The Effects of Fuel Distribution, Velocity Distribution, and Fuel Composition on Static and Dynamic Instabilities and NO_x Emissions in Lean Premixed Combustors

Principal Investigator: Domenic A. Santavicca

SCIES Project 03-01-SR109

DOE COOPERATIVE AGREEMENT DE-FC26-02NT41431

Tom J. George, Program Manager, DOE/NETL

Richard Wenglarz, Manager of Research, SCIES

Project Awarded (7/01/03, 36 month duration)

$403,777 Total Contract Value ($403,777 DOE)

Gas Turbine Technology Needs

- Lower Emissions
- Improved Static and Dynamic Stability
- Fuel Versatility
- Improved Design Methodology

PENNSTATE 1855

Project Objectives

- to determine the effect of combustor operating conditions on the static and dynamic stability characteristics of lean premixed combustors operating on natural gas and coal-derived syngas fuels

- to develop a methodology for predicting the effect of operating conditions and fuel type on the lean blowout limits and stability characteristics of lean premixed combustors

- to use this information to support the development of advanced numerical models and phenomenological models of unstable combustion

PENNSTATE 1855

Approach

Task	Description	Status
1	Determine the lean blowout limits for natural gas fuel over a range of inlet temperatures, inlet velocities and inlet fuel distributions.	100% complete
new	Determine the effects of equivalence ratio, velocity and temperature on the relationship between chemiluminescence intensity and the rate of heat release in lean premixed combustors operating on natural gas and simulated syngas fuels under stable and unstable operating conditions.	50% complete
new	Over a range of inlet fuel distributions, inlet temperatures, inlet velocities, equivalence ratios and combustor lengths measure the combustor, mixing section, and fuel line pressure fluctuations for natural gas fuel.	50% complete
new	Over a range of inlet fuel distributions, inlet temperatures, inlet velocities, and equivalence ratios obtain 2-D chemiluminescence images of the stable flame structure for natural gas fuel.	50% complete
2	Implement simulated coal derived syngas fuel supply system.	100% complete
3	Over a range of inlet fuel distributions, inlet temperatures and inlet velocities determine the lean blowout limits for a range of natural gas – hydrogen – carbon monoxide fuel mixtures.	100% complete
~~4~~	~~Over a range of operating conditions measure NOx emissions for the two simulated coal derived syngas fuels.~~	~~0% complete~~

PENNSTATE
1 8 5 5

Approach (continued)

Task	Description	Status
5	Over a range of inlet fuel distributions, inlet temperatures, inlet velocities, equivalence ratios and combustor lengths measure the combustor, mixing section and fuel line pressure fluctuations for a range of natural gas – hydrogen – carbon monoxide fuel mixtures.	10% complete
6	Over a range of inlet fuel distributions, inlet temperatures, inlet velocities, equivalence ratios and combustor lengths measure the equivalence ratio fluctuations at the exit of the mixing section for a range of natural gas – hydrogen – carbon monoxide fuel mixtures.	0% complete
7	Over a range of inlet fuel distributions, inlet temperatures, inlet velocities, equivalence ratios obtain 2-D chemiluminescence images of the flame structure for a range of natural gas – hydrogen – carbon monoxide fuel mixtures under stable and unstable conditions.	0% complete
8	Analyze and use the results to formulate, evaluate and improve phenomeno-logical models of the effect of operating conditions and fuel composition on lean blowout and combustion dynamics.	60% complete
~~9~~	~~Implement the flow diverter technique as a means of producing a range of velocity distributions over the operating range of the combustor.~~	~~0% complete~~

PENNSTATE 1855

Accomplishments

(since the last workshop)

- Lean blowout limits have been measured for a broad range of natural gas – hydrogen – carbon monoxide fuel mixtures.
- A stirred reactor model of combustion in the dump plane recirculation zone has given very encouraging predictions of the lean blowout limit and its dependence on fuel composition.
- The viability of making chemiluminescence-based heat release measurements during unstable combustion in the absence of equivalence ratio fluctuations has been demonstrated.
- A previously proposed strategy for making chemiluminescence-based heat release measurements during unstable combustion with equivalence ratio fluctuations has been assessed.
- A flame-vortex time-lag model has been shown to be capable of predicting whether a combustor is stable or not for given operating conditions and fuel properties.

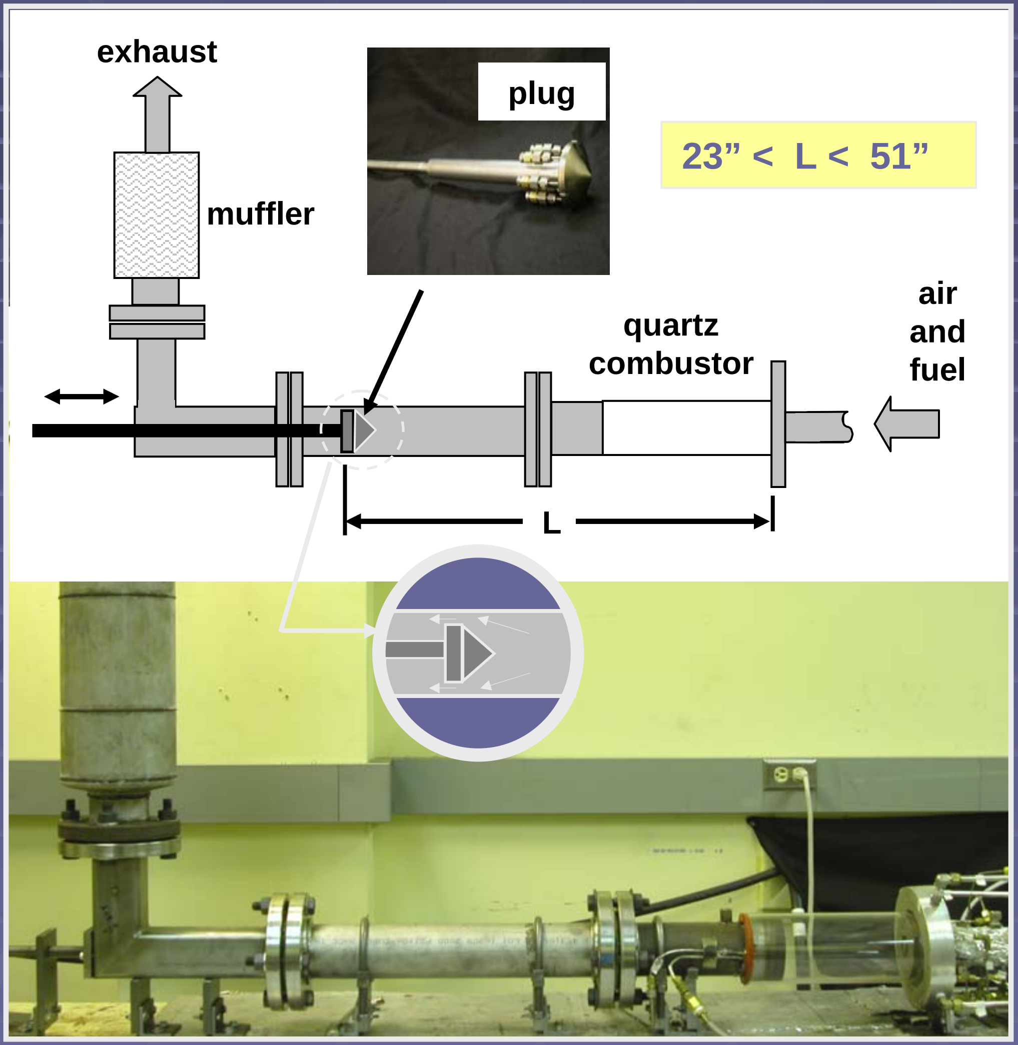
PENNSTATE 1855

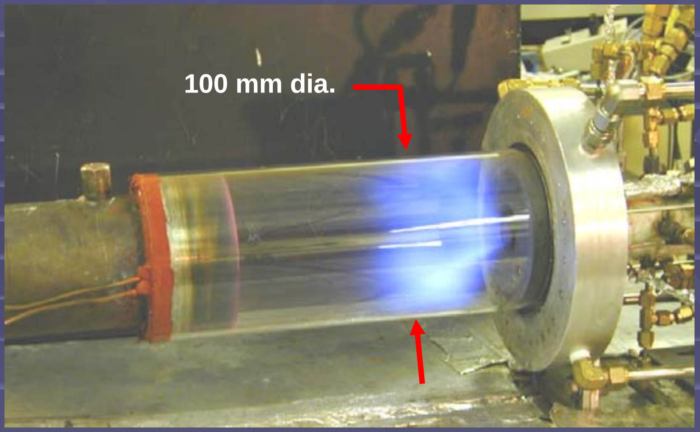
Technical Results

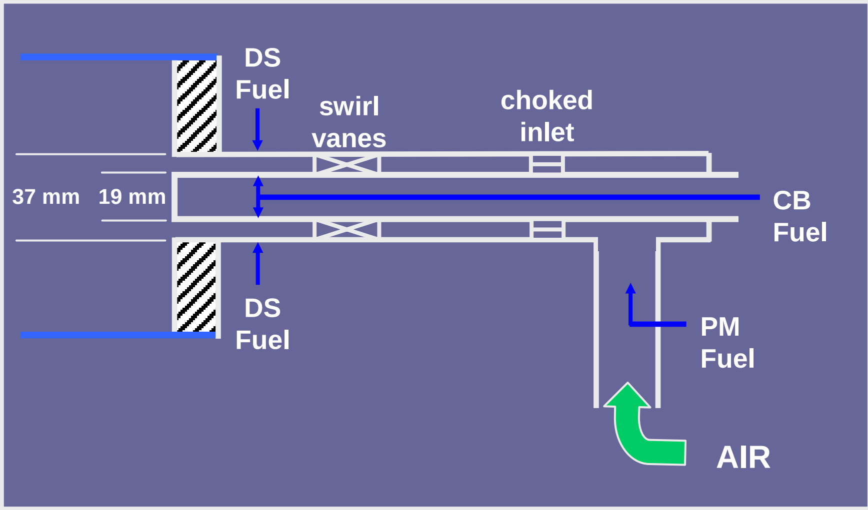
- Lean blowout measurements and predictions for natural gas – hydrogen – carbon monoxide fuel mixtures.
- Chemiluminescence measurements of heat release fluctuations during unstable combustion.
- Predictions of unstable combustion using a flame-vortex time-lag model.

