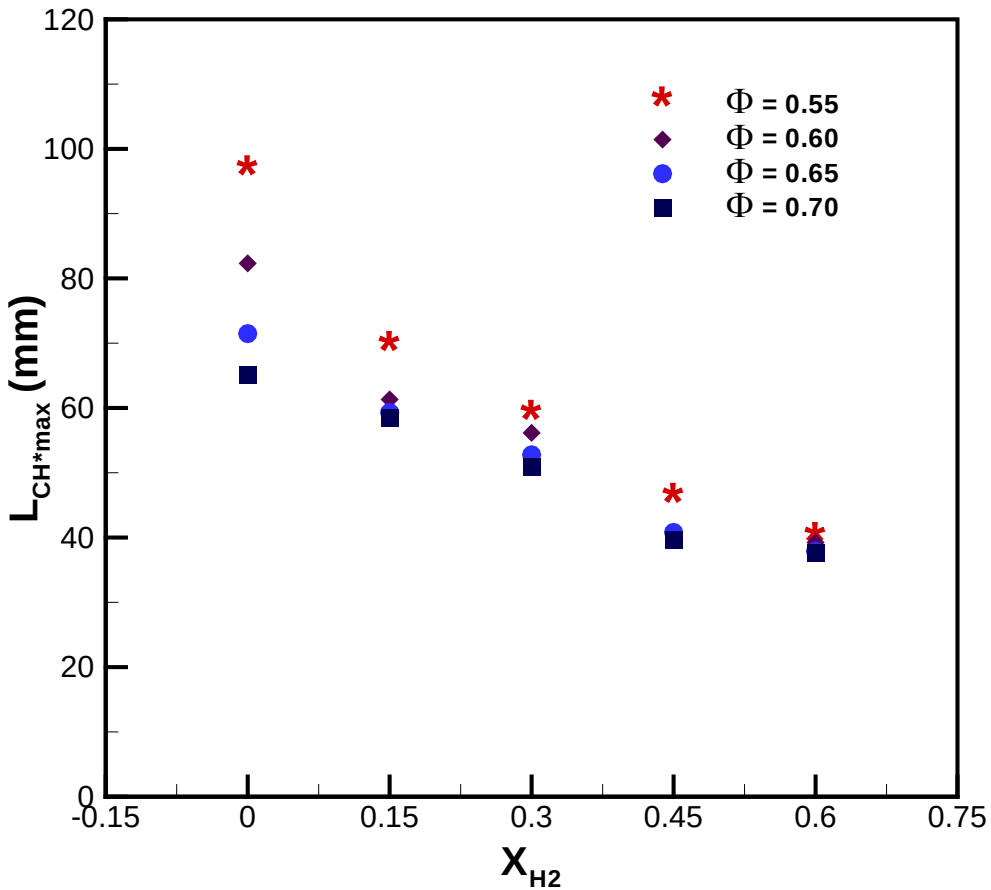
Stable Flame Structure

Inlet conditions: T_{in} = 200 C, V_{in} = 60 m/s

X_{H2} \ Φ	0.55	0.60	0.65	0.70
0.00				
0.15				
0.30				
0.45				
0.60				

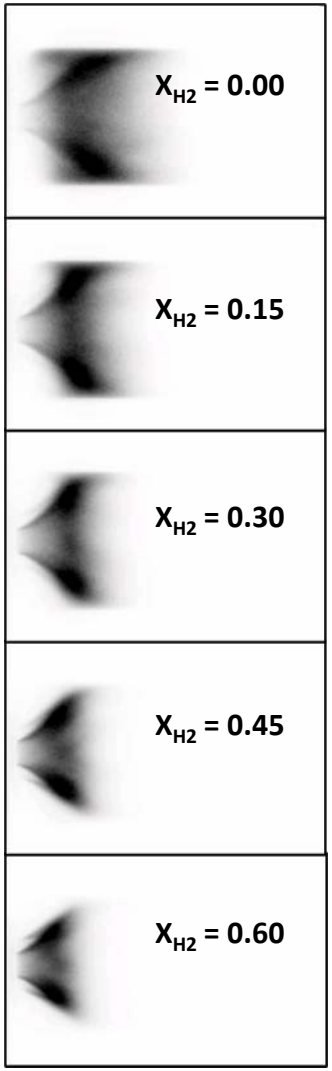
→ Flame length decreases with increasing Φ and X_{H2}

