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

DOE Project DE-FC26-08NT05054

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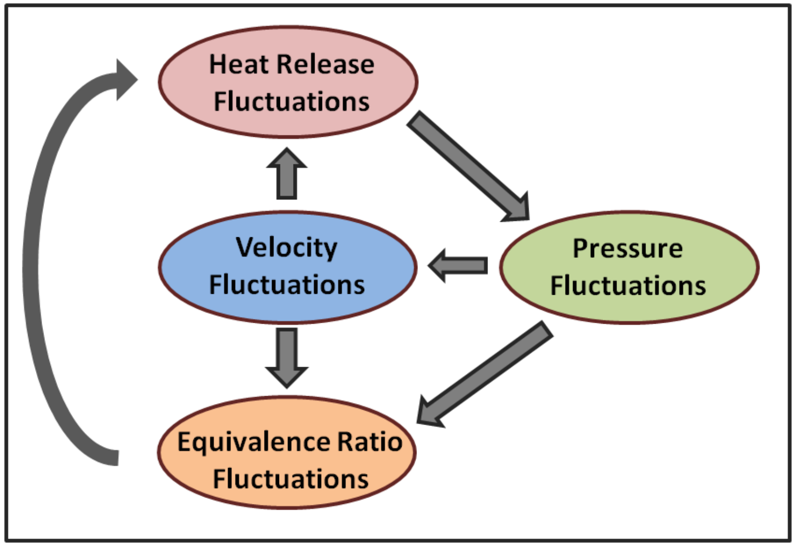
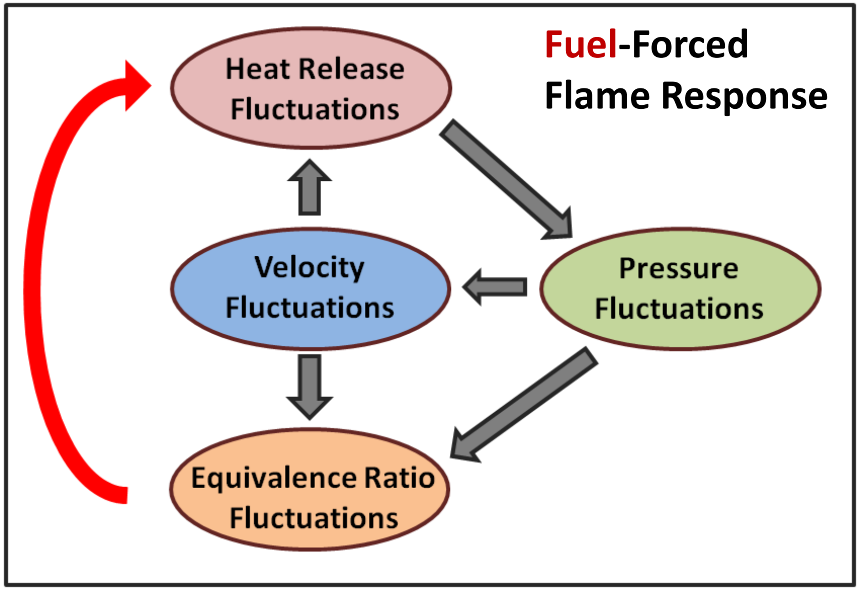
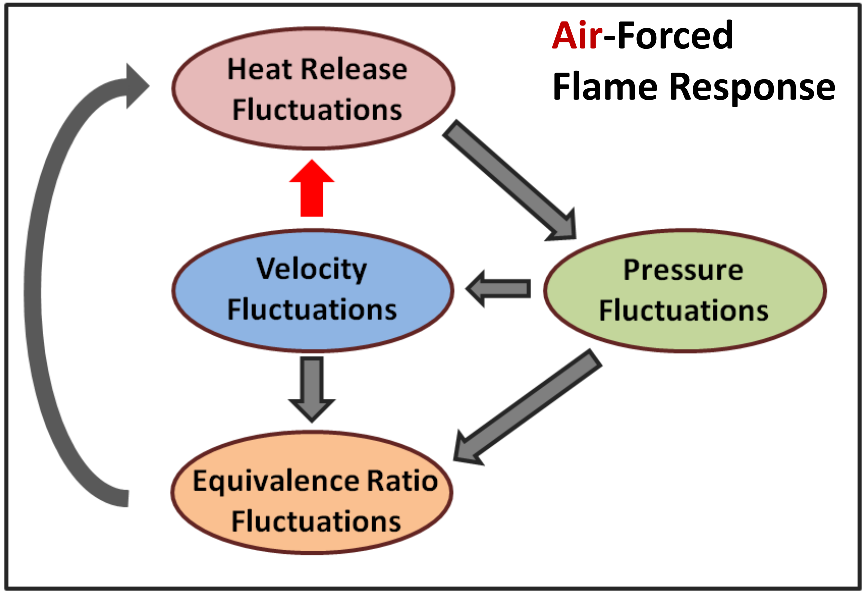
Instability Mechanisms



Self-Excited Instabilities
"Partially-Premixed"
Conditions





Flame Transfer Function

Flame Transfer Function

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

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

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

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

Motivation

Actual gas turbine combustors are based on multi-nozzle annular or multi-nozzle can 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 the understanding that has been obtained from studies of longitudinal-mode instabilities in single-nozzle combustors relevant to these 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.

Previous Multi-Nozzle Research

Author(s)	Year	Exp. or Comp.	Nozzle Configuration	Lam or Turb	PM or PPM	Stable or Self-Exc	Results
T. Poinsot, A. Trouve, D. Veynante, S. Candel, and E. Esposito	1986	E	Multi-Slot Burner	Turb	PM	Self-Exc	Schlieren, phase averaged images, stability maps
J. Hermannm, A. Orthmann, S. Hoffmann, P. Berenbrink	2000	E	Annular Multi-Nozzle	Turb	PPM	Self-Exc	Active/Passive Combustion Control
G.A. Richards and E.H. Robey	2008	E	Duel Nozzles	Turb	PPM	Self-Exc	Active/Passive Combustion Control
G. Staffenbach, L.Y.M. Gicquel, G. Boudier, and T. Poinsot	2010	C	Annular Multi-Nozzle	Turb	PPM	Self-Exc	LES, temperature and pressure fields
D. Fanaca, P.R. Alemela, C. Hirsch, and T. Sattelmayer	2010	E	Annular Multi-Nozzle	Turb	PM	Stable	PIV with and w/o flame OH* Chem Flame Images
F. Boudy, D. Durox, T. Schuller, G. Jomaas, and S. Candel	2010	E	Perforated Plate Burner	Trans / Turb	PM	Forced and Self-Exc	Flame Transfer Function
C. Fureby	2010	C	Annular Multi-Nozzle	Turb	PPM	Self-Exc	LES, reacting flow field