PENNSTATE 1855

Variable-Length, Optically-Accessible Lean Premixed Combustor







pressure	up to 2 atm
inlet temp	up to 450°C
inlet velocity	up to 120 m/s
swirl	30° and 45°

Lean Blowout Fuel Matrix

Case	Swirl	Inlet Temp	% Nat Gas	% H_2	% CO
1	30°	200°C	100	0	0
2	30°	300°C	100	0	0
3	30°	400°C	100	0	0
4	30°	200°C	90	10	0
5	30°	200°C	75	25	0
6	30°	200°C	60	40	0
7	30°	200°C	45	55	0
8	30°	200°C	30	70	0
9	30°	200°C	15	85	0
10	30°	200°C	0	100	0
11	30°	200°C	45	45	10
12	30°	200°C	45	35	20
13	30°	200°C	45	25	30
14	30°	200°C	30	60	10
15	30°	200°C	30	50	20
16	30°	200°C	30	40	30
17	30°	200°C	15	75	10
18	30°	200°C	15	65	20
19	30°	200°C	15	55	30

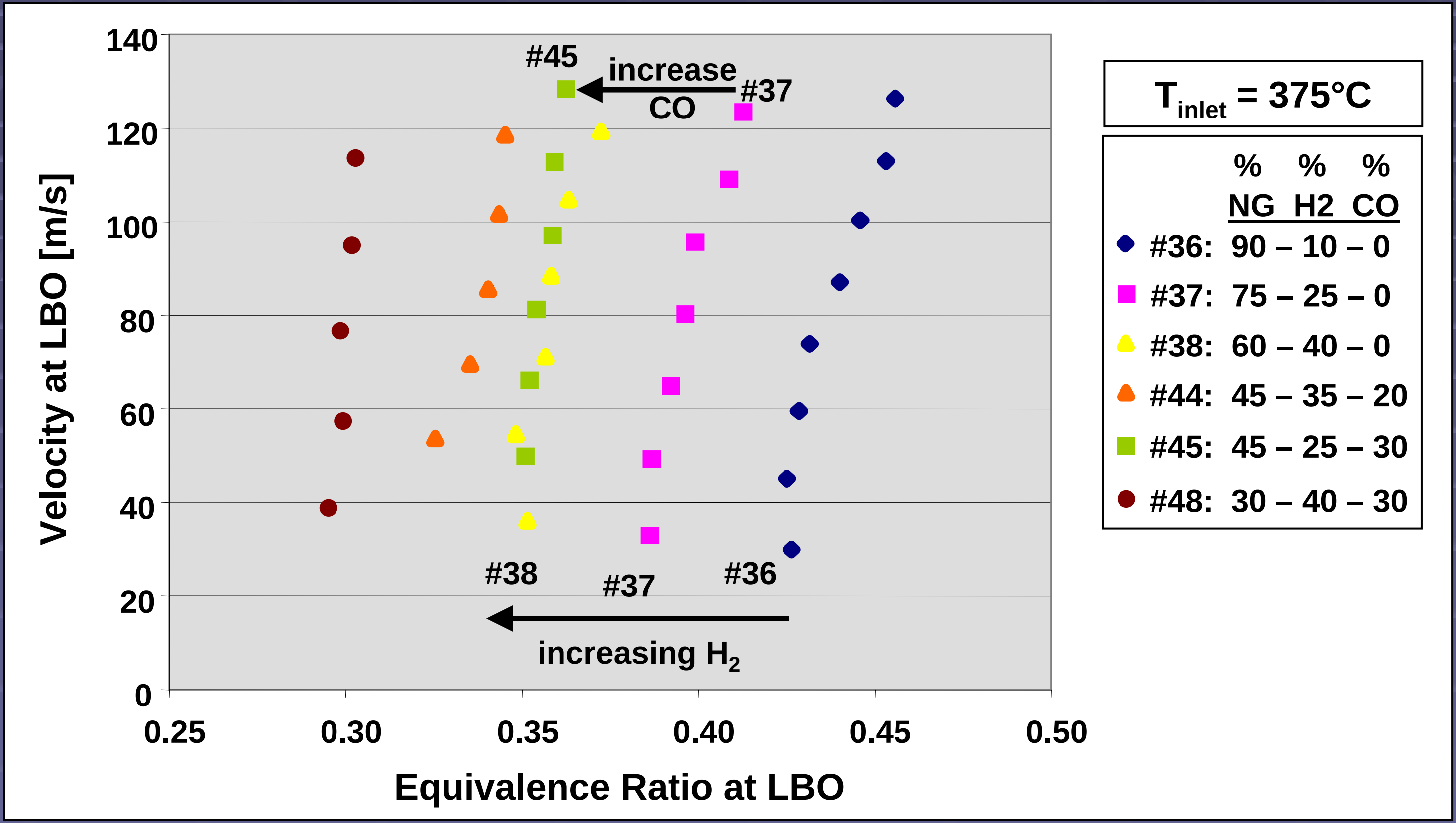
Case	Swirl	Inlet Temp	% Nat Gas	% H_2	% CO
20	30°	300°C	90	10	0
21	30°	300°C	75	25	0
22	30°	300°C	60	40	0
23	30°	300°C	45	55	0
24	30°	300°C	30	70	0
25	30°	300°C	15	85	0
26	30°	300°C	0	100	0
27	30°	300°C	45	45	10
28	30°	300°C	45	35	20
29	30°	300°C	45	25	30
30	30°	300°C	30	60	10
31	30°	300°C	30	50	20
32	30°	300°C	30	40	30
33	30°	300°C	15	75	10
34	30°	300°C	15	65	20
35	30°	300°C	15	55	30

Case	Swirl	Inlet Temp	% Nat Gas	% H_2	% CO
36	30°	375°C	90	10	0
37	30°	375°C	75	25	0
38	30°	375°C	60	40	0
39	30°	375°C	45	55	0
40	30°	375°C	30	70	0
41	30°	375°C	15	85	0
42	30°	375°C	0	100	0
43	30°	375°C	45	45	10
44	30°	375°C	45	35	20
45	30°	375°C	45	25	30
46	30°	375°C	30	60	10
47	30°	375°C	30	50	20
48	30°	375°C	30	40	30
49	30°	375°C	15	75	10
50	30°	375°C	15	65	20
51	30°	375°C	15	55	30

NG
NG -- H_2
NOT TESTED
NG -- H_2 -- CO

PENNSTATE 1855

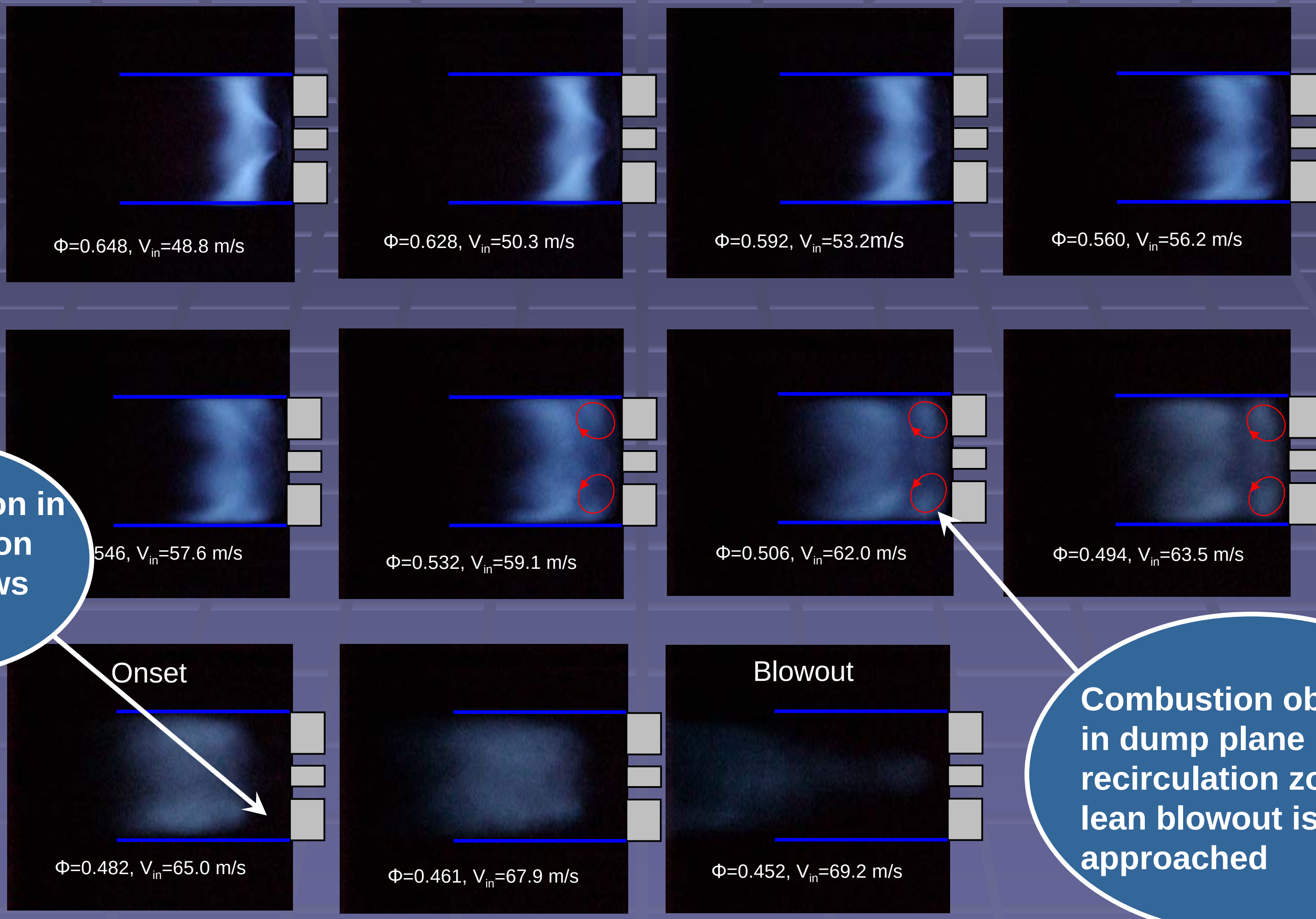
Lean Blowout Limits – Effect of Fuel Composition



→ both H_2 and CO lower the lean blowout limit, H_2 more than CO

PENNSTATE 1855

Transition to Lean Blowout



Combustion in recirculation zone "blows out"

