Combustion Dynamics in Multi-Nozzle Combustors Operating on High-Hydrogen Fuels

DOE Project DE-FC26-08NT05054

Start date: October 1, 2008

End date: January 31, 2012

Penn State

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PENN STATE

Center for Advanced Power Generation

Georgia Tech College of Engineering

Daniel Guggenheim School of Aerospace Engineering

Motivation

Actual gas turbine combustors employ multi-nozzle combustors, where both transverse mode and longitudinal mode instabilities have been observed

Our current understanding of combustion dynamics in lean premixed gas turbine systems is primary limited to longitudinal-mode instabilities in single-nozzle combustors operating on natural gas.

To what extent is this understanding relevant to transverse mode instabilities?

To what extent is this understanding relevant to multi-nozzle combustors?

This project builds on our current understanding and extends it to the case of longitudinal and transverse-mode instabilities in multi-nozzle combustors operating on high-hydrogen fuels.

Objectives

1) obtain a phenomenological and quantitative understanding of transverse and longitudinal mode instabilities in lean premixed multi-nozzle combustors operating on high hydrogen, coal derived fuels.

2) use this understanding to develop and validate transverse flame response models and multi-nozzle longitudinal flame response models.

→ The flame response models will be incorporated into thermo-acoustic models for predicting instability frequencies and amplitudes in multi-nozzle combustors

→ Such models are essential tools for preventing or minimizing the incidence of detrimental combustion instabilities in future gas turbines.

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Penn State's focus is on longitudinal oscillations in multi-nozzle can combustor configurations

Georgia Tech's focus is on transverse oscillations in single-nozzle annular combustor configurations

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Center for Advanced Power Generation
Penn State University

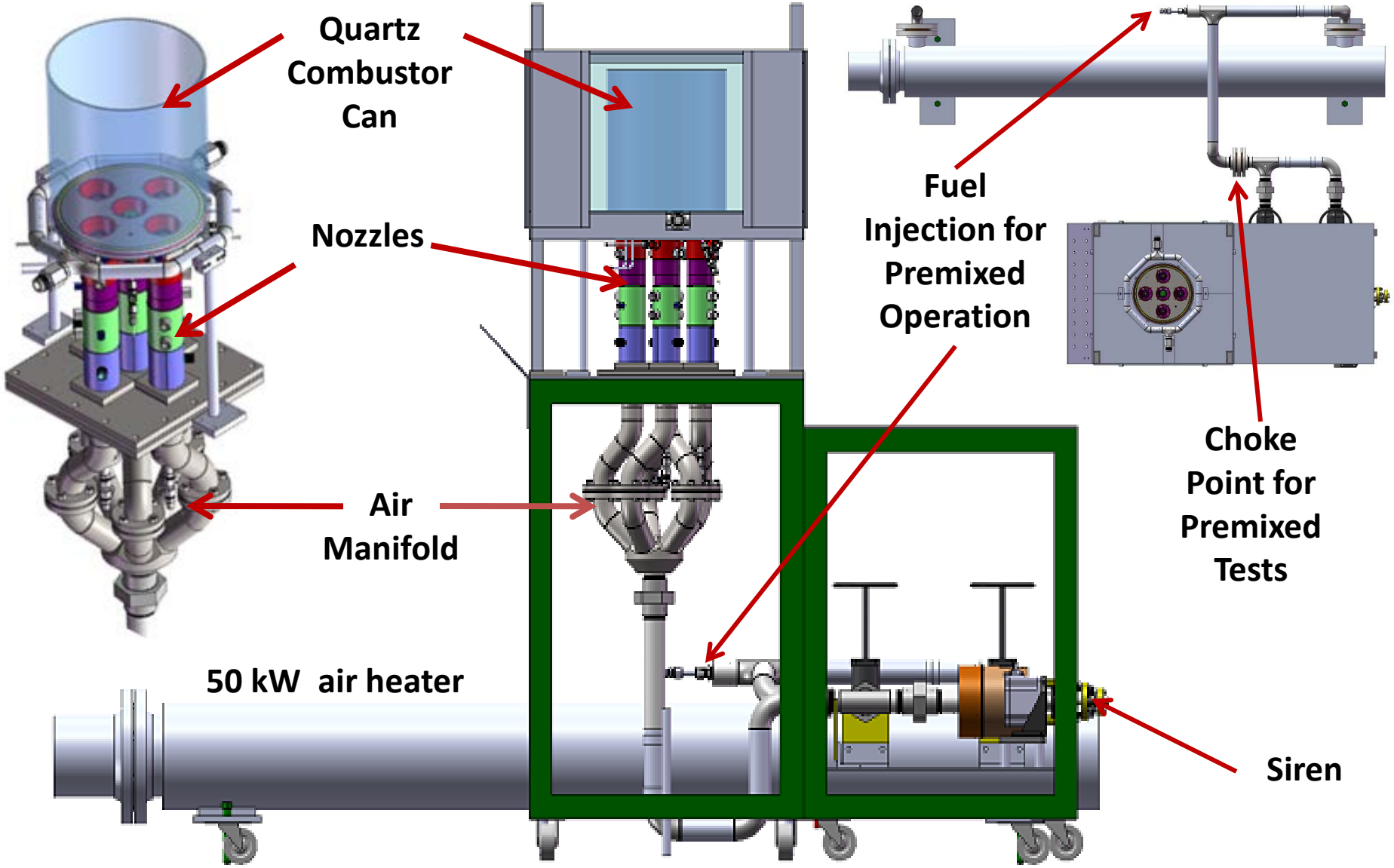
Objectives (PSU)

1) To experimentally determine the air-forced flame transfer function of a multi-nozzle can combustor operating on high hydrogen content fuels.

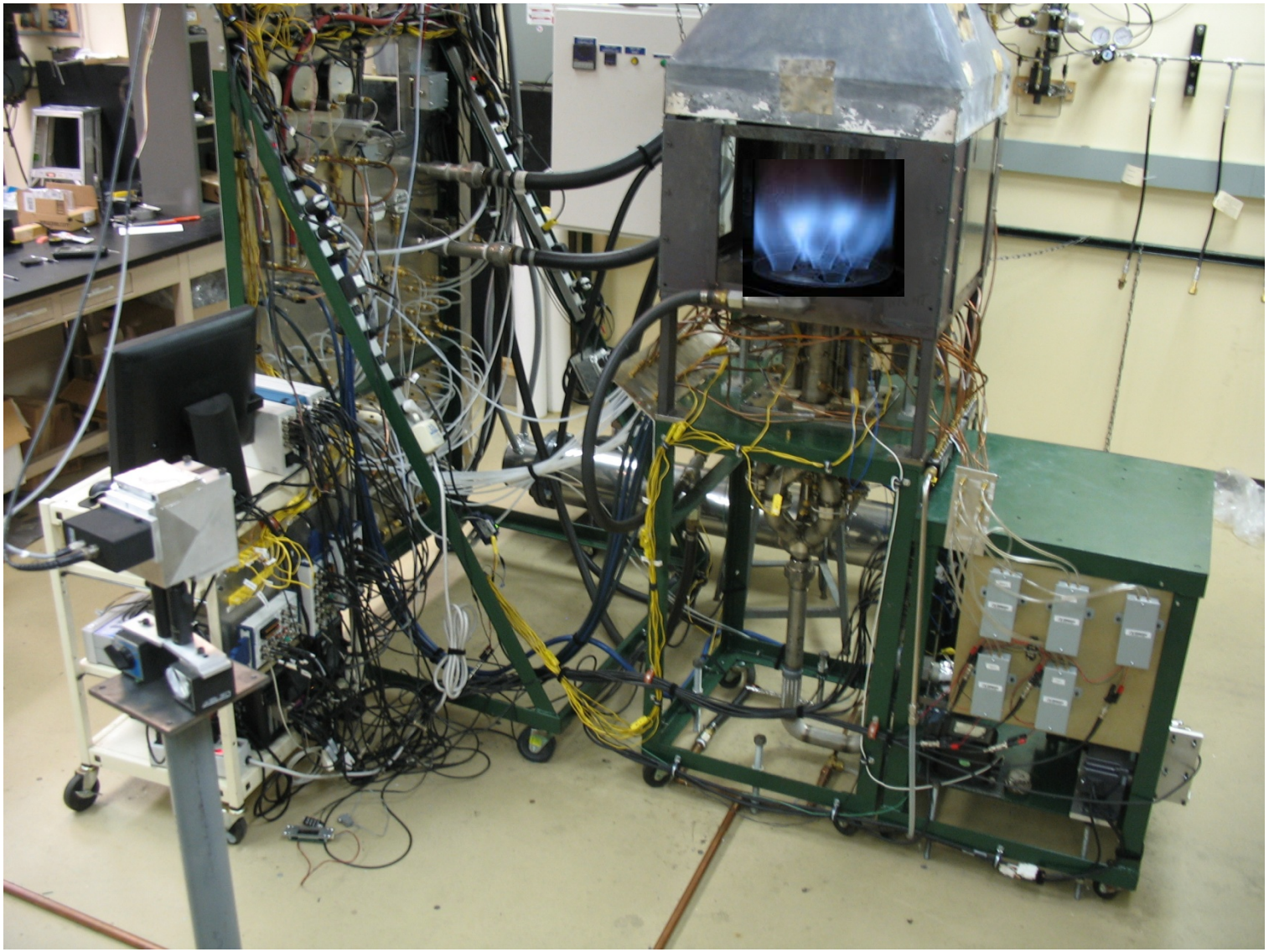
2) To identify and characterize the instability driving mechanisms through which velocity fluctuations result in heat release fluctuations in a multi-nozzle combustor.

3) To characterize the role of flame-flame interactions in the air-forced flame response of a multi-nozzle combustor.