- → **Several instability studies of multi-nozzle annular combustors have been published.**
- → **No instability studies of multi-nozzle can combustors have been reported.**
- → **No flame transfer function calculations or measurements in a multi-nozzle combustor have been reported.**

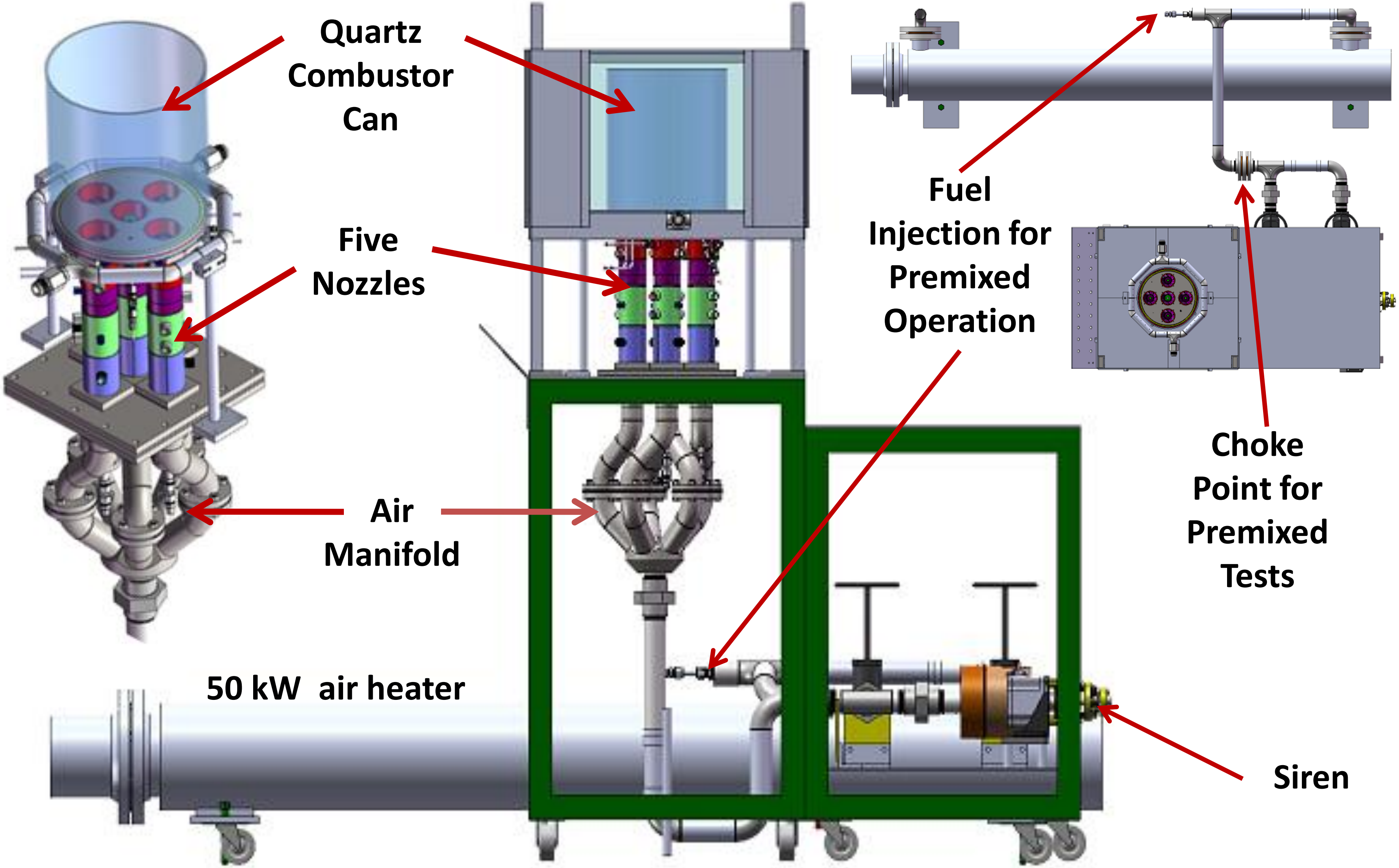
Objectives (PSU)

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

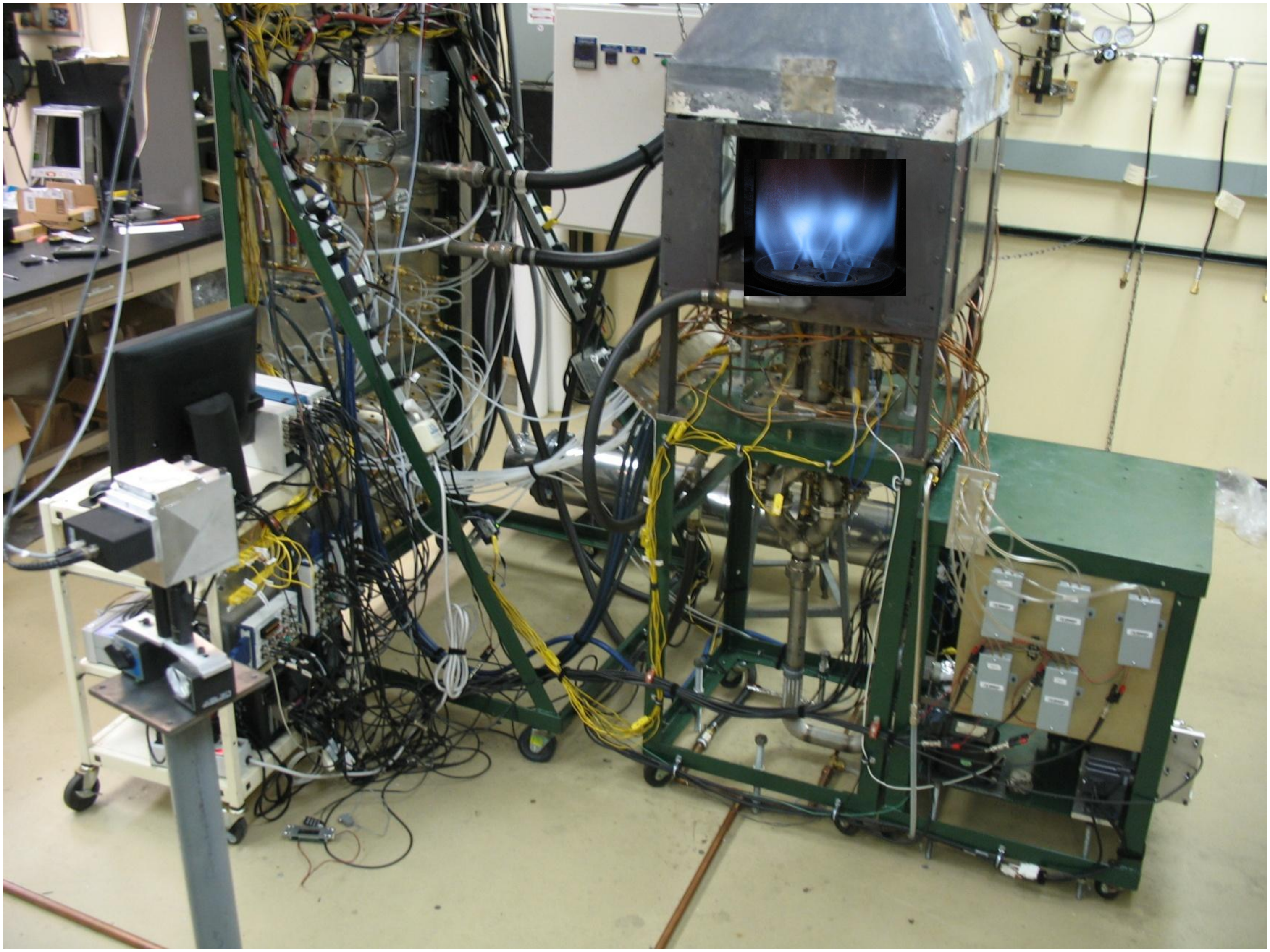
2) To identify and characterize the instability driving mechanisms through which velocity fluctuations result in heat release fluctuations in a multi-nozzle combustor.