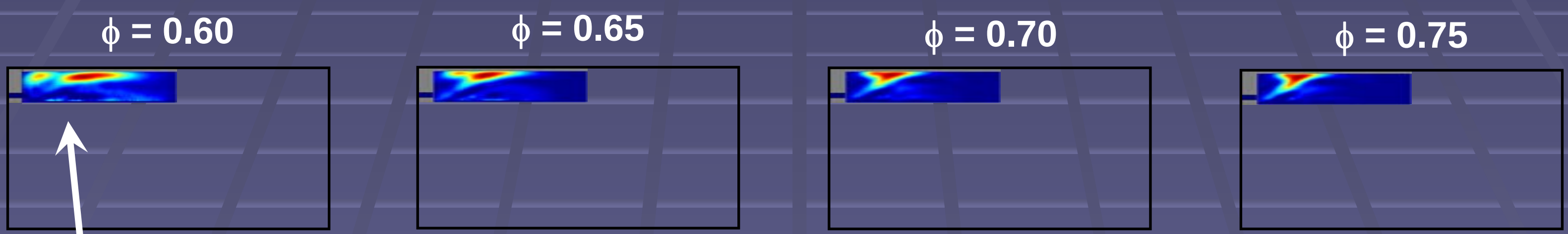
Combustion observed in dump plane recirculation zone as lean blowout is approached

PENNSTATE 1855

*** NOTE THAT FLOW IS FROM RIGHT TO LEFT**

2-D Chemiluminescence Images of the Transition to Lean Blowout

approaching lean blowout ←



Combustion in dump plane recirculation zone as lean blowout is approached

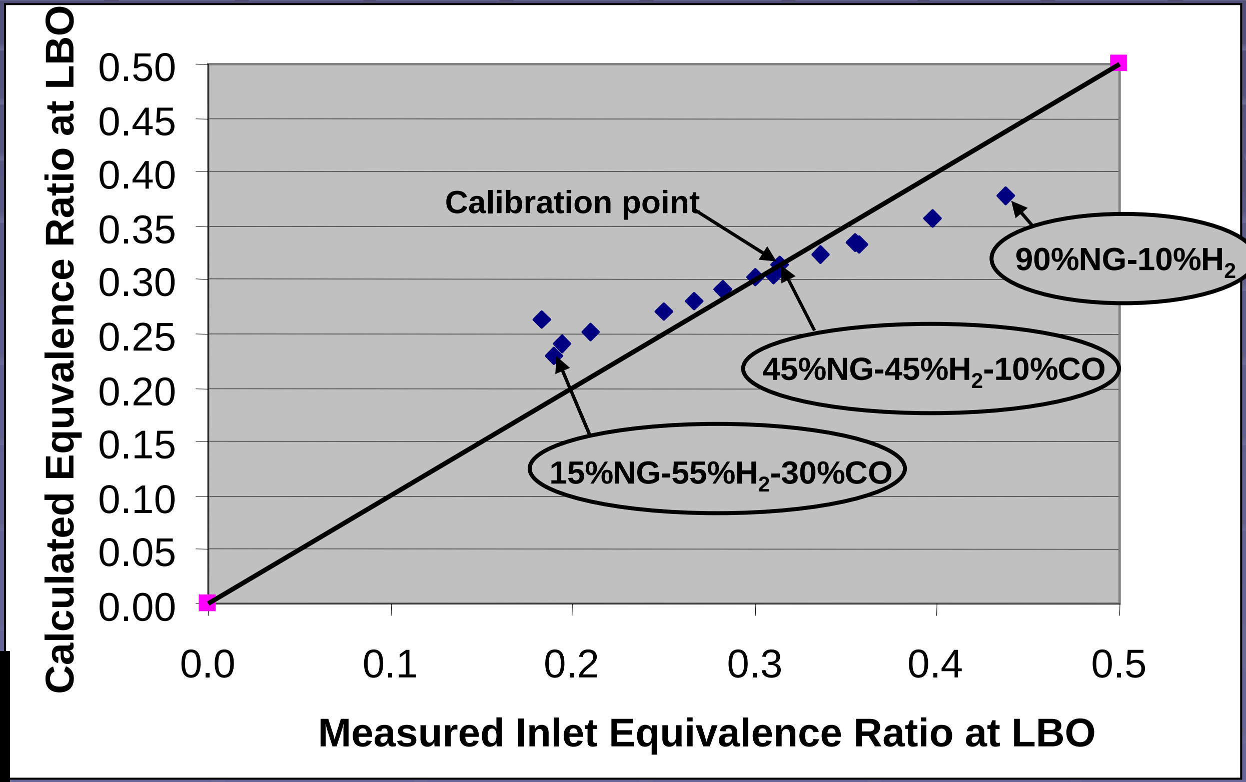
Use stirred reactor calculation to model lean blowout

PENNSTATE
1 8 5 5

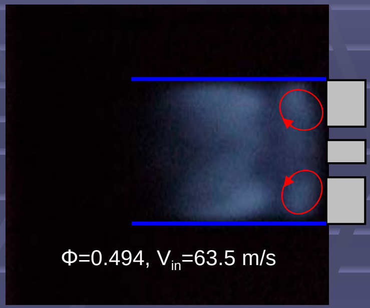
* NOTE THAT FLOW IS FROM LEFT TO RIGHT

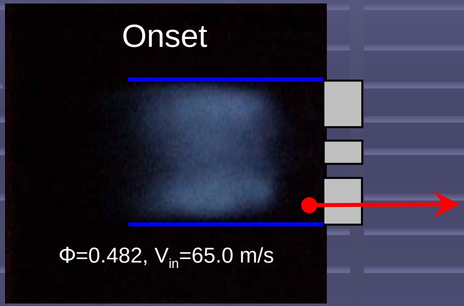
Stirred Reactor Prediction of Lean Blowout

- Chemkin with GRI MECH 3.0
- lean blowout of stirred reactor = LBO of combustor
- use inlet equivalence ratio and temperature
- cases 36 – 41 and 43 – 51 at 80 m/s
- calibrated at case 43 → τ_{res}= 0.584 msec

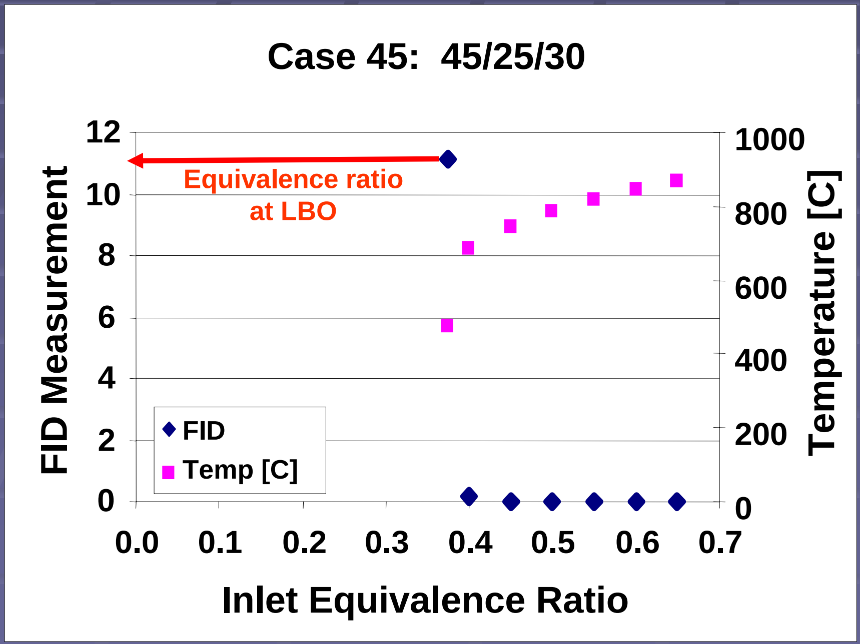


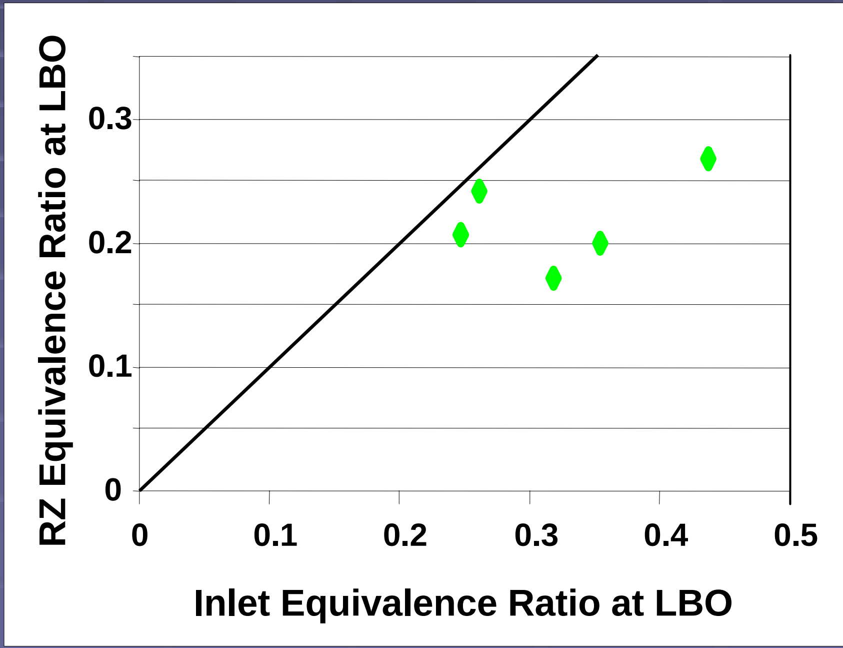
Improved(?) Stirred Reactor Prediction of LBO





Use equivalence ratio measured in dump plane recirculation zone at onset of LBO.





→ still working on this

Can Chemiluminescence Emission be used to Measure the Rate of Heat Release During Unstable Combustion?