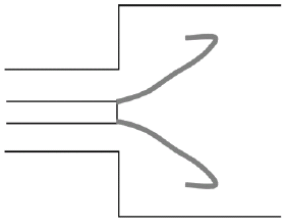
L_{CH^*max} vs. X_{H2}

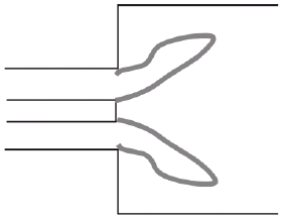


- At X_{H2} = 0.60, the effect of differences in flame speed on changes in flame stabilization locations is relatively negligible.
- Varying the equivalence ratio does not affect changes in the convection time scale.

Bifurcation of Flame Shapes

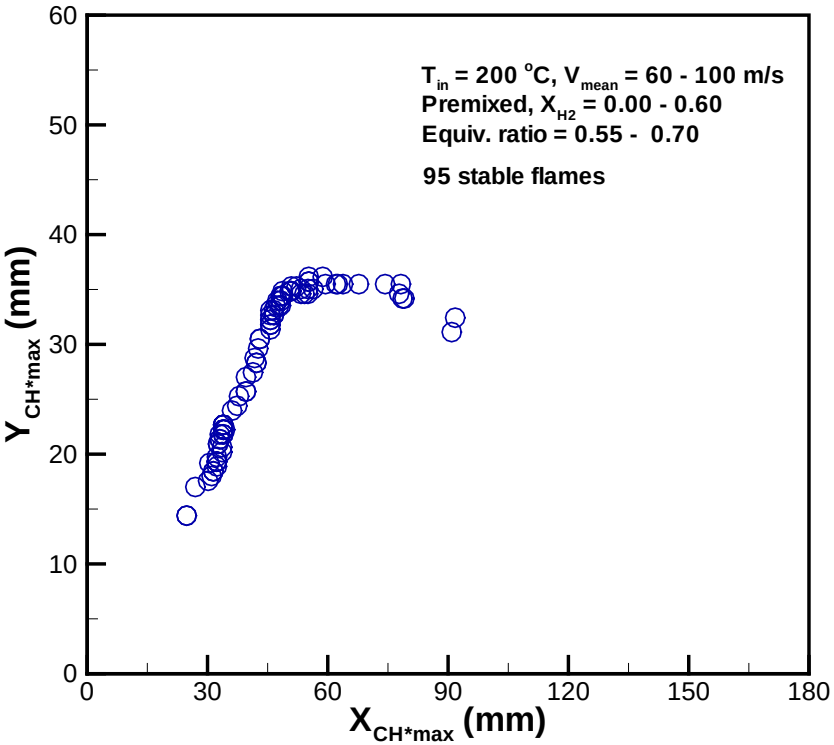


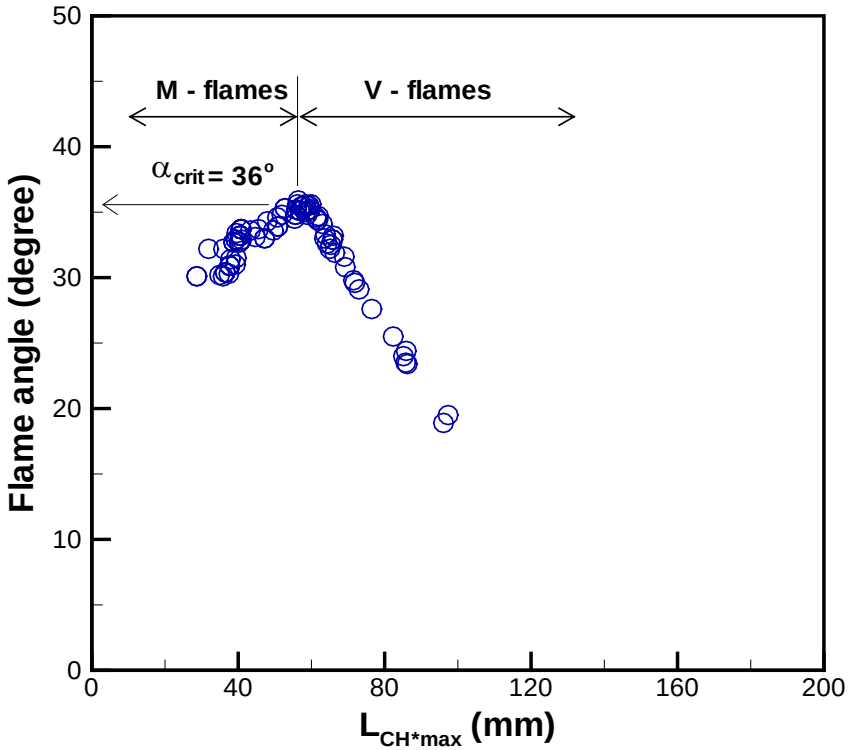




- $X_{H2} < 0.30$: dihedral "V" structure
- $X_{H2} > 0.30$: enveloped "M" structure
- Conical flames: the contribution of the flame tip to fluctuation of the flame area is very small.