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

Five-Nozzle Can Combustor



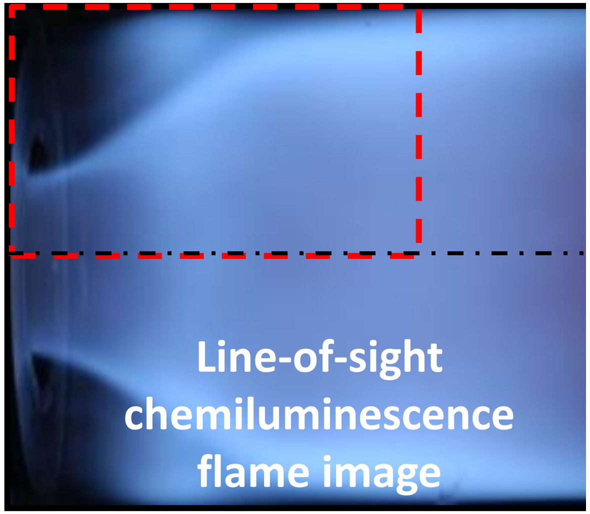
Five-Nozzle Can Combustor



Measurements

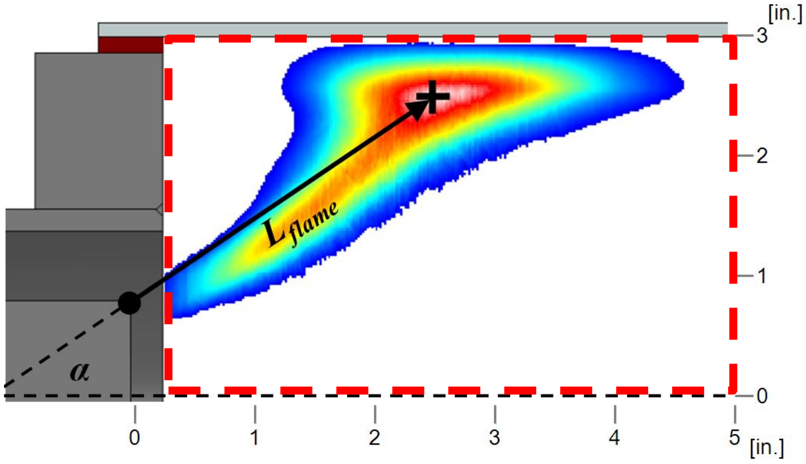
- **ΔP across the swirler in each nozzle**
  - → Mean velocity in each nozzle
- **Dynamic pressure measurements at several locations in each nozzle and the combustor**
  - → Characterize acoustic field in nozzle and combustor
- **Two-microphone method**
  - → Inlet velocity fluctuation in each nozzle
- **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

Flame Length in Multi-Nozzle Combustors?



Abel Inversion

Center of Heat Release

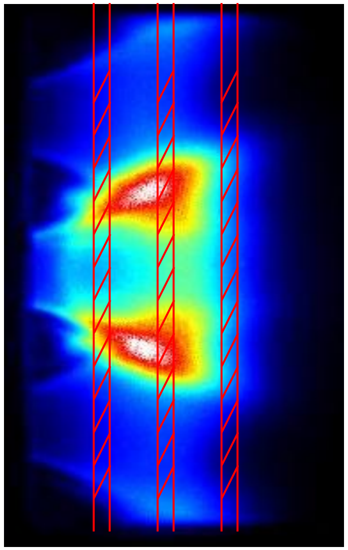


Flame Length in Multi-Nozzle combustor?

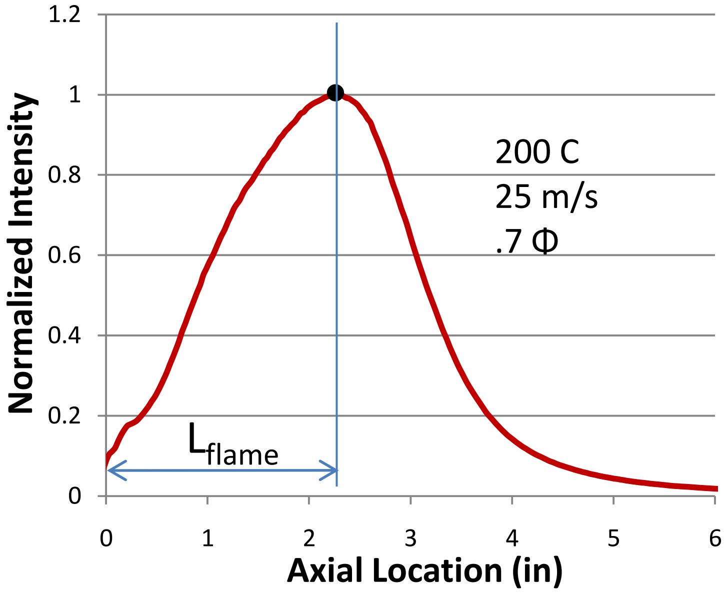
Flame Length in a Multi-Nozzle Combustor