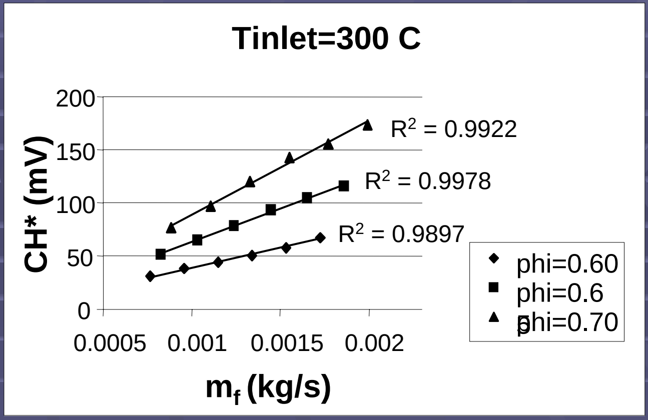
Previously, in steady flames it was shown that:

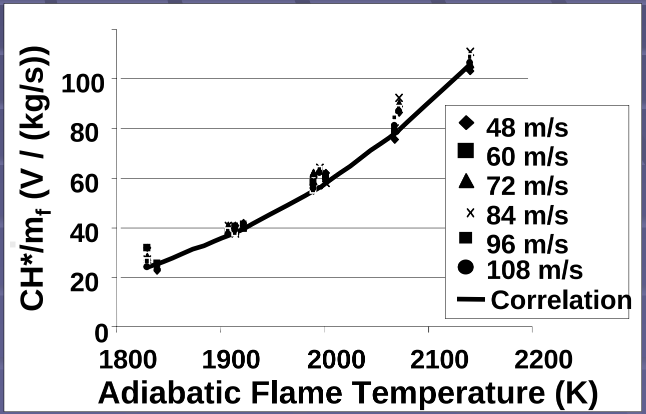
$$I_{CH^*\text{-}CO2^*\text{-}overall} = \kappa(\phi,T_{in})\,\dot{Q}_{overall}$$

$$= \kappa(\phi,T_{in})\cdot\dot{m}_{fuel}\cdot HV_{fuel}$$

$$= \kappa(T_{flame})\cdot\dot{m}_{fuel}\cdot HV_{fuel}$$

$$= e^{-1850/T_{flame}}\cdot\dot{m}_{fuel}\cdot HV_{fuel}$$





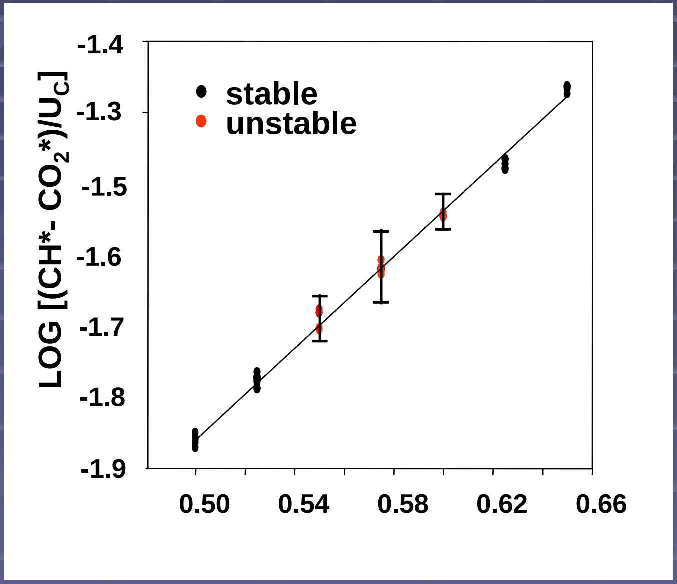
$I_{CH^*\text{-}CO2^*}$ is linearly dependent on the rate of heat release and exponentially dependent on the equivalence ratio.

Therefore, if there are equivalence ratio fluctuations, the average chemiluminescence intensity will be greater than if there were no equivalence ratio fluctuations.

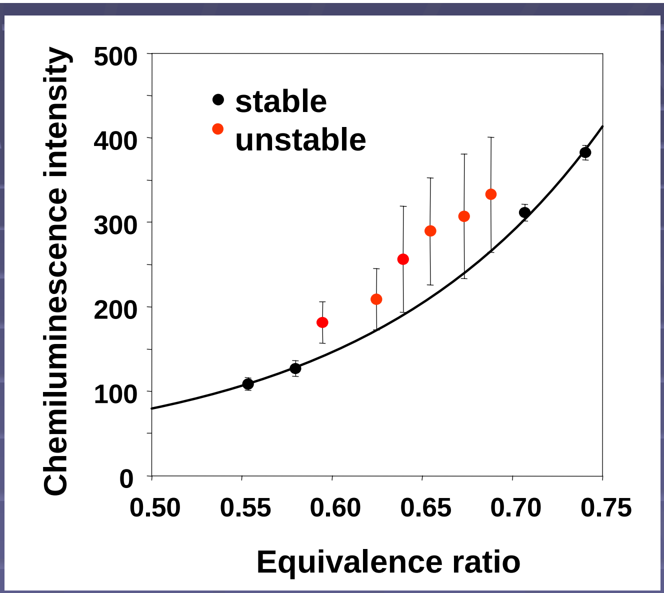
PENNSTATE
1 8 5 5

Chemiluminescence Measurements under Stable and Unstable Conditions

Heat release fluctuations, but no equivalence ratio fluctuations



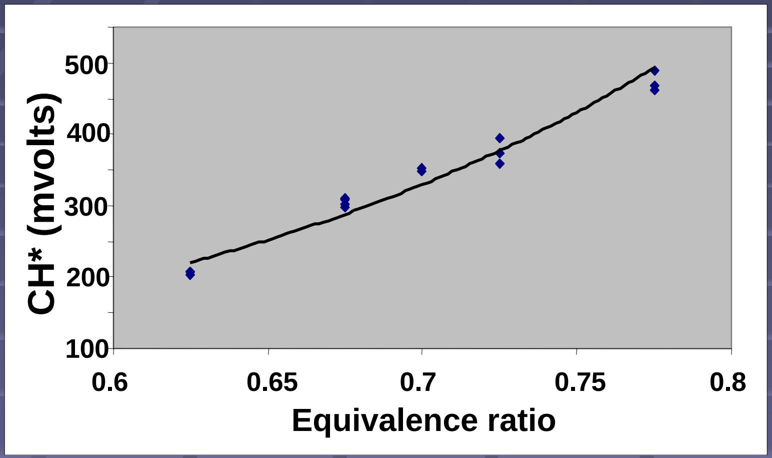
Heat release fluctuations and equivalence ratio fluctuations

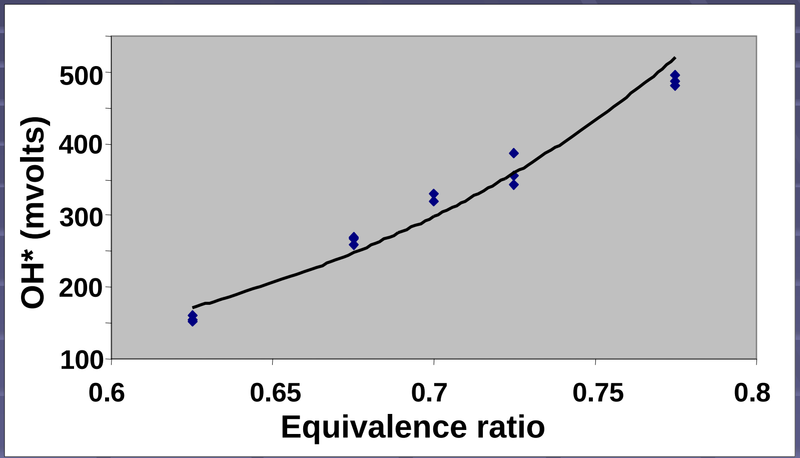


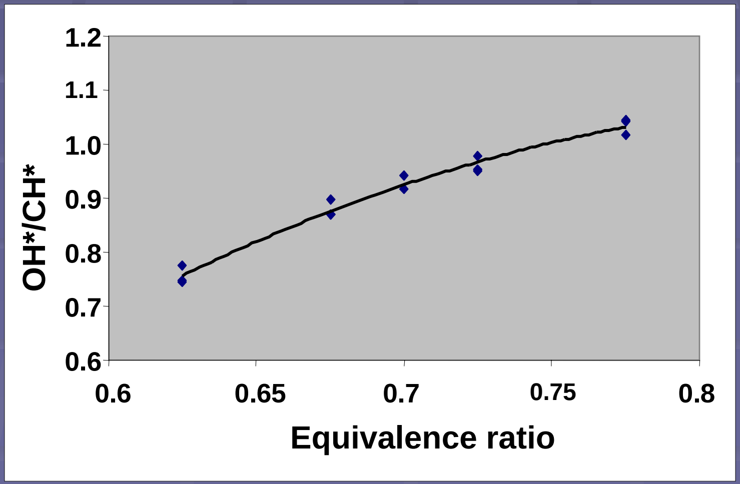
CONCLUSION → The fluctuating chemiluminescence intensity provides a direct measurement of the time-varying rate of heat release during unstable combustion if there are no equivalence ratio fluctuations.

→ If there are equivalence ratio fluctuations, they must be independently measured to determine the heat release fluctuation.