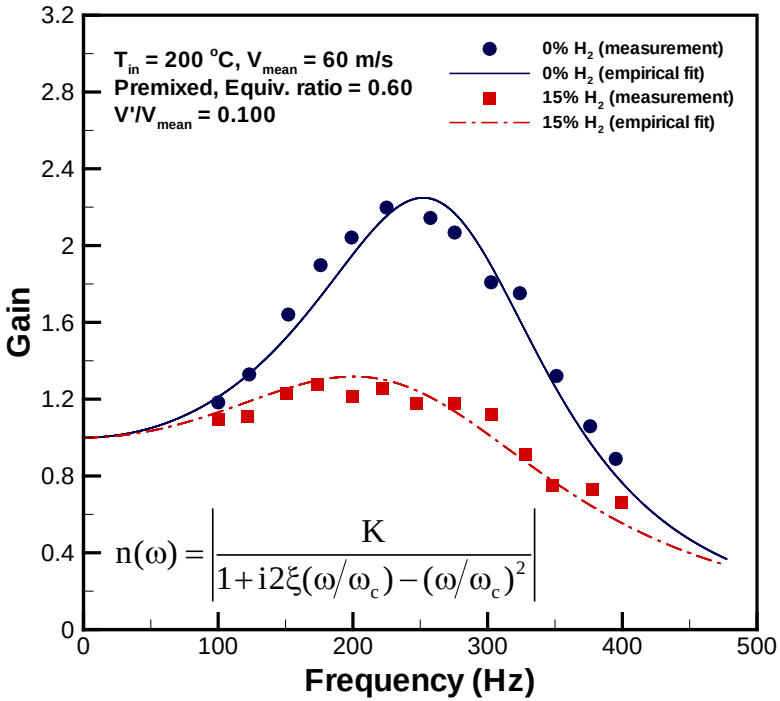
Maximum CH* Intensity Locations

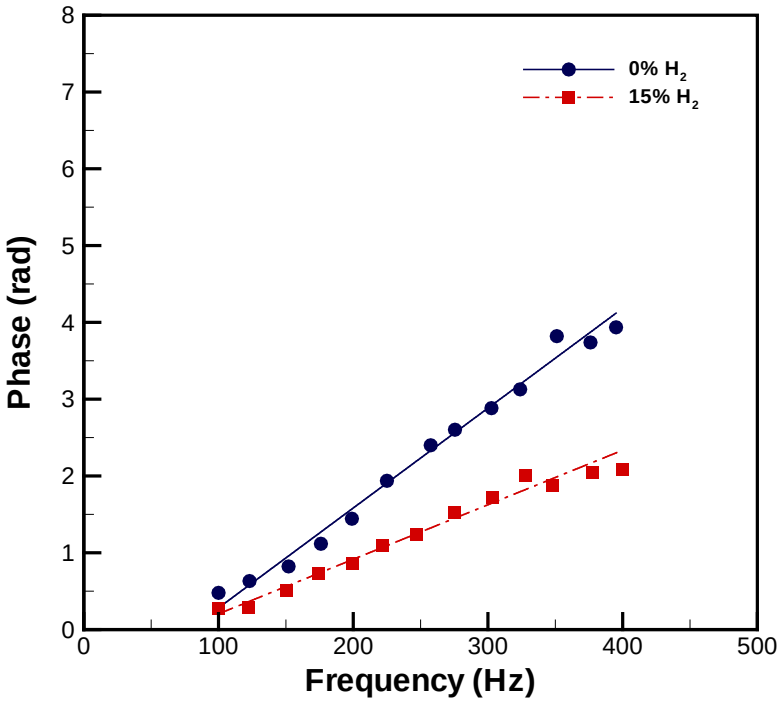




- L_{CH*max} varies along a well-defined curve, as inlet flow conditions change.
- There is a demarcation point between "V" and "M" flames.