Axial Heat Release Distribution

Multi Nozzle Flame



$$I_{axial}(x) = \int_{-R}^{R} I(r,x)\,dr \Big/ I_{max}$$



→ **The axial location of the greatest chemiluminescence intensity is defined as the flame length.**

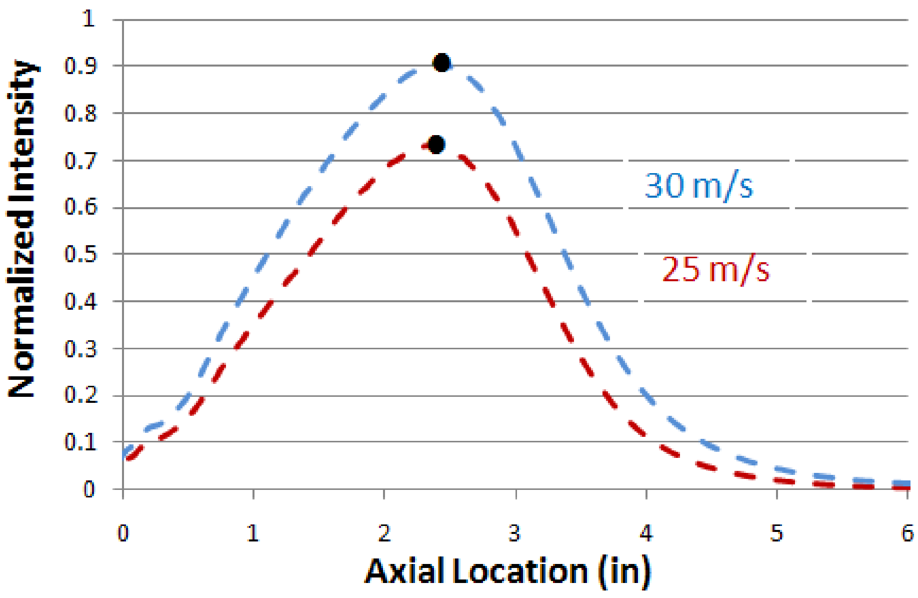
Operating Conditions

	Test Conditions	(Capabilities of the rig)
•Velocity (m/s)	15 – 30	(15 - 35)
• Equivalence Ratio	.6 - .7	(.45 - .7)
• Inlet Temperature (C)	200	(20 – 250)
• Forcing amplitude (u' / u_{mean})	5% - 10%	(5%-25%)
• Forcing Frequencies (hz)	100 – 400	(100 – 450)

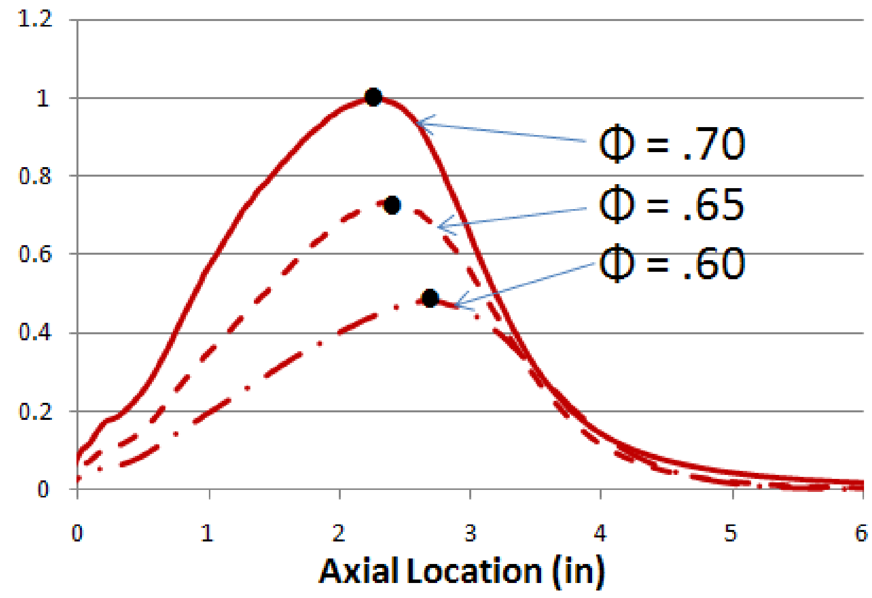
Inlet Temp. **(°C)**	Velocity **(m/s)**	Equivalence Ratio	Forcing Amplitude
200	15	0.6	5.00%
200	15	0.6	10.00%
200	20	0.6	5.00%
200	20	0.6	10.00%
200	25	0.6	5.00%
200	25	0.6	10.00%
200	30	0.6	5.00%
100	25	0.65	5.00%