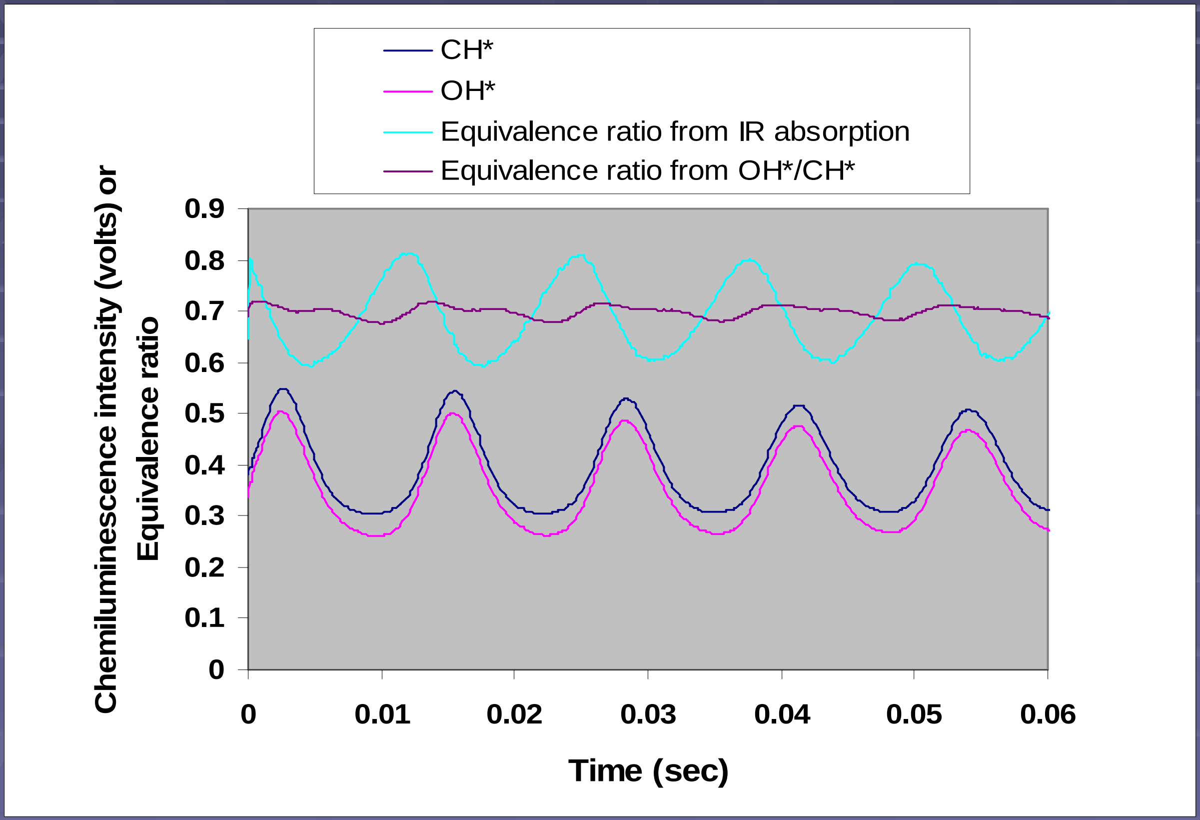
Recall Previously Proposed Strategy for Measuring Heat Release Fluctuations When There Are Equivalence Ratio Fluctuations



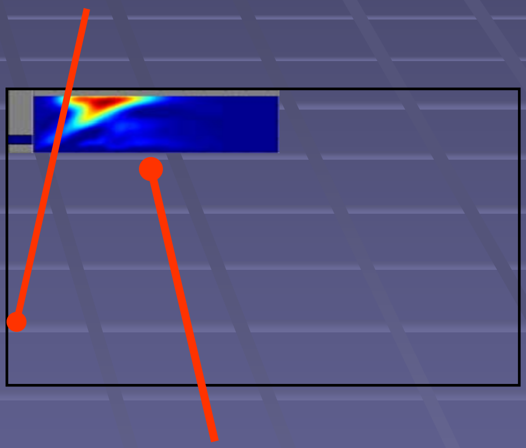




Compare IR and Chemiluminescence Equivalence Ratio Measurements During Unstable Combustion



→ IR absorption measurement near exit of mixing section.



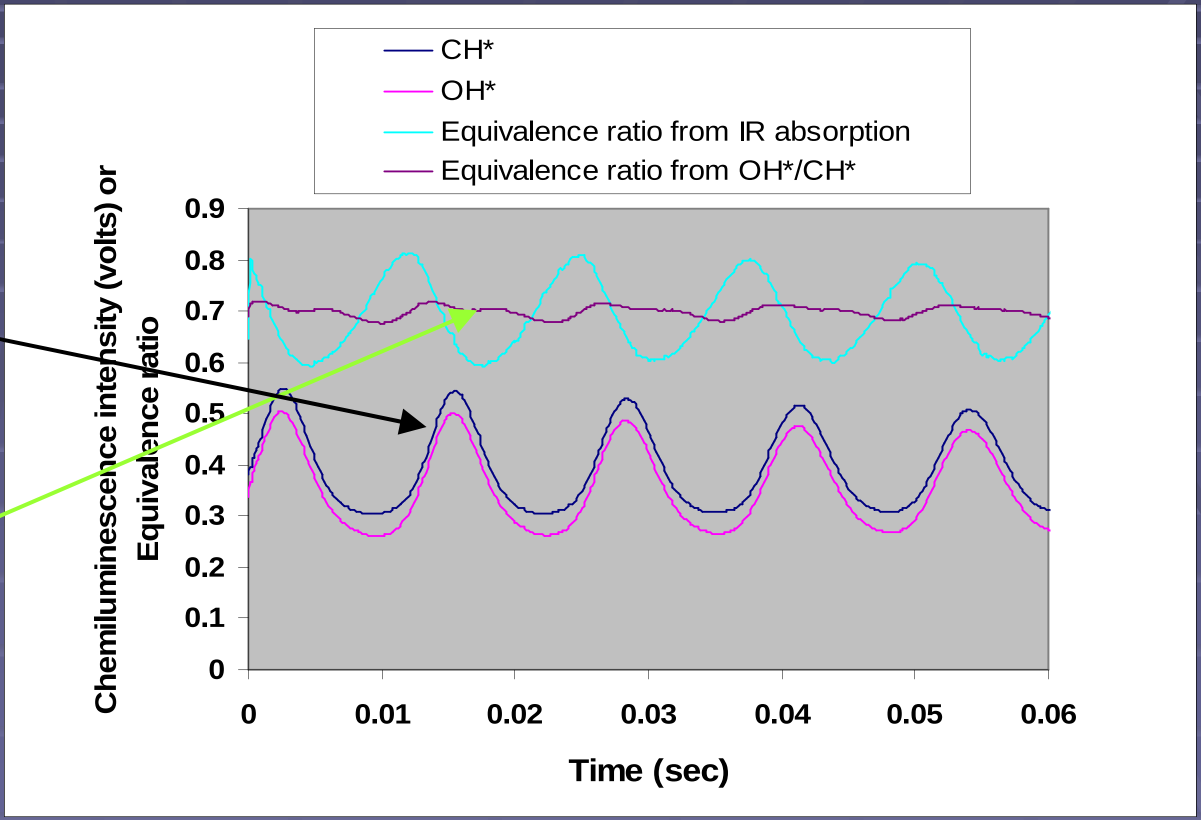
→ chemiluminescence measurement at flame front.

→ Indicates that equivalence ratio fluctuation at flame front is much smaller than in premixer

PENNSTATE 1855

Compare IR and Chemiluminescence Equivalence Ratio Measurements During Unstable Combustion

Therefore, part of the fluctuation in the chemiluminescence signal is due to heat release fluctuations and part is due to the indicated equivalence ratio fluctuations.



PENNSTATE
1 8 5 5

Predictions of unstable combustion using a flame-vortex time-lag model

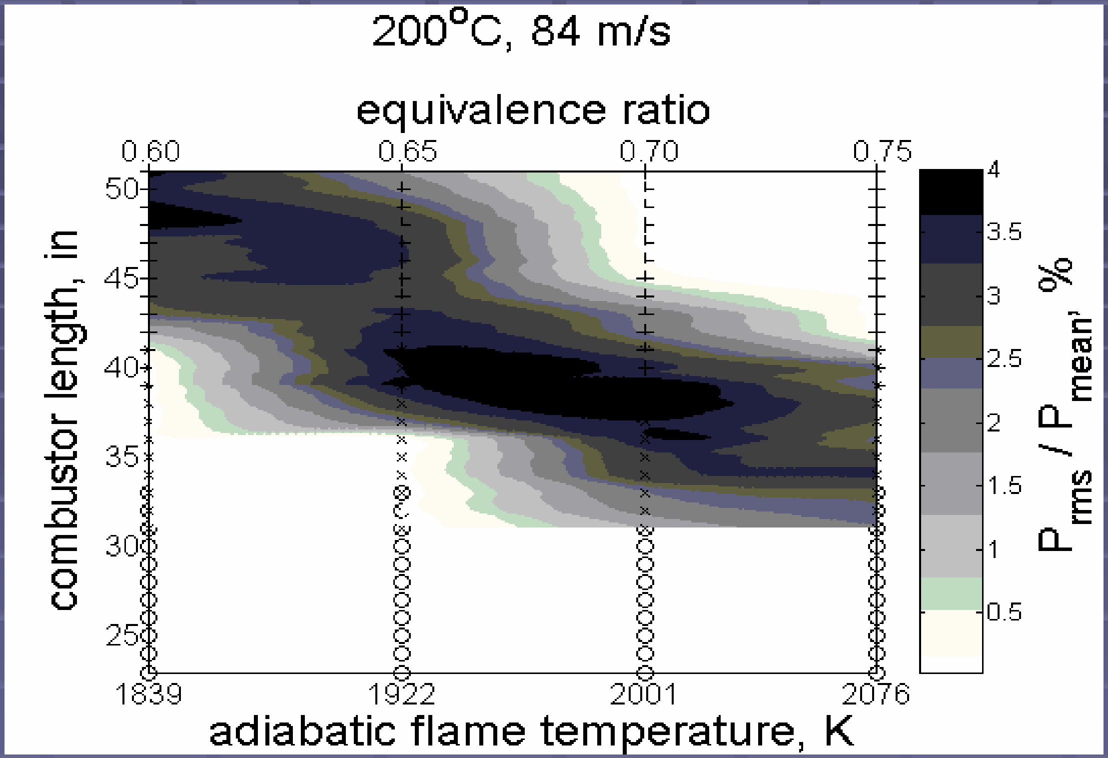
Test Conditions for Flame-Vortex Study in Variable-Length, Lean Premixed Combustor

Inlet Temperature	200°C and 400°C
Equivalence Ratio	0.55, 0.60, 0.65, 0.70, 0.75
Inlet Velocity	60, 72, 84, 96 m/s
Combustor Length	23 inch to 51 inch
Pressure	~110 kPa
Swirl	30 °
Fuel	natural gas

→ Fuel and air are premixed upstream of choked inlet to mixing section, therefore there are NO equivalence ratio fluctuations.