Five-Nozzle Can Combustor



Five-Nozzle Can Combustor



Video of Multi-Nozzle Flame

Measurements

- **ΔP across the swirler in each nozzle**
  - → Mean velocity in each nozzle
- **Dynamic pressure measurements at several locations in each nozzle and the combustor**
  - → Characterize acoustic field in nozzle and combustor
- **Two-microphone method**
  - → Inlet velocity fluctuation in each nozzle
- **OH*, CH*, CO_2* chemiluminescence intensity measurements**
  - → Characterize the temporal fluctuation of the heat release
- **Global CH* (OH*) chemiluminescence imaging (time-averaged and phase-synchronized)**
  - → Chemiluminescence imaging to characterize flame structure and heat release distribution
- **Absorption measurements**
  - → Temporal fluctuation of the equivalence ratio at the exit of each nozzle

Operating Conditions for FTF* Measurements

T_{inlet} = 100°C, 150°C, 200°C

U_{inlet} = 15, 17.5, 20, 22.5, 25, 27.5m/s

Φ = 0.50, 0.55, 0.60, 0.65, 0.70

u'/U_{inlet} = 5%, 10%

$f_{forcing}$ = 100 – 450 Hz

Ref.	T_{inlet} °C	U_{inlet} m/s	Φ	u'_{rms} / u_{mean}	F_{Gmin} Hz
1	100	15.0	0.70	5%	150
2	100	15.8	0.65	5%	150
3	100	20.0	0.65	5%	175
4	100	25.0	0.60	5%	190
5	100	25.0	0.65	5%	225
6	150	15.0	0.60	5%	150
7	150	15.0	0.65	5%	150
8	150	17.5	0.60	5%	150
9	150	17.9	0.65	5%	175
10	150	20.0	0.60	5%	175
11	150	20.0	0.65	5%	200
12	150	22.5	0.55	5%	180
13	150	22.5	0.60	5%	200
14	150	22.5	0.65	5%	200
15	150	25.0	0.60	5%	200
16	150	27.5	0.60	5%	225
17	200	15.0	0.60	5%	150
18	200	15.0	0.60	10%	150
19	200	15.0	0.65	5%	150
20	200	15.0	0.70	5%	150

Ref.	T_{inlet} °C	U_{mean} m/s	Φ	u'_{rms} / u_{mean}	F_{Gmin} Hz
21	200	17.5	0.65	5%	180
22	200	17.5	0.65	5%	175
23	200	20.0	0.50	5%	150
24	200	20.0	0.60	5%	190
25	200	20.0	0.60	10%	175
26	200	20.0	0.65	5%	200
27	200	20.0	0.70	5%	200
28	200	22.5	0.65	5%	225
29	200	25.0	0.55	10%	200
30	200	25.0	0.55	5%	200
31	200	25.0	0.60	5%	225
32	200	25.0	0.60	10%	225
33	200	25.0	0.65	5%	250
34	200	30.0	0.60	5%	275

* flame transfer function

Flame Transfer Function

Flame Transfer Function

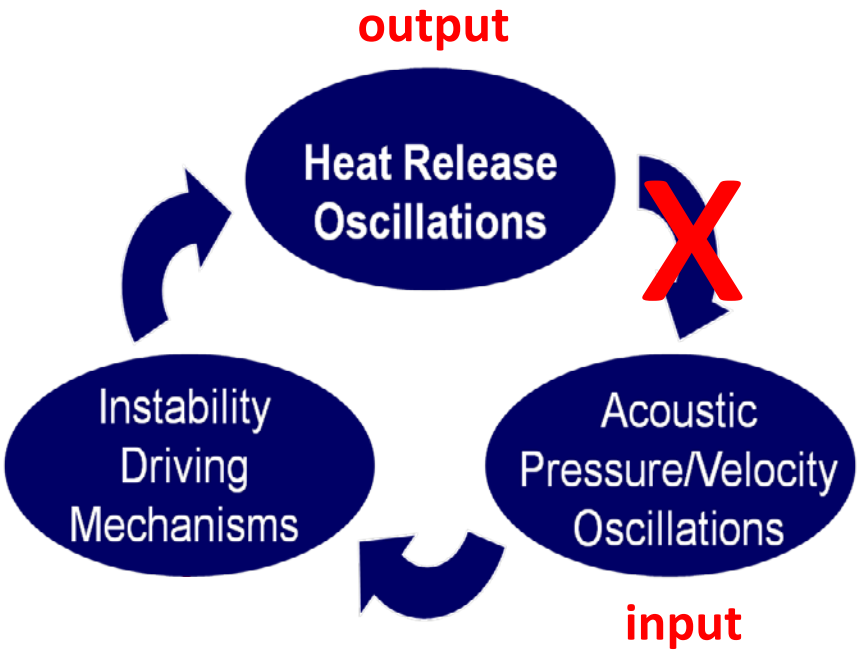
$$(H_{YX})_n = \frac{Y(f)/\langle \bar{Y} \rangle}{X(f)/\langle \bar{X} \rangle}$$

Gain

$$G(f) = \left|(H_{YX})_n\right|$$

Phase

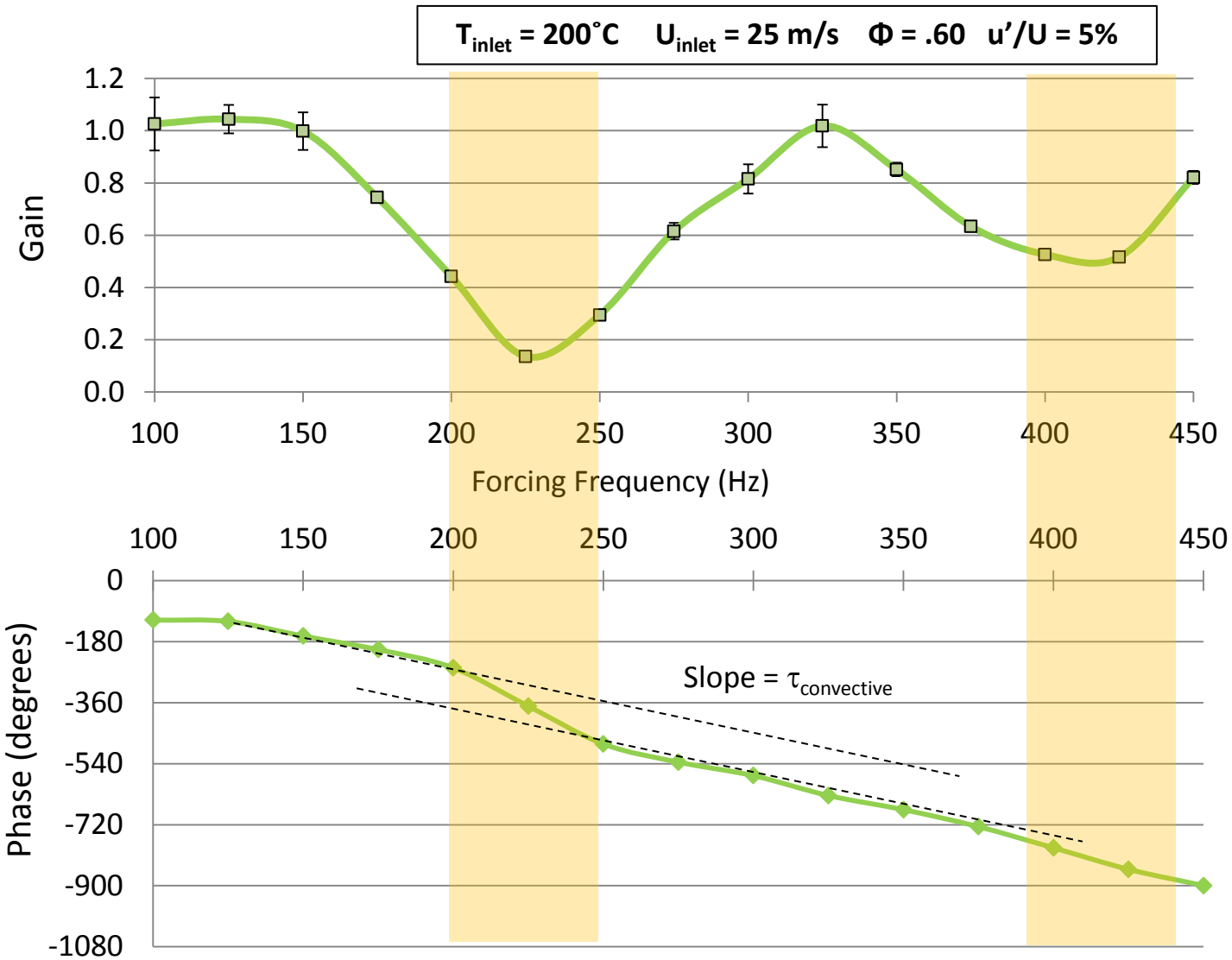
$$\phi(f) = \tan^{-1}\left[\frac{(H_{YX})_{IM}}{(H_{YX})_{RE}}\right]$$



Forced Flame Response

- **Input function, X(f): Inlet velocity or fuel flow rate fluctuations**
- **Output function, Y(f): Overall rate of heat release fluctuation**