Axial Heat Release Distribution

Effect of V_{mean}



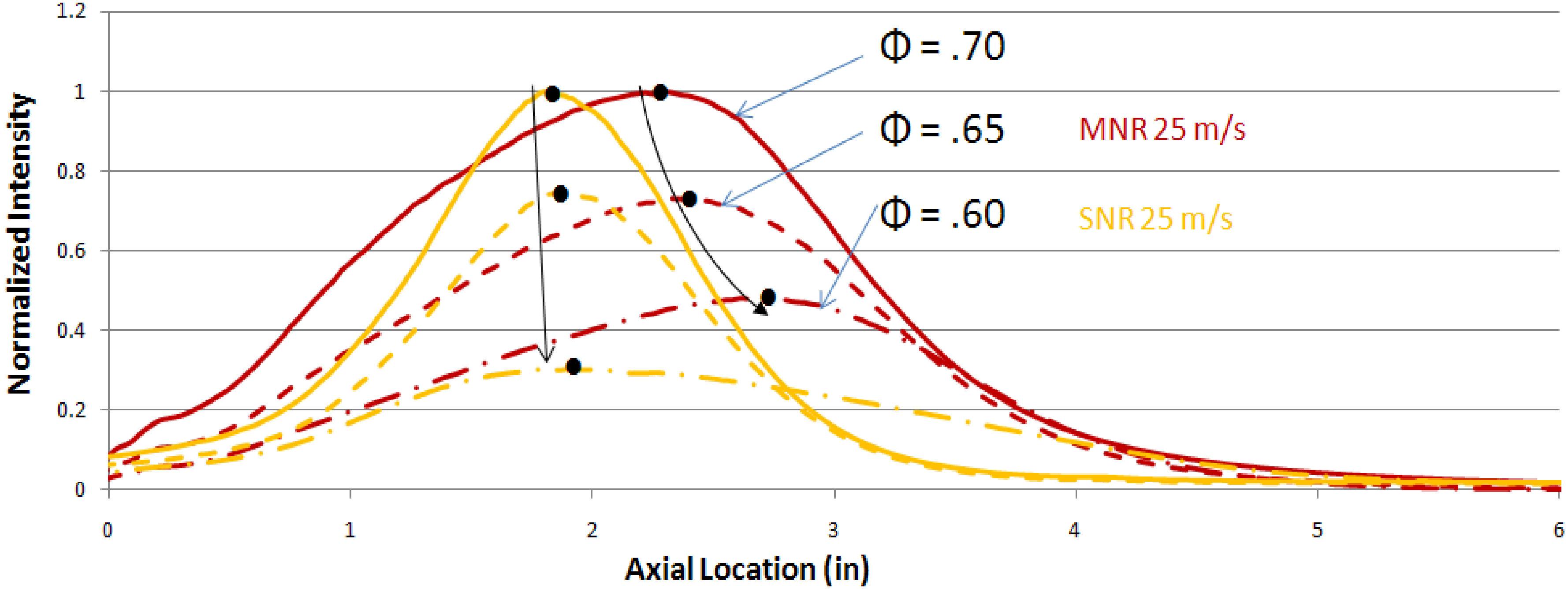
Effect of ϕ



- **The axial location of maximum heat release shows little change with velocity, but increases noticeably with decreasing equivalence ratio.**
  - → **The change in equivalence ratio changes the convective time by changing the flame length.**
  - → **The change in velocity changes the convection time directly.**

Axial Heat Release Distribution

Comparison of SNF to MNF – effect of equivalence



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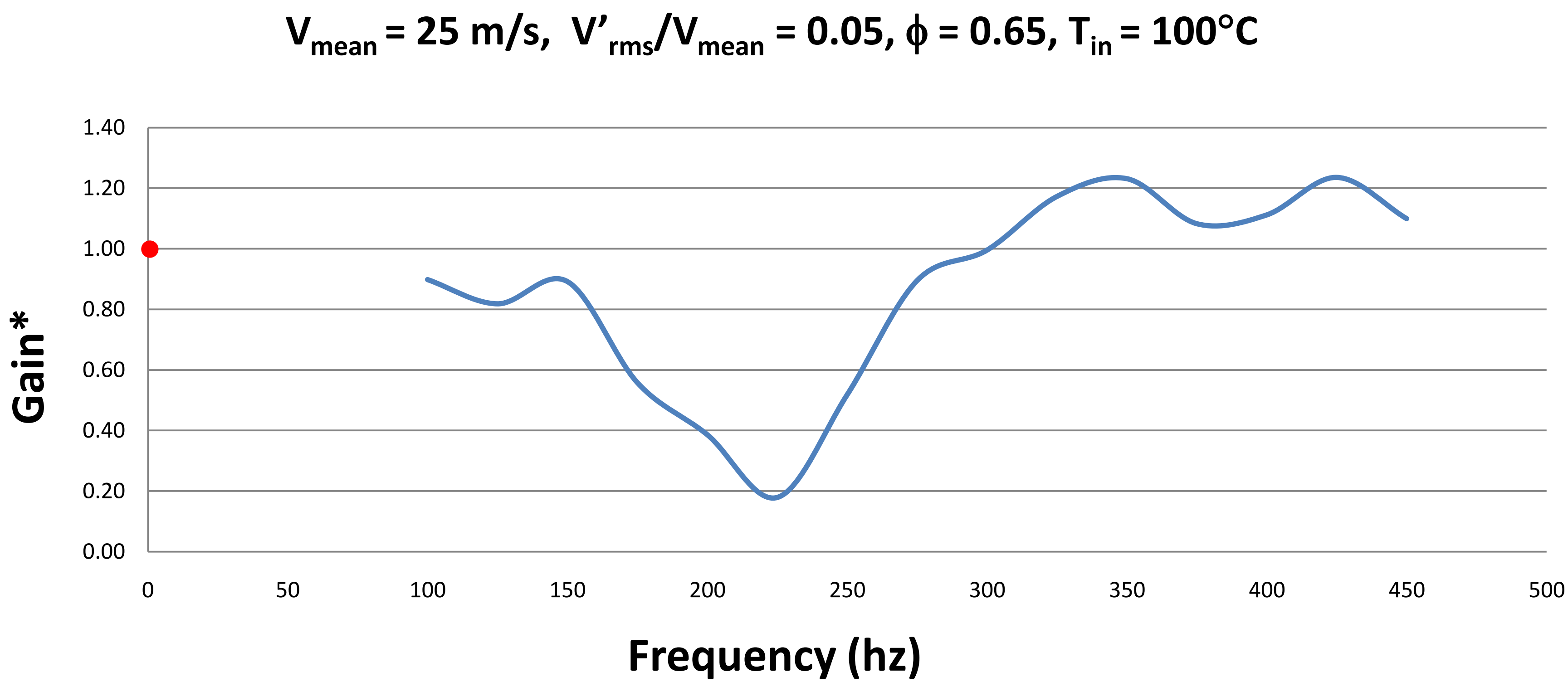
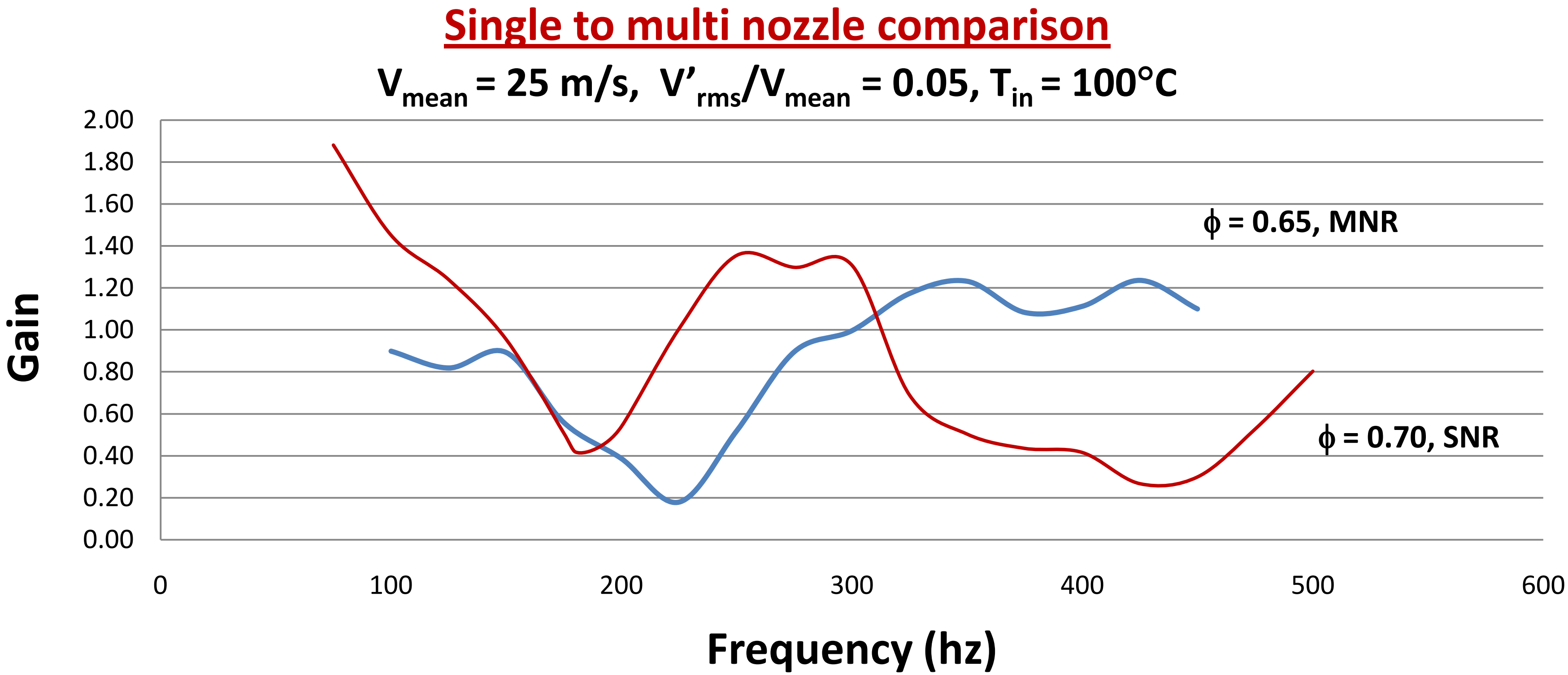
Multi-Nozzle Flame Transfer Function - Gain