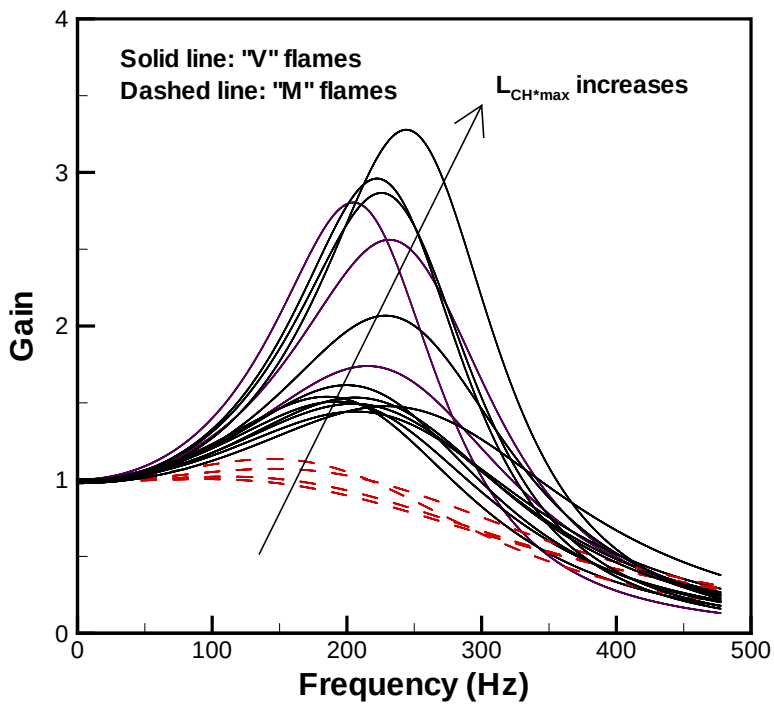
Effect of Fuel Composition

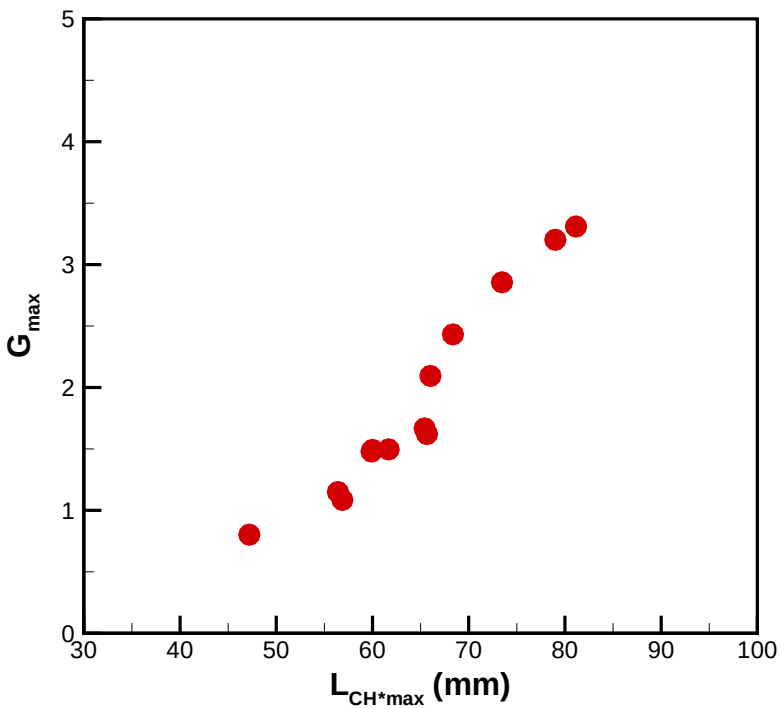




- **The gain and phase decrease with increasing X_{H2} due to decreased flame length.**
- **The gain is well-fitted by a second order oscillator model.**