Typical MN FTF Gain and Phase vs Frequency

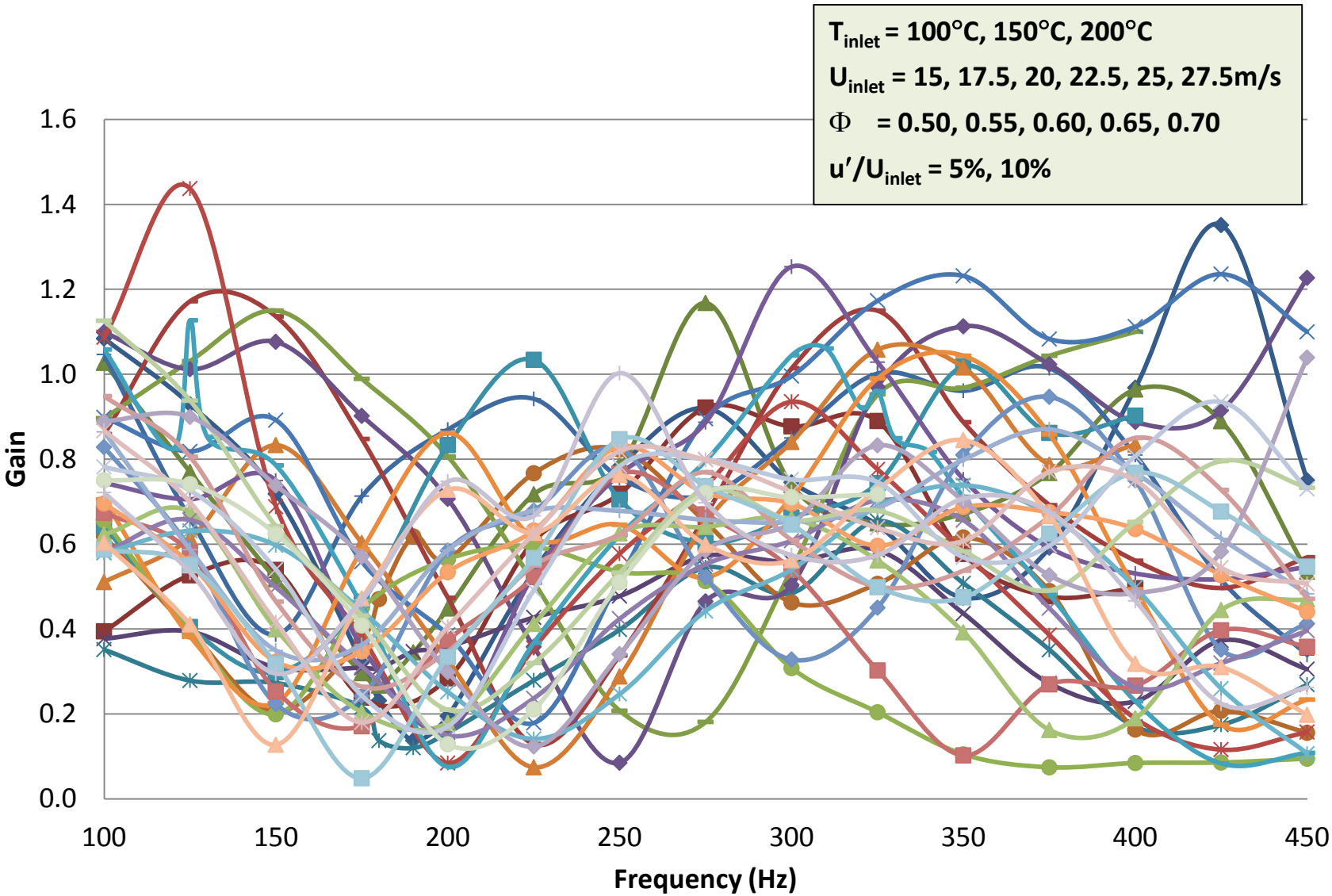


Gain exhibits minimum and maximum values. Suggests interference effects.

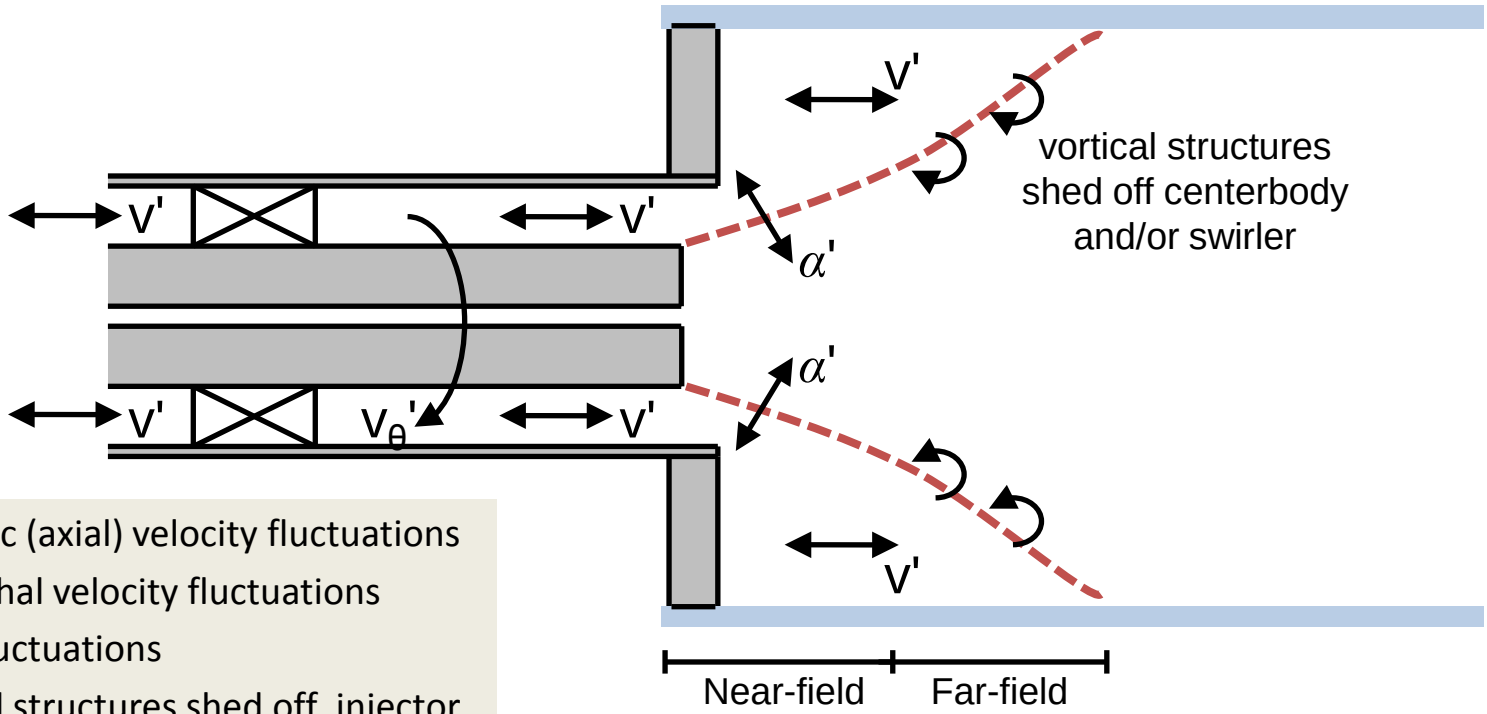
At minimum gain frequencies there is an inflection in phase curves.

The slope of the phase vs frequency curve equals the time between the input perturbation (V') and the output perturbation (Q').

Multi-Nozzle FTF Gain Results (34 cases)



Velocity-Forced Flame Response Mechanisms



- Acoustic (axial) velocity fluctuations
- Azimuthal velocity fluctuations
- Swirl fluctuations
- Vortical structures shed off injector and/or swirler
- Flame angle fluctuations
- Flame near-field effects
  - Flame anchoring
- Flame far-field effects
  - Vortical dissipation
  - Kinematic restoration

Strouhal Number Scaling

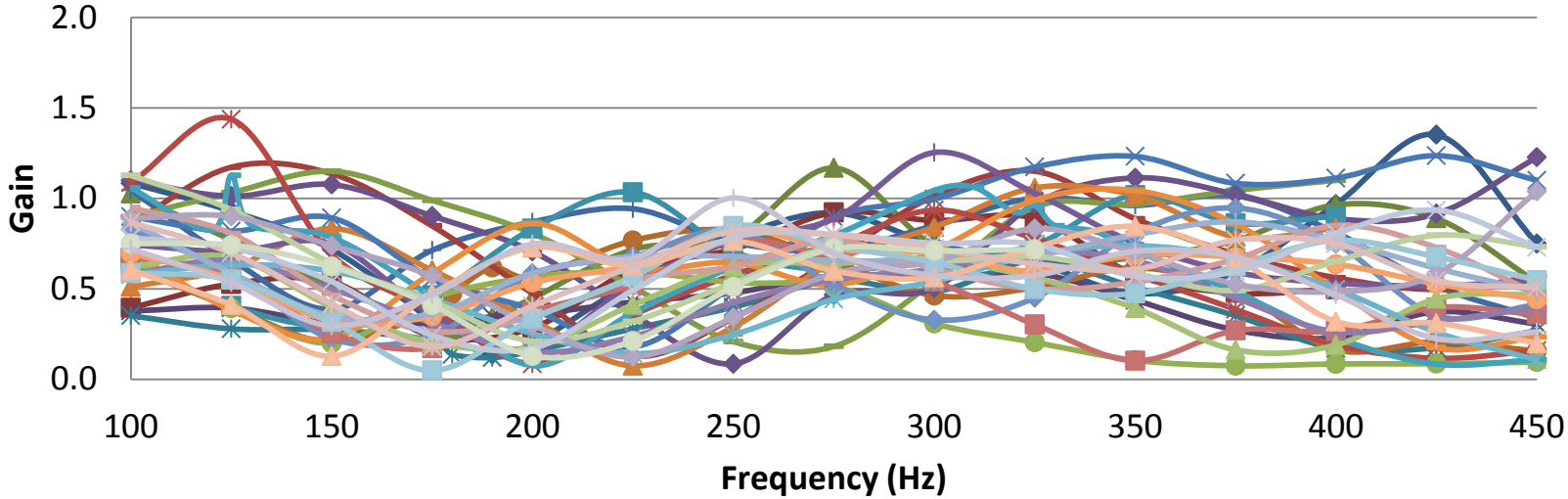
$$\text{Strouhal Number} = St = \frac{\tau_{perturbation}}{\tau_{forcing}}$$