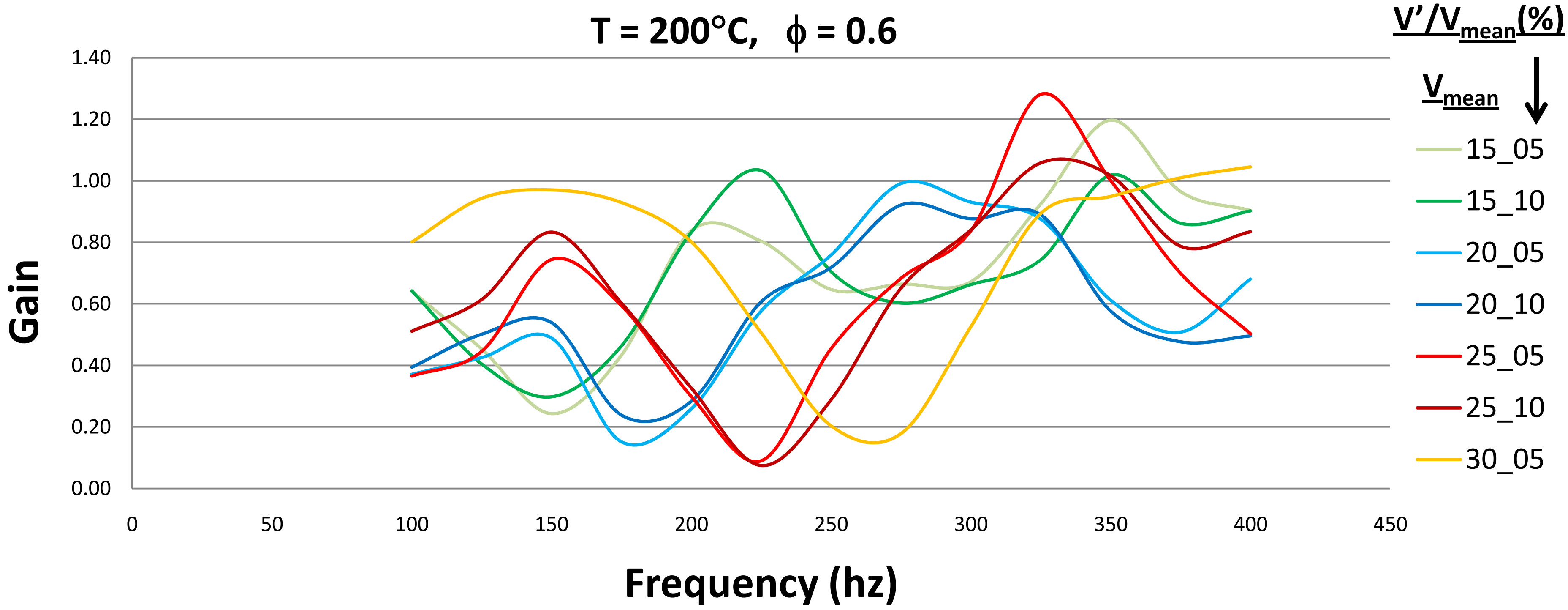


***Gain = $(Q'/Q_{mean})/(V'/V_{mean})$**

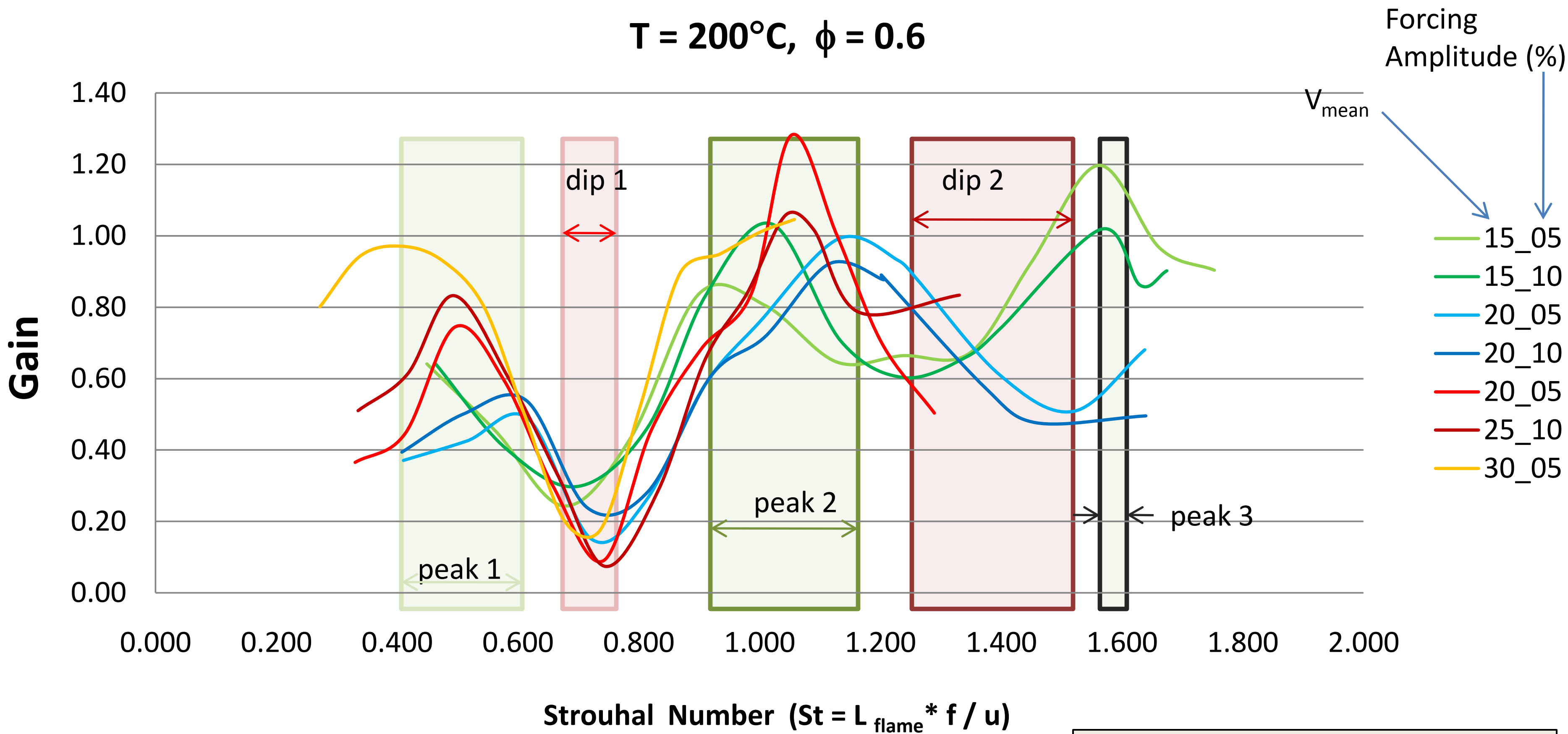
Flame Transfer Function - Gain



Multi-Nozzle Flame Transfer Function - Gain



Flame transfer functions - Gain



$St = f_{acoustic}/f_{convective}$

The presence of minima and maxima correspond to constructive and destructive interference between two instability mechanisms

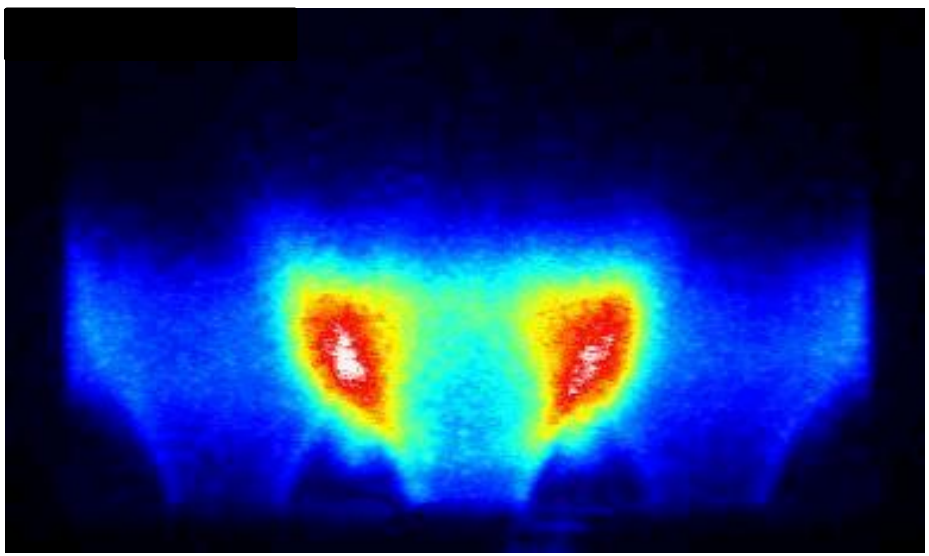