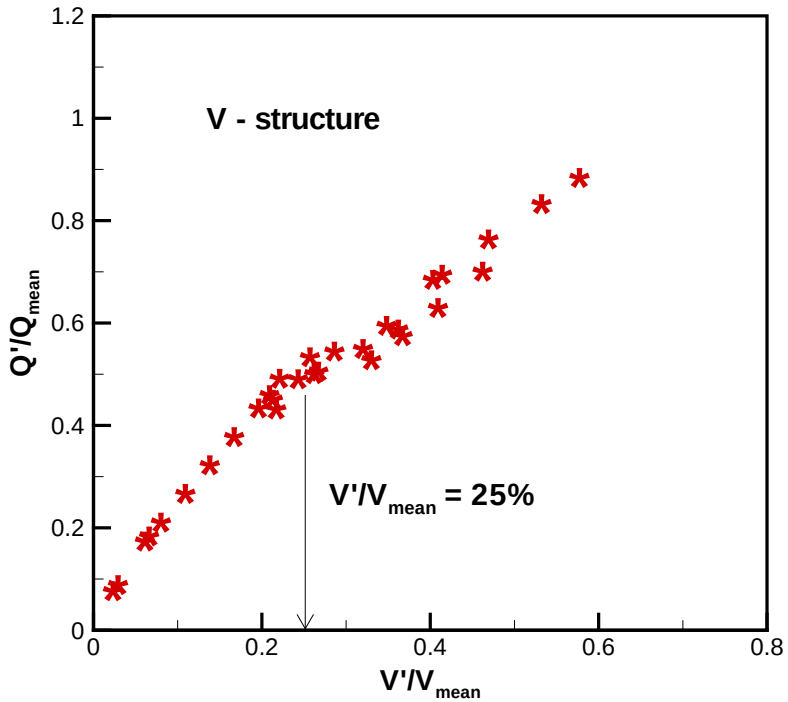
Flame Response: Effect of Flame Length

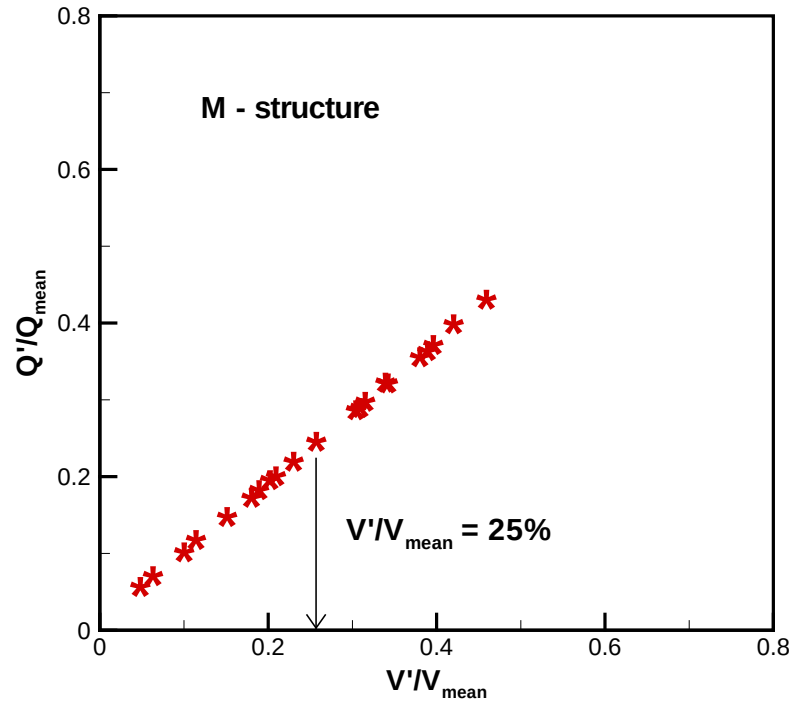




- **The gain of enveloped "M" flames is much smaller than that of "V" flames.**
- **The maximum gain is proportional to flame length.**