$$\tau_{forcing} = 1/f_{forcing}$$

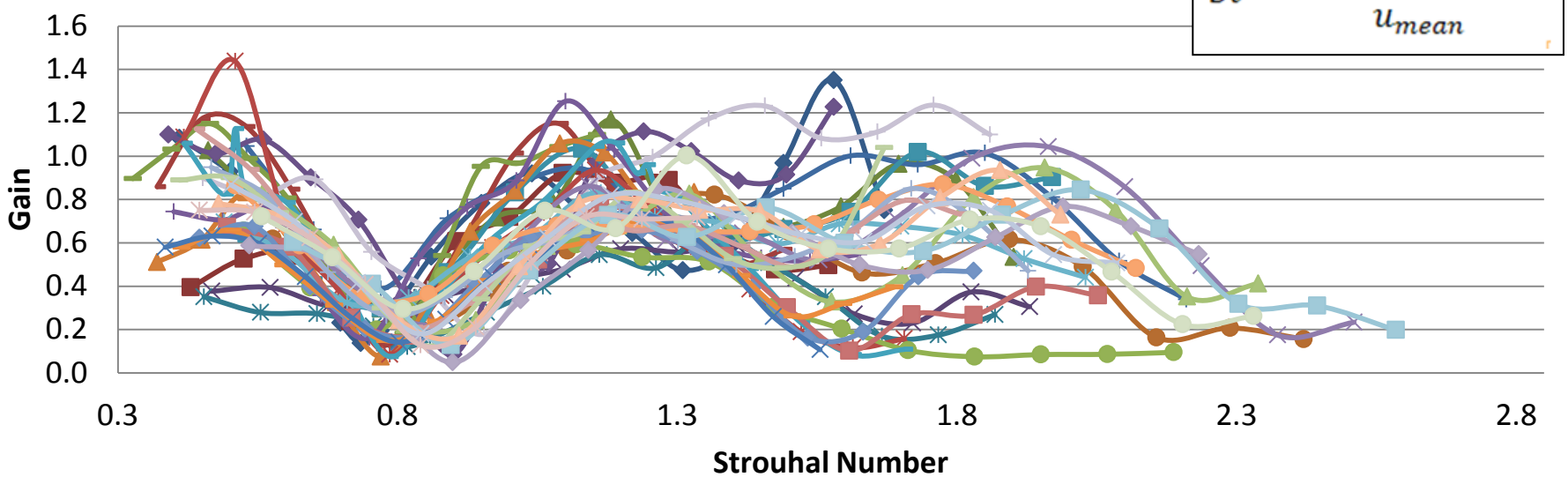
$\underline{\tau_{perturbation}}$

- The convective time of a perturbation generated at the swirl vanes to the end of the centerbody: $\tau_1 = \frac{\Delta_{sw}}{U}$
- The sound propagation time from the swirler exit to the end of the centerbody: $\tau_2 = \frac{\Delta_{sw}}{c}$
- The flame's characteristic response time to a perturbation at the entrance to the combustor: $\tau_3 = \frac{L_{flame}}{U}$

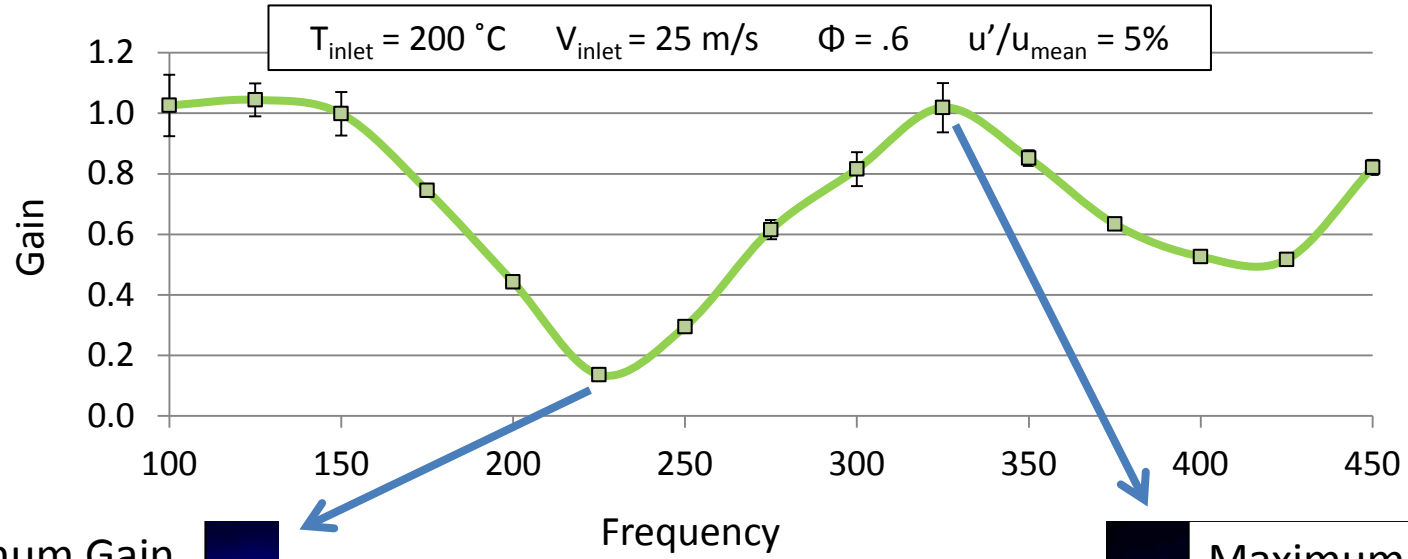
FTF Gain versus Strouhal

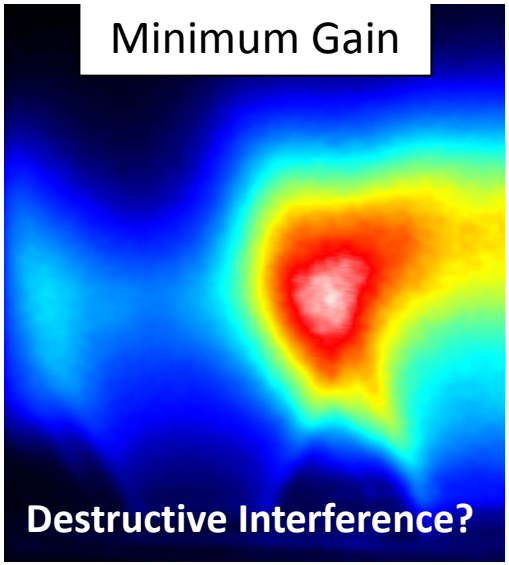


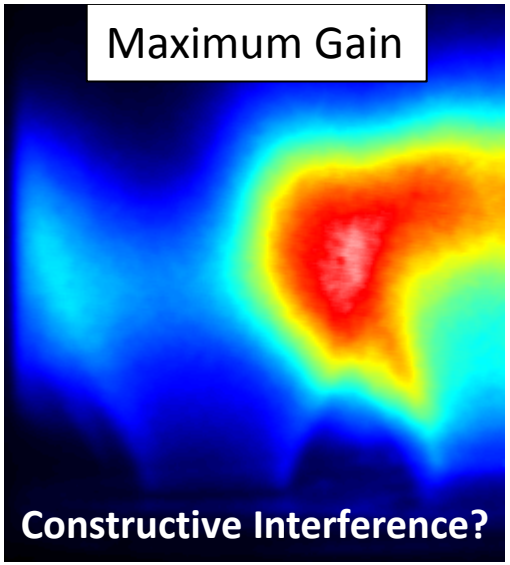
$$St = \frac{L_{flame} * f_{forcing}}{u_{mean}}$$



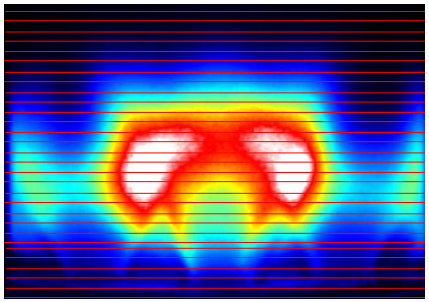
Phase-Synchronized Flame Structure Evolution at Minimum and Maximum Gain Conditions