- What are these mechanisms?
- Are the same mechanisms responsible for different operating conditions?
- Are the mechanisms the same for each nozzle?

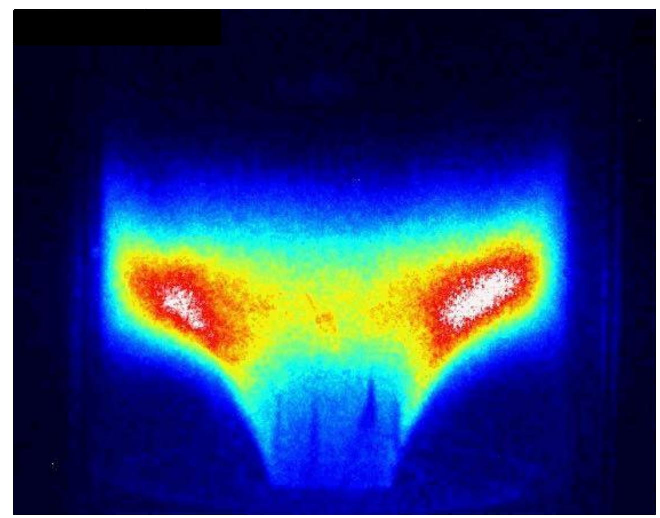
Characterizing the Instability Mechanisms

The flame structure is key to understanding the affect of different instability mechanisms

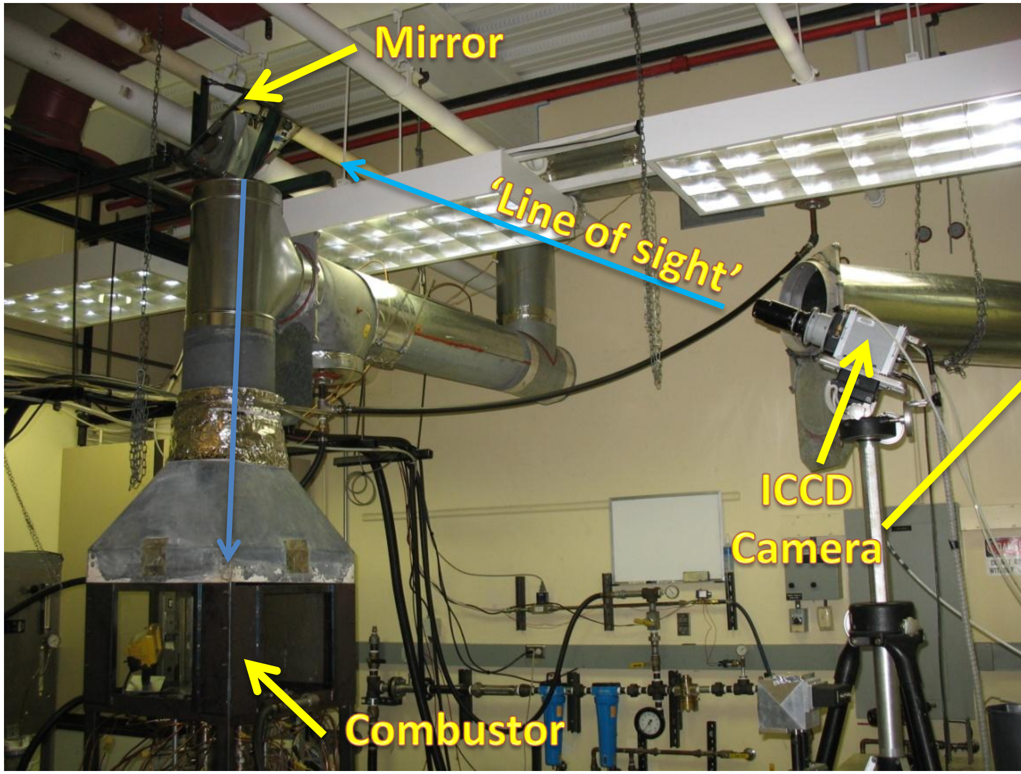
A number of flame imaging techniques will be used to identify and characterize the instability mechanisms