PENNSTATE 1855

Stability Map from Variable-Length Combustor



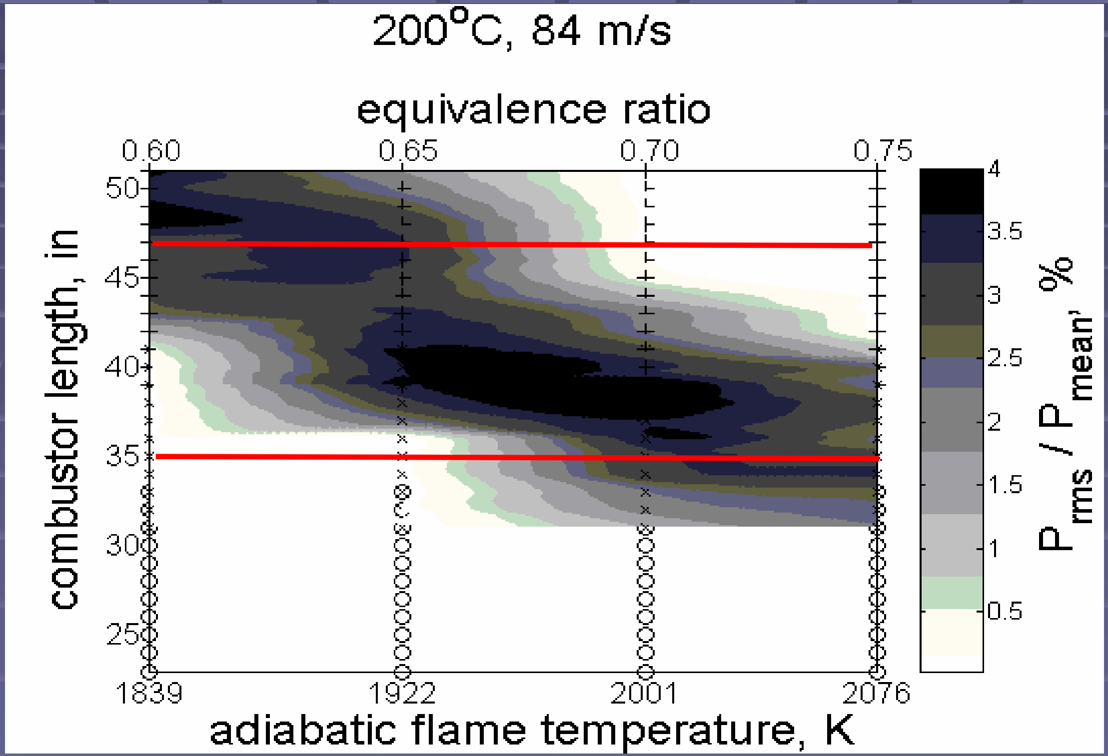
→ At every operating condition (T_{in}, V_{in}, ϕ) there is a combustor length at which the combustor is unstable.

→ Note that P_{rms}/P_{mean} is for fundamental frequency only.

→ For every operating condition we can identify the frequency at which the flame "wants" to go unstable.

PENNSTATE 1855

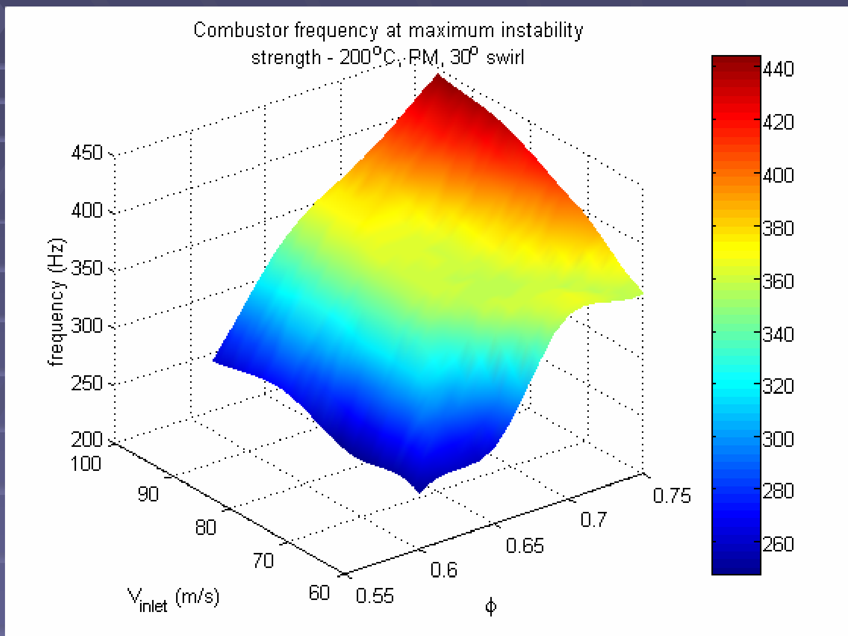
Fixed Combustor vs Variable-Length Combustor Stability Maps

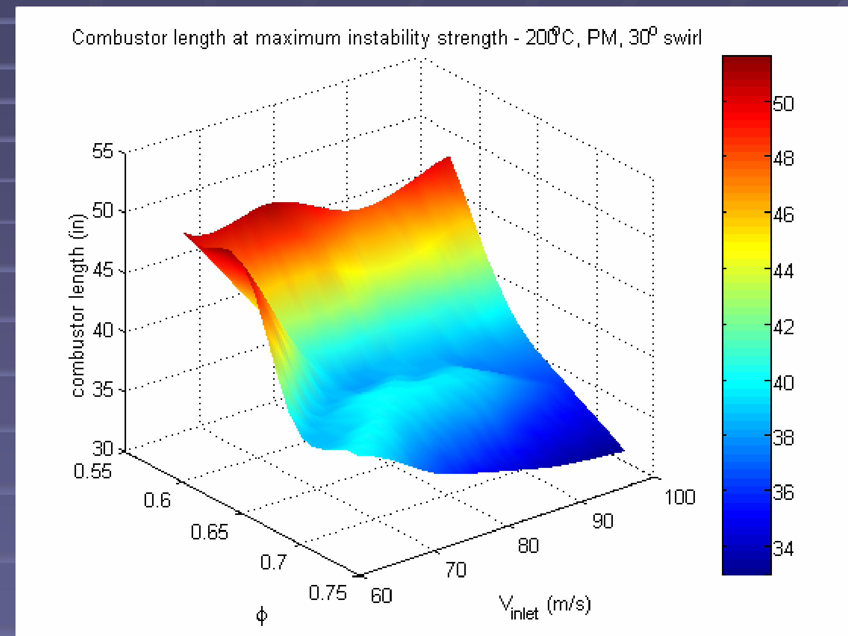


→Two fixed length combustors can give completely different stability characteristics at the same operating conditions.

PENNSTATE
1 8 5 5

Combustor Length and Instability Frequency for Strongest Instability as a Function of Operating Condition

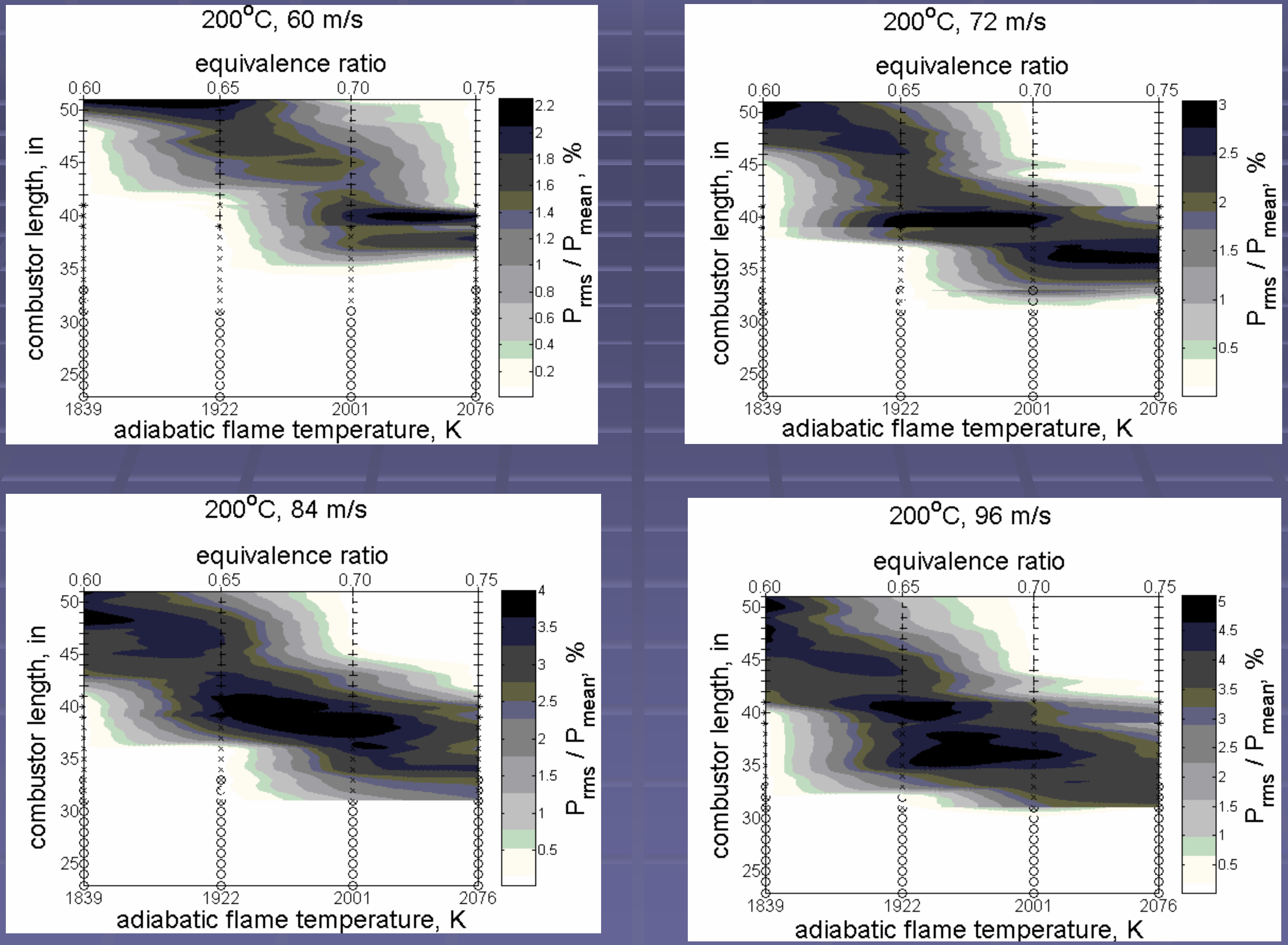




→ **These results indicate what combustor length and acoustic frequencies need to be avoided to avoid unstable combustion as a function of operating condition.**