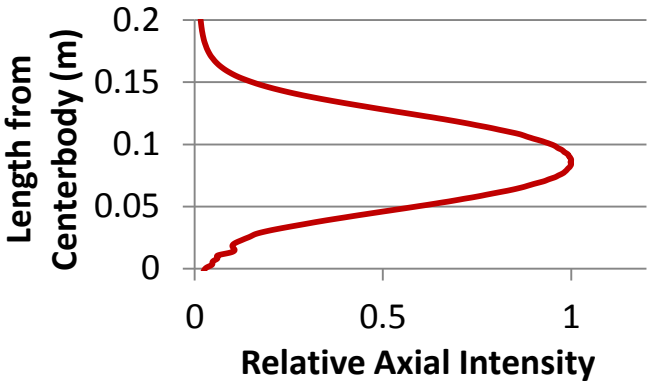


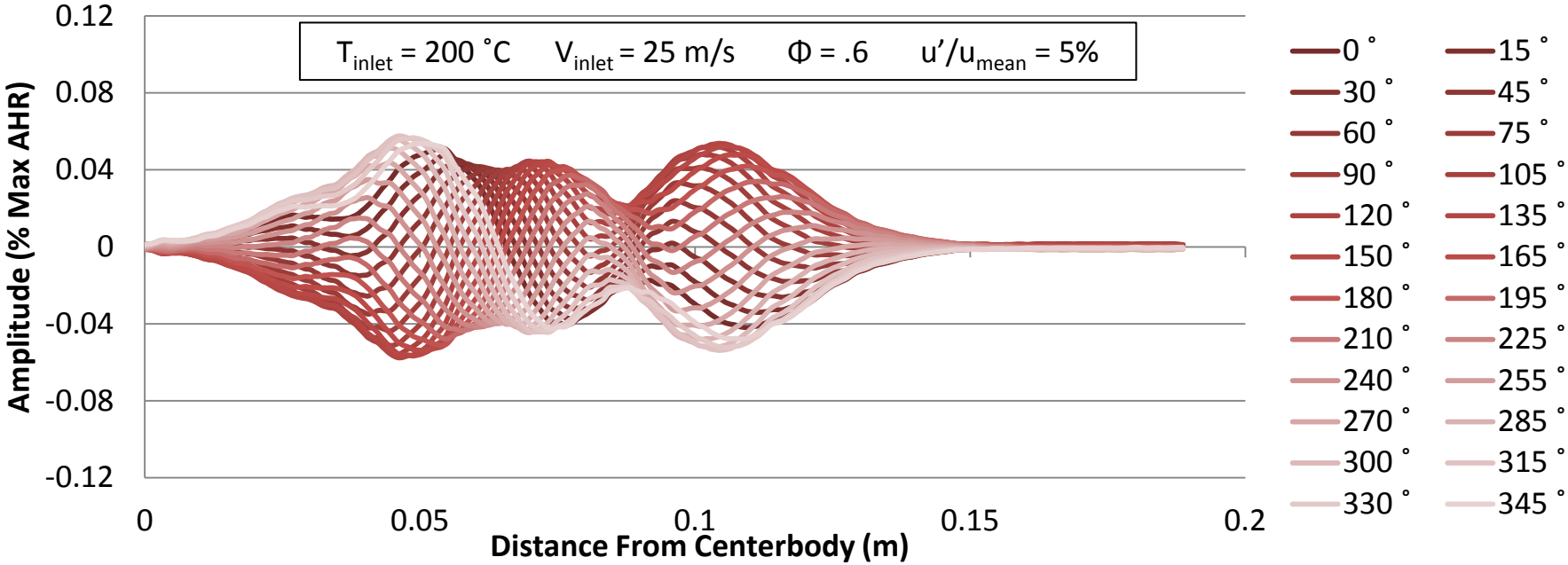




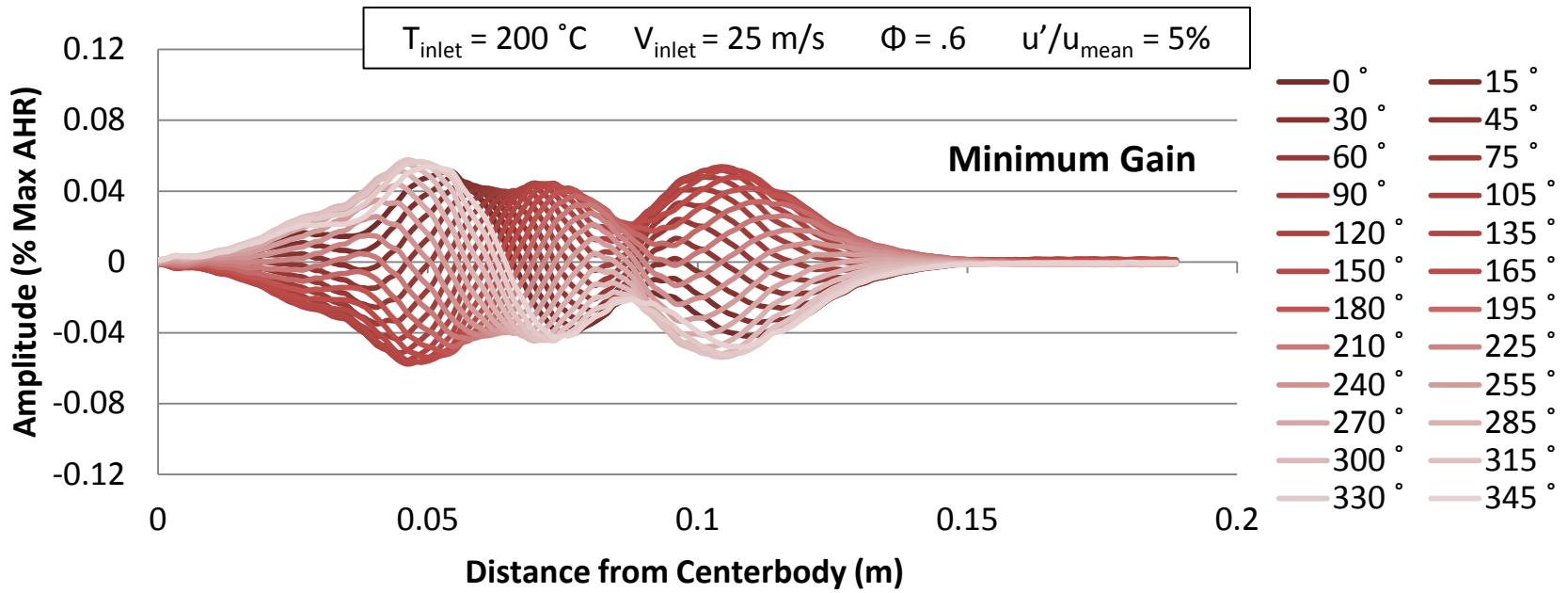
Axial Heat Release Distribution – Mean and Fluctuation

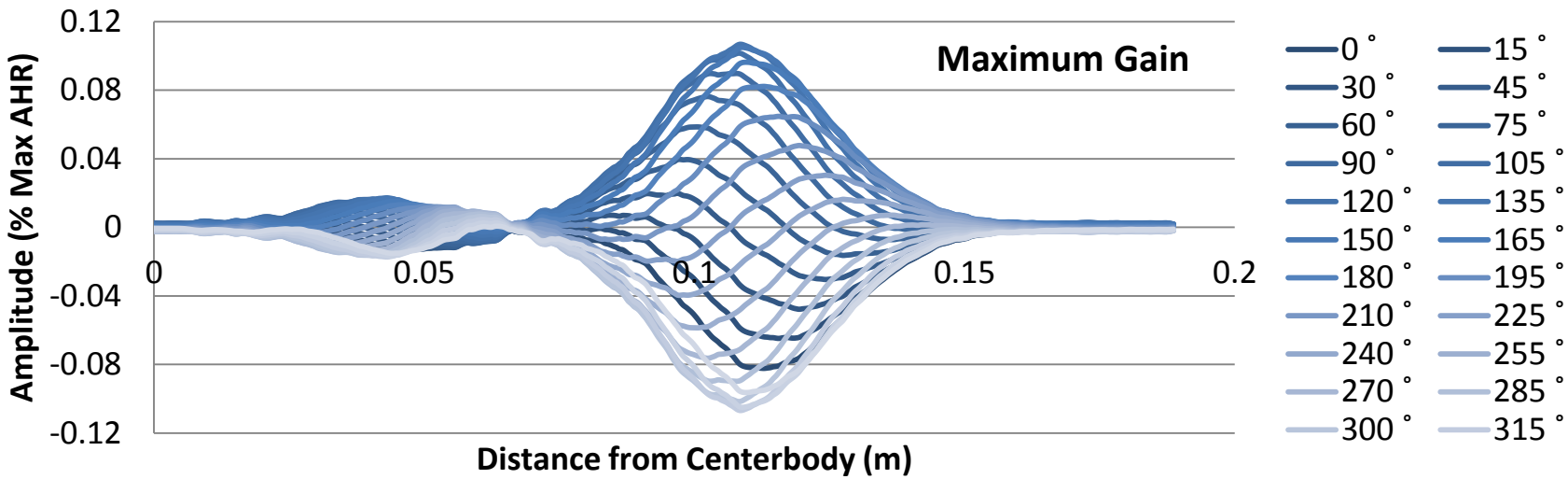






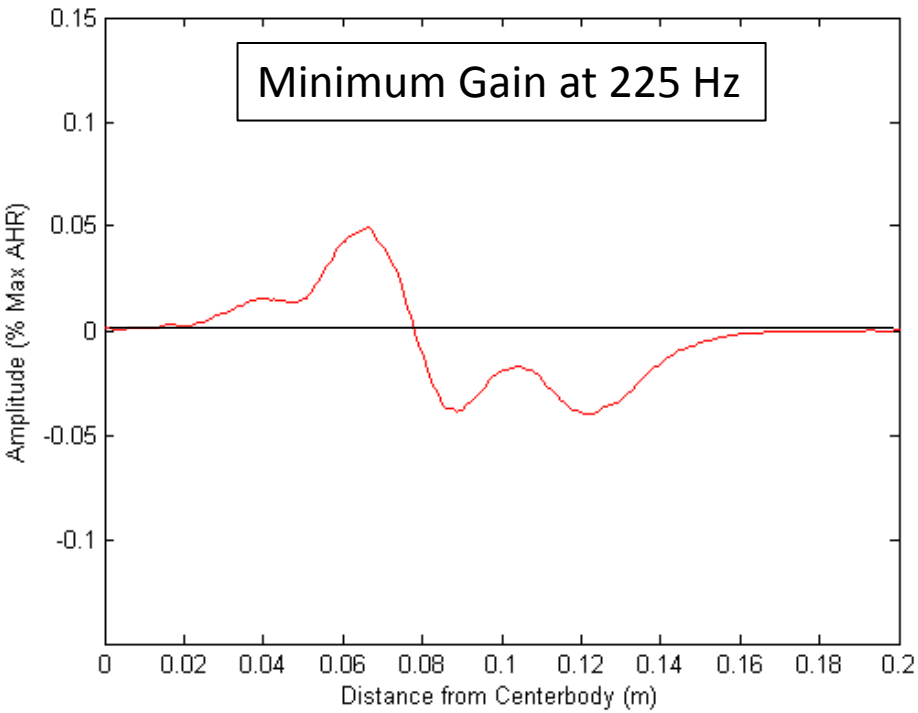
Axial Heat Release Distribution Fluctuation