Amplitude Dependence

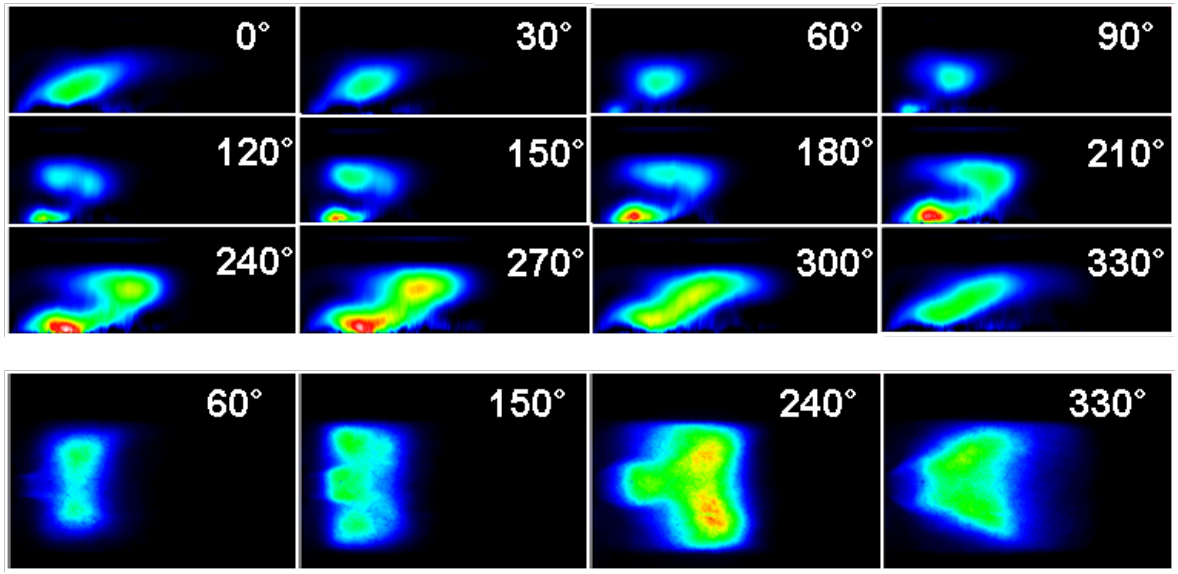




- T_{in} = 200 °C, V_{mean} = 60 m/s, Φ = 0.60, X_{H2} = 0.00, 0.30, f = 200 Hz.
- The response of M flames remains in the linear region, even at high modulation amplitudes.

Nonlinear Dynamics of Dihedral "V" flames

f = 200 Hz, V'/ V_{mean} = 25%



- **The nonlinear dynamics of the natural gas/air premixed flame is governed by the flame-vortex interaction.**

- **The flame front bends toward the inner recirculation zone at φ = 270 .**

Summary – FTF Measurements

- **Effects of hydrogen enrichment:**
  - Hydrogen enrichment results in a decrease in flame response (perfectly premixed).
  - The response of perfectly premixed enveloped "M" flames remains in the linear region, irrespective of shedding of a vortex structure.
  - When hydrogen-enriched flames are perturbed by V' and Φ', however, the nonlinear response was observed and it is related to **local extinction**.

- **Forced response to V perturbations:**
  - The response of perfectly premixed flames is strongly dependent on **stable flame structures**.

Concluding Remarks

- Investigations contributing significantly to quantitative understanding of high H_2 flame response to flow and fuel/air ratio perturbations.

- Strong graduate and undergraduate student involvement contributing to critical future clean energy workforce.

- Strong industrial interactions to ensure relevance and transition
  - Summer internships
  - Bi-weekly telecons