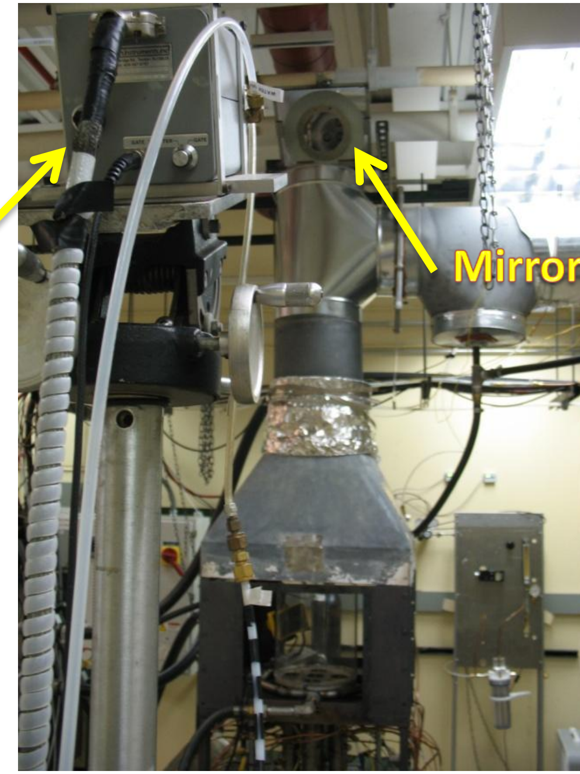
Phase-Synchronized Chemiluminescence Images





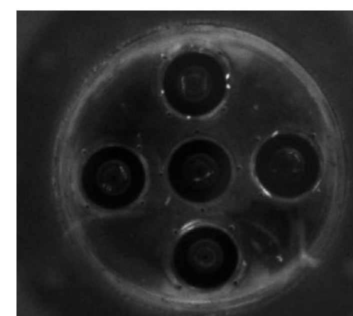
Downstream Imaging



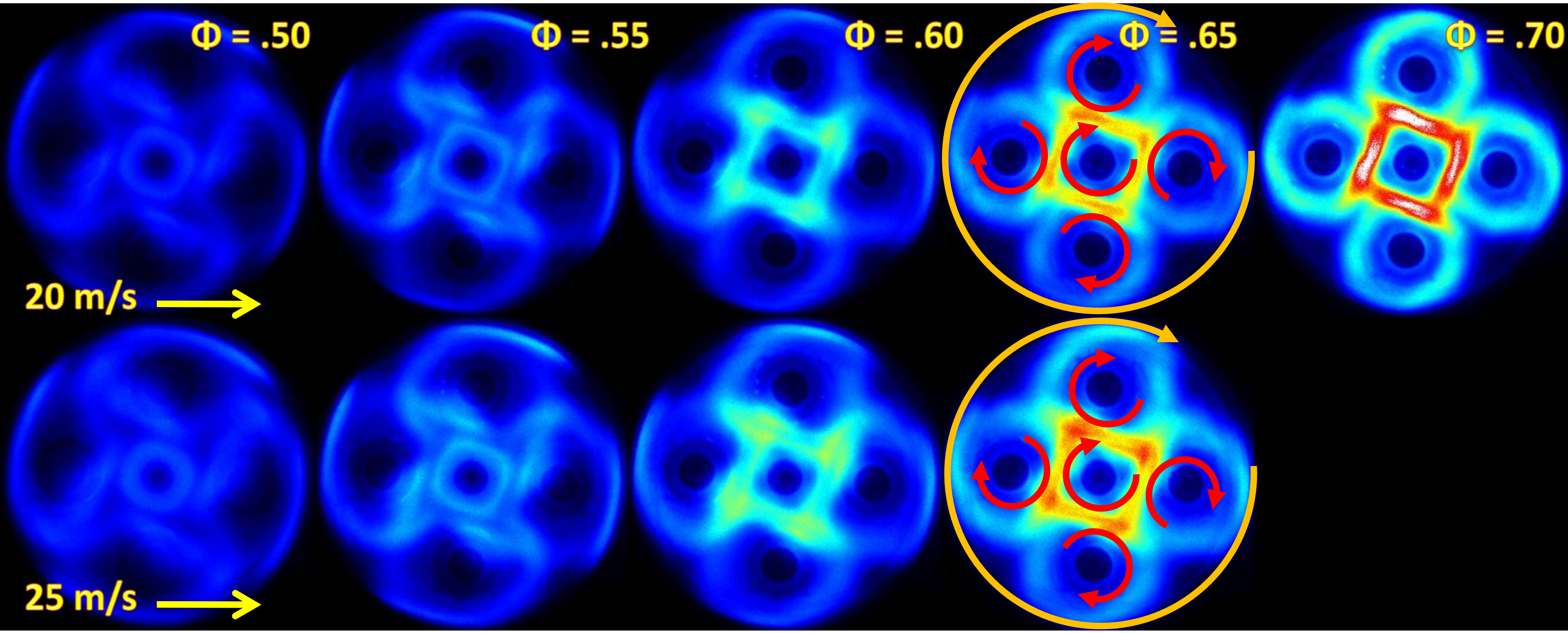


- By using a mirror positioned outside of a window in the downstream duct work we can visualize all 5 flames

- This will allow us to look at the spatially resolved heat release of each flame individually



Downstream Imaging



- We can now visualize the flame interaction region

- This will allow us to look at the spatially resolved heat release of each flame individually