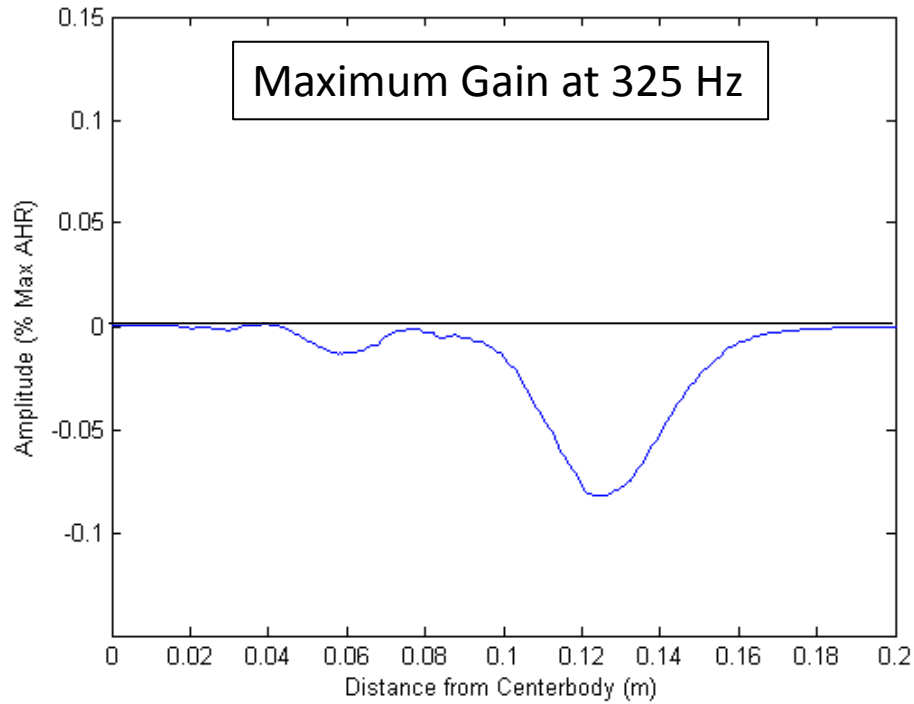




Axial Heat Release Distribution Fluctuations

T_{inlet} = 200 ˚C V_{inlet} = 25 m/s Φ = .6 u'/u_{mean} = 5%





Note that $\lambda_{conv\text{-}225} < \lambda_{conv\text{-}325}$, therefore, this behavior can not be attributed to a single convective perturbation.

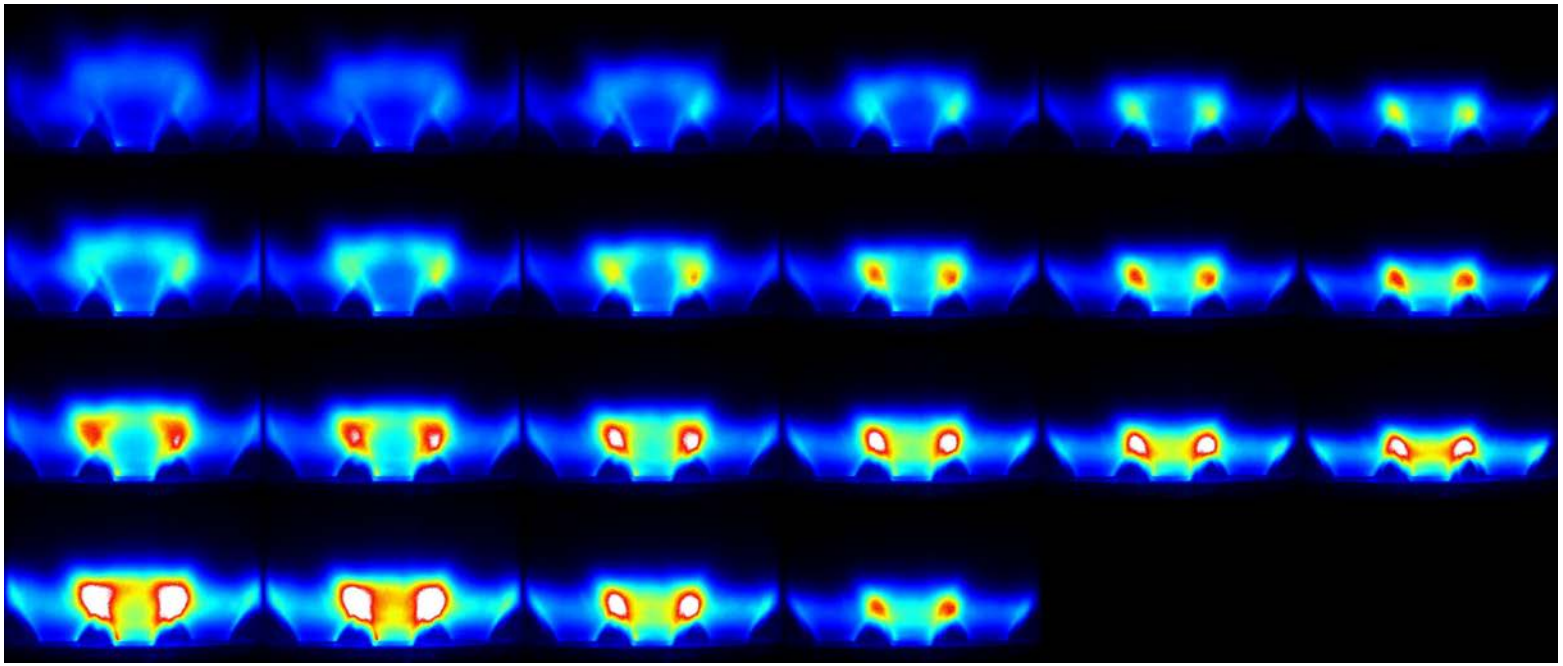
PPM Stable Flame Imaging with 20m/s Inlet Velocity & 200°C Preheat for Flames with Varying Equivalence Ratio and H_2 Percentage in the Fuel

- CH* chemiluminescence
- All images use the same scaling factor

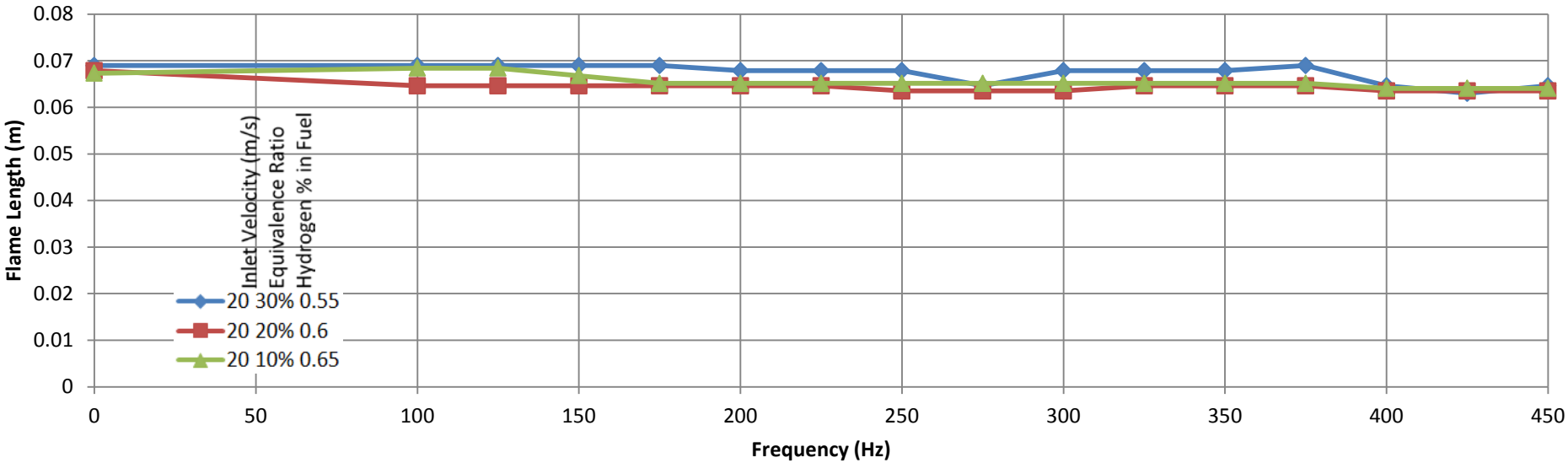
Percentage H_2 in fuel

0% 10% 20% 30% 40% 50%

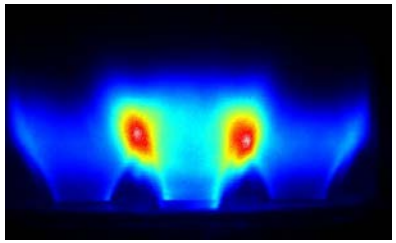
Φ: 0.5, 0.55, 0.6, 0.65



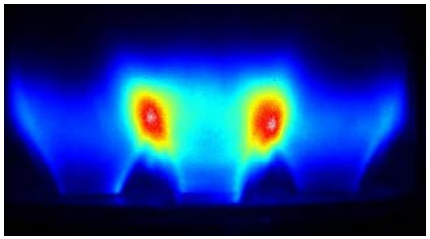
Flame Length Comparison for 3 flames with Inlet Velocity 20m/s, 5% forcing, 200°C Inlet Temp. but varying ϕ and Percent H_2 Enrichment