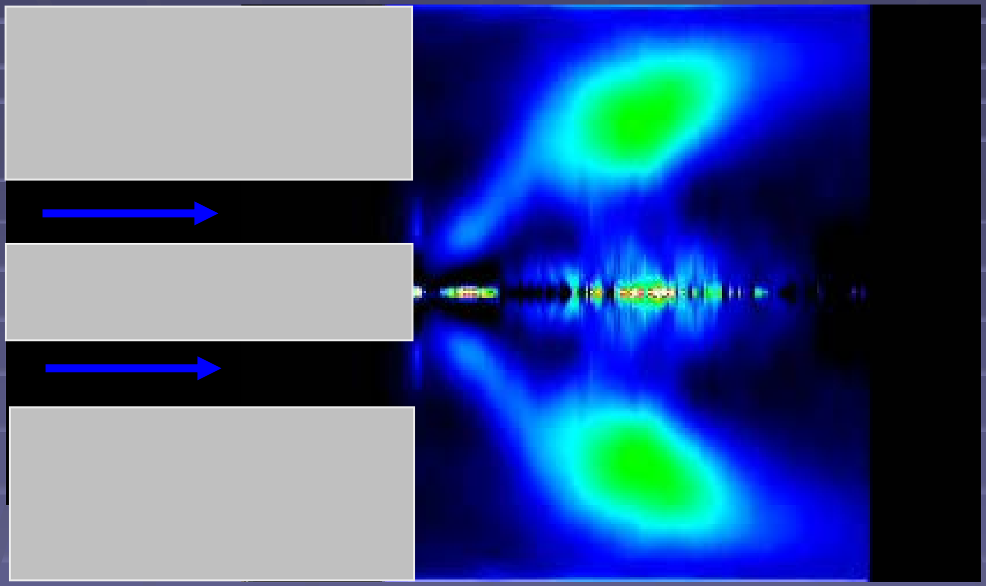
PENNSTATE

Stability Maps for 200°C Inlet Temperature



→ **Unstable regime moves to shorter combustors (higher frequencies) as velocity and equivalence ratio increase.**

Flame Structure Evolution During Unstable Combustion



→ Images are 2-D deconvolution of line-of-sight CH* chemiluminescence images.

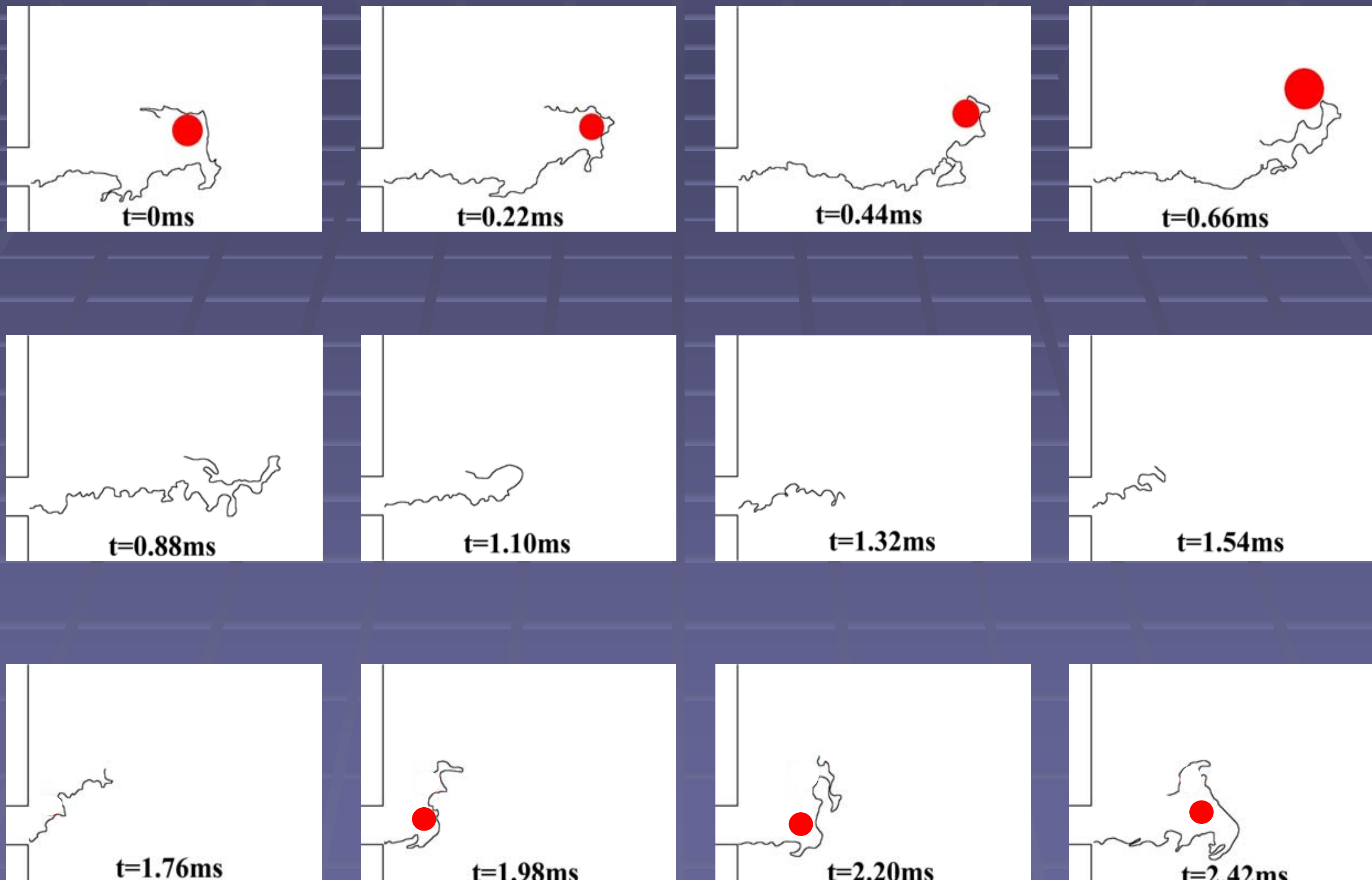
→ "Movie" is created from a sequence of phase-synchronized chemiluminescence images.

→ Shows evidence of flame-vortex interaction.

PENNSTATE

1 8 5 5

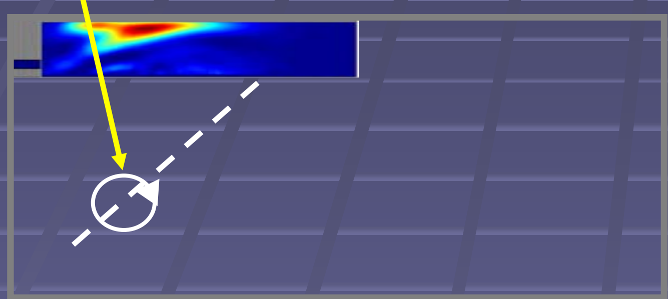
OH PLIF Measurement of Flame Structure Evolution During Unstable Combustion



PENNSTATE
1 8 5 5

Instability Mechanism: Forced Vortex Shedding Due to Acoustic Velocity Fluctuations

Vortex shed at time of maximum acceleration of flow.

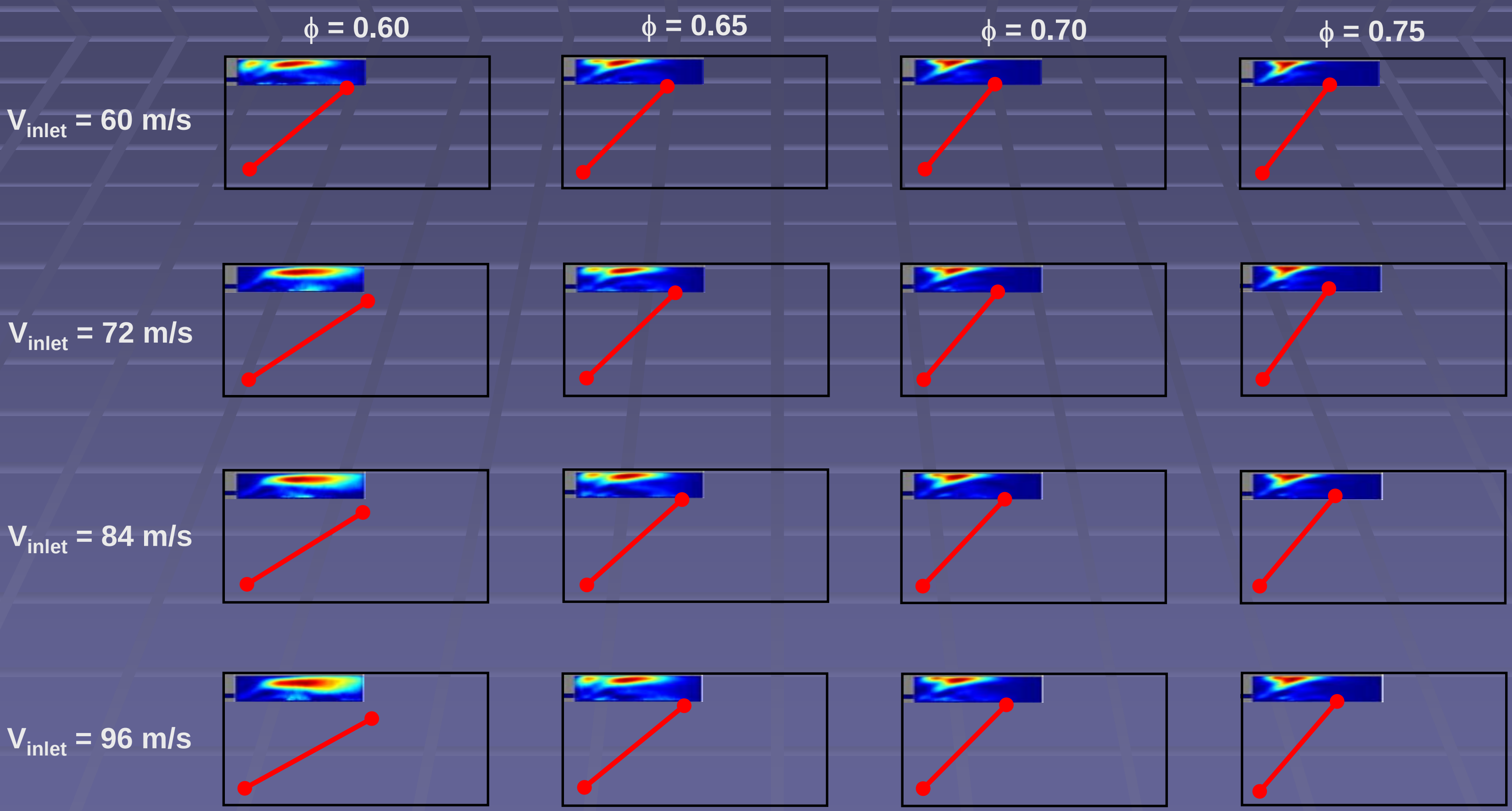


- Vortex entrains fuel and air, and then is convected to the flame location where it burns.
- Vortex transit time, $\tau_{vortex} = L_{fc} / V_{vortex}$ where L_{fc} is the distance from the edge of center body to the location of flame center and V_{vortex} is the convective velocity of the vortex and is a fraction, α, of V_{inlet}

→ if $\frac{1}{2} < \tau_{vortex} / T_{acoustic} < 1$ the heat release and the pressure fluctuations are positively correlated and the instability is encouraged

→ Need L_{fc} and α to predict whether or not a given combustor will go unstable at a given operating condition.