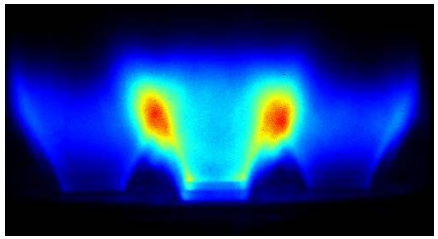
Φ0.55 30%H2



Φ0.65 10% H2

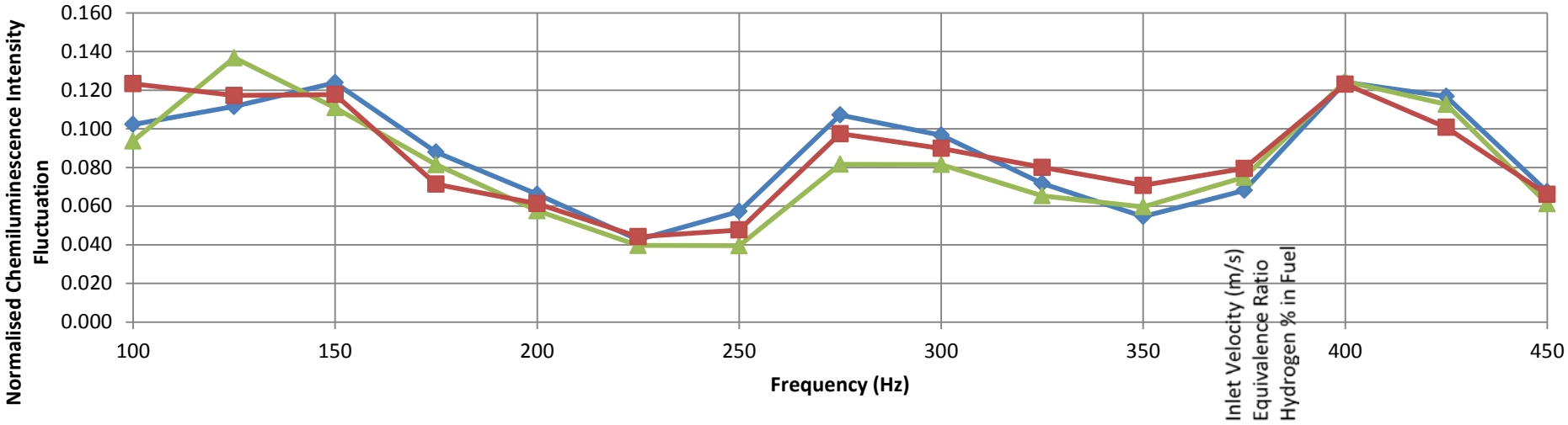


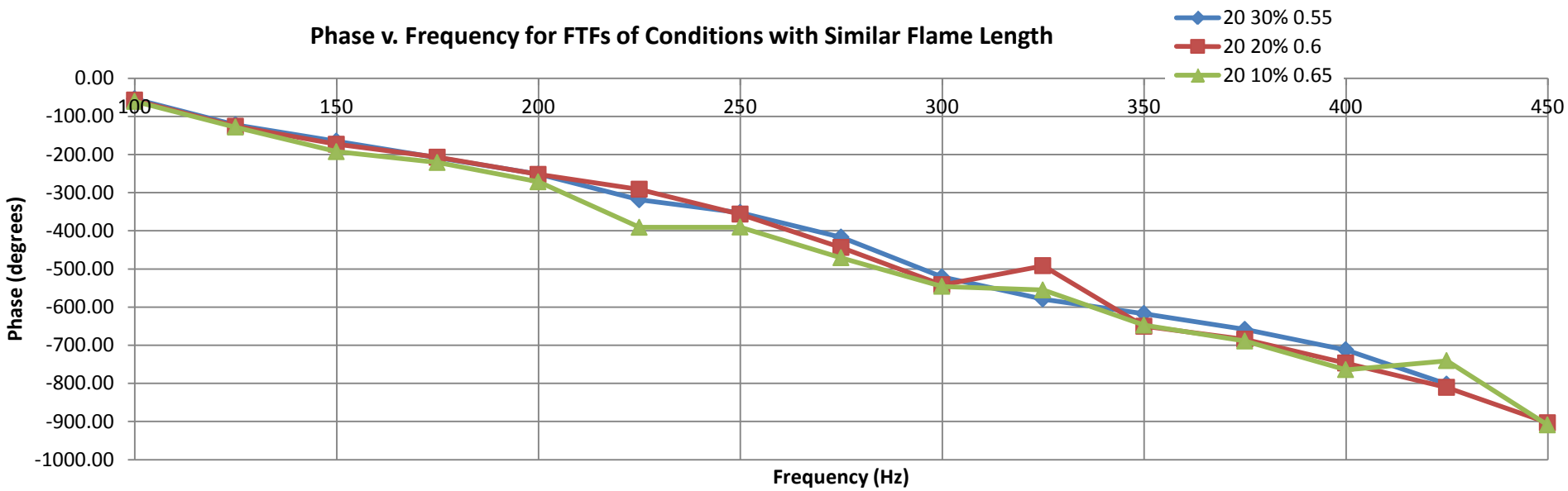
Φ0.6 20% H2



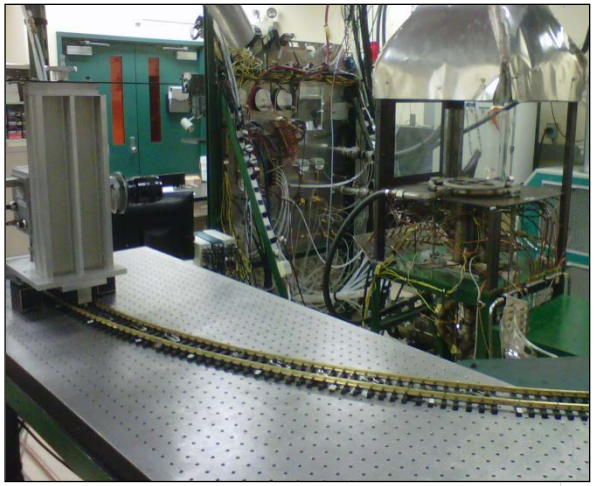
- For the same inlet conditions, it is possible to get the same flame length by varying equivalence ratio/H_2 percentage in the fuel
- The result of having the same flame length and inlet conditions is that the Strouhal number is the same for these flames

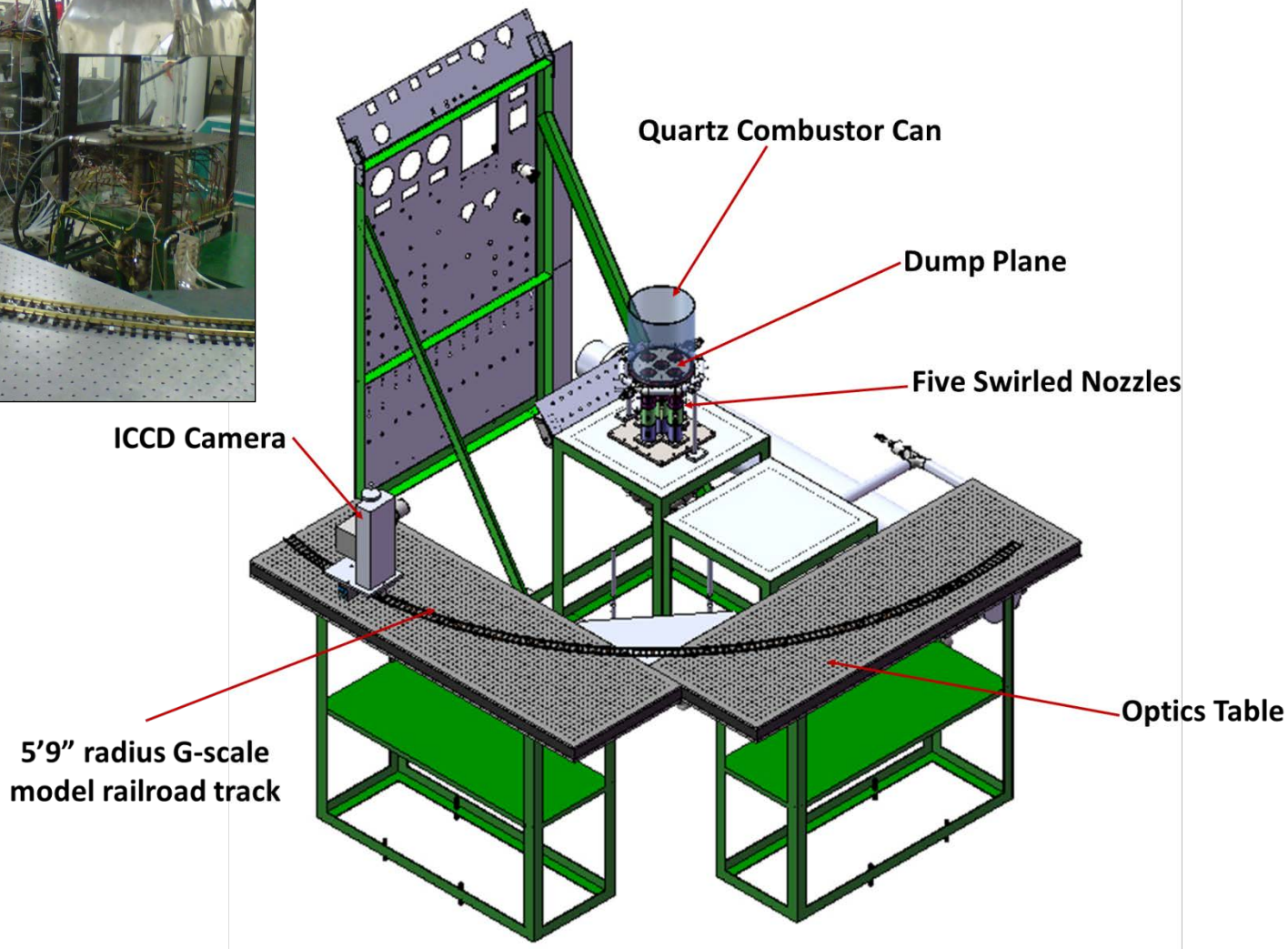
Comparison of Normalised OH* Chemiluminescence Response for Flames with Differing Equivalence Ratio & H_2 Percentage in the Fuel but Similar Flame Lengths (20m/s Inlet Velocity, 200°C Preheat and 5% Forcing)



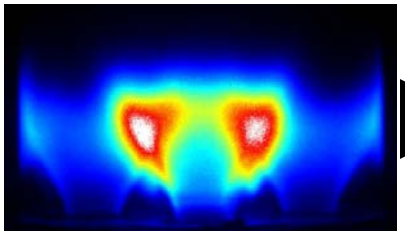


3-D Imaging of Multi-Nozzle Flames

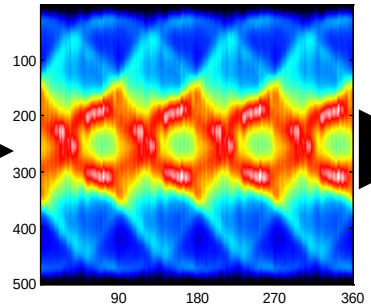




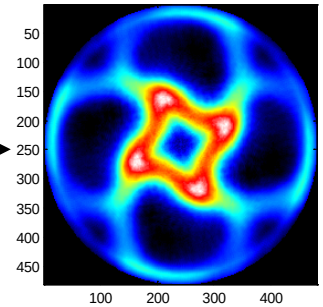
3-D Image Processing



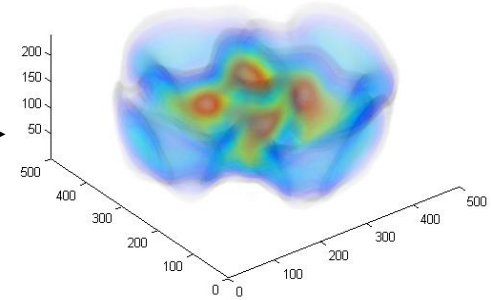
Integrated line-of sight images obtained at various angles



Horizontal slices of images at all angles are input as an array into the inverse radon transform



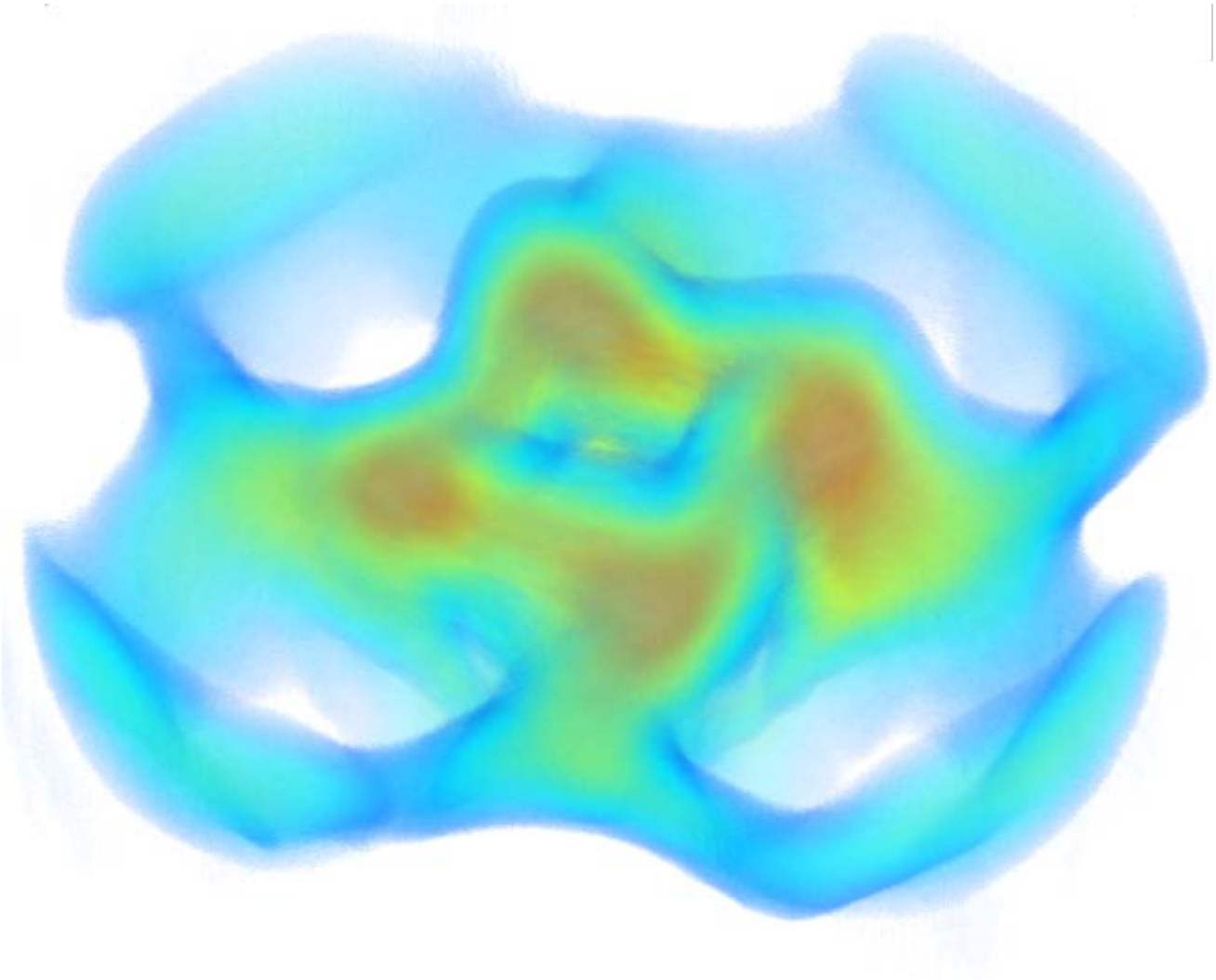
Inverse radon transform reconstructs a horizontal slice of the flame



Horizontal slices are stacked up to obtain a 3D image matrix

3-D Flame Image – Stable Flame

3D inverse Radon Transform based reconstruction of five nozzle flame (Background Removed)



3-D Flame Imaging Validation – Stable Flame

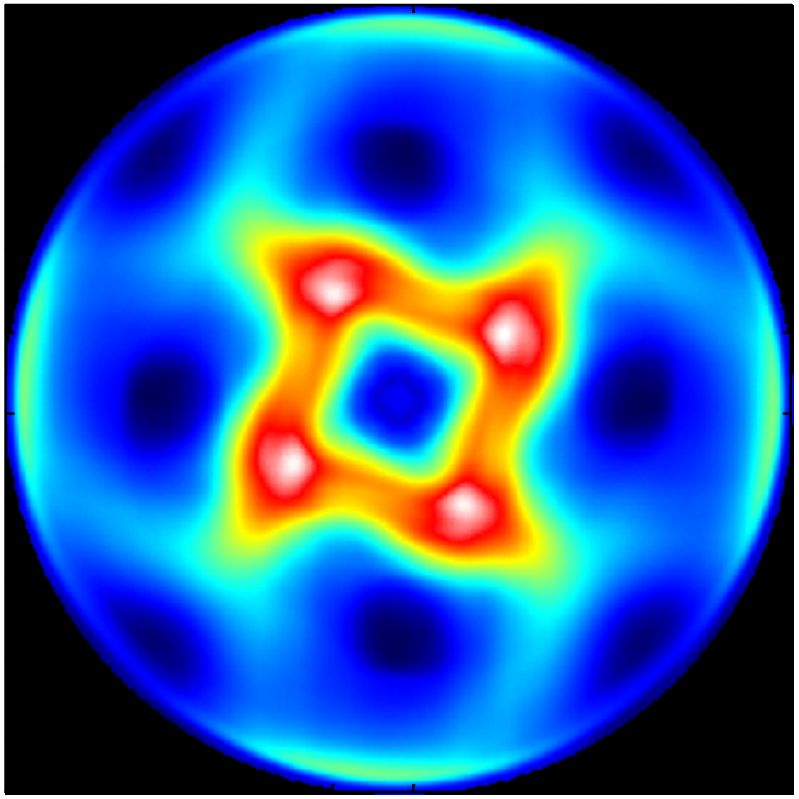
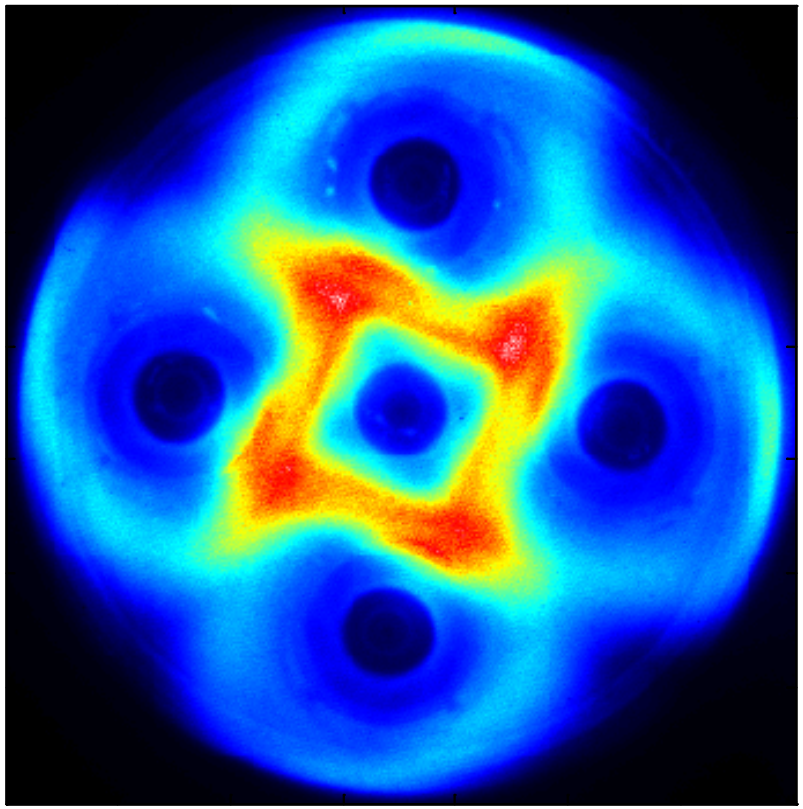


Image of summed horizontal slices of inverse radon reconstruction



Downstream image at same operating conditions