Distance to flame center (L_{fc}) was determined from CH* images of stable flames



** Stable flame give flame location at the onset of unstable combustion.

α is determined from phase-synchronized chemiluminescence images

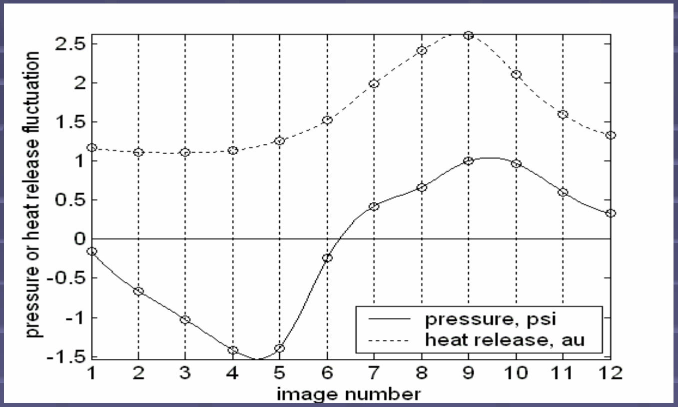


Image 1

Image 2

Image 3

Image 4

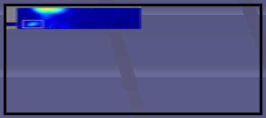


Image 5

Image 6

Image 7

Image 8

Image 9

Image 10

Image 11

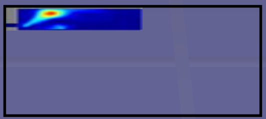
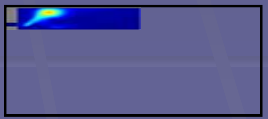


Image 12



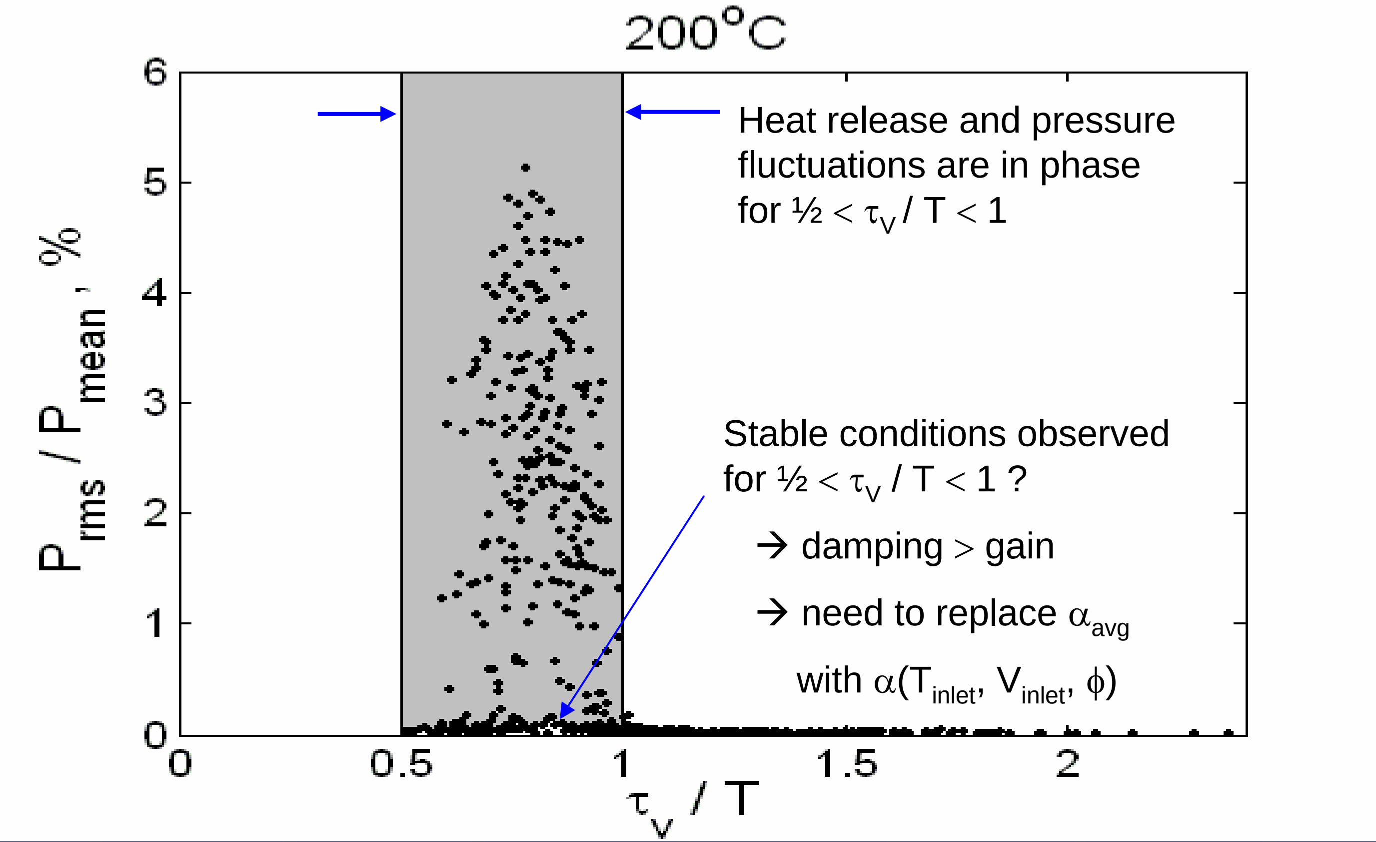
PENNSTATE

1 8 5 5

$0.29 \leq \alpha \leq 0.40$ for all cases → used $\alpha_{avg} = 0.345$

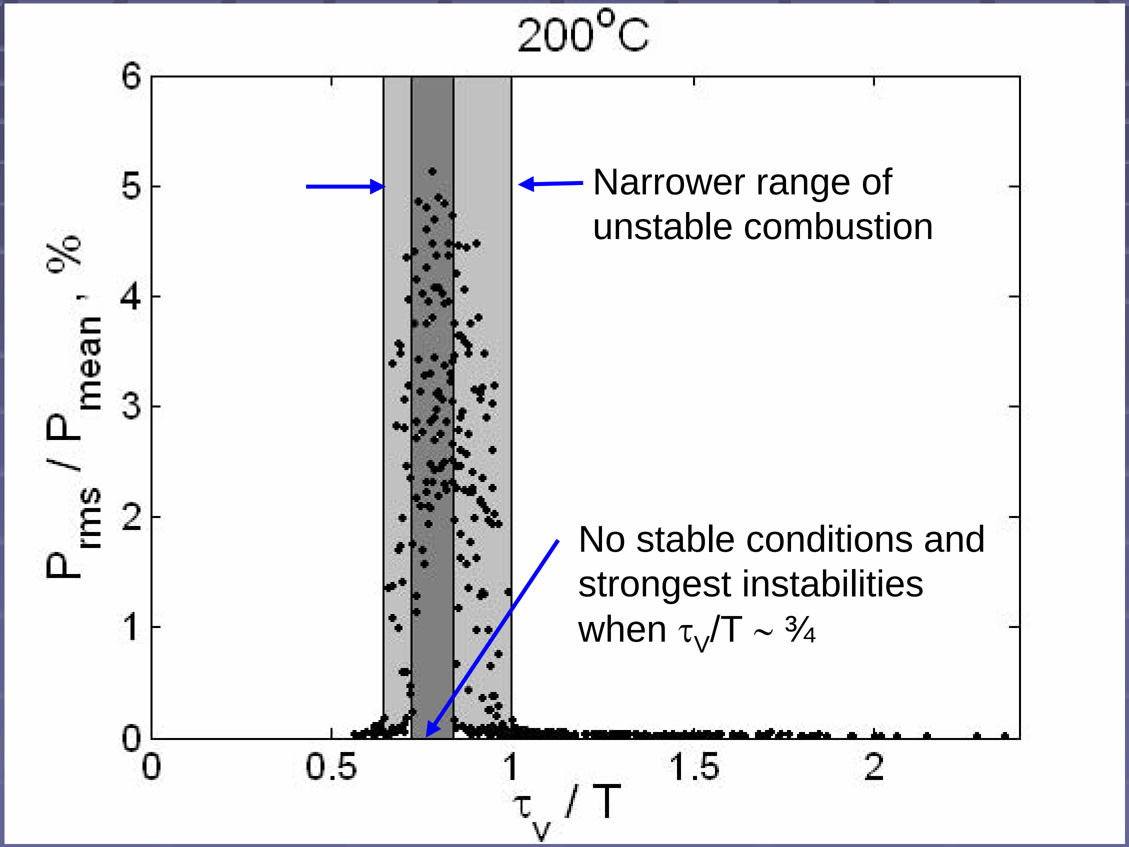
→ This is based on a limited set of conditions.

Time Lag Analysis of 200°C Data using $\alpha_{avg} = 0.345$



PENNSTATE 1855

Time Lag Analysis of 200°C Data using α_{avg} = 0.345 but eliminating data for shortest flames



Correlation for Prediction of Instability Frequency

→ Using 200ºC data and α_{avg} = 0.345 gives the following correlation with an R^2 value of 0.91 (0.95)

$$\boxed{f_{instability} = 0.96\ \alpha\ V_{inlet} / L_{flame\ center}}$$

→ Using measured or calculated $L_{flame\ center}$ for stable flames as a function of operating conditions, this correlation can be used to predict the frequency of the instability at a given operating condition, from which it can be determined whether or not the combustor will be unstable.

PENNSTATE
1 8 5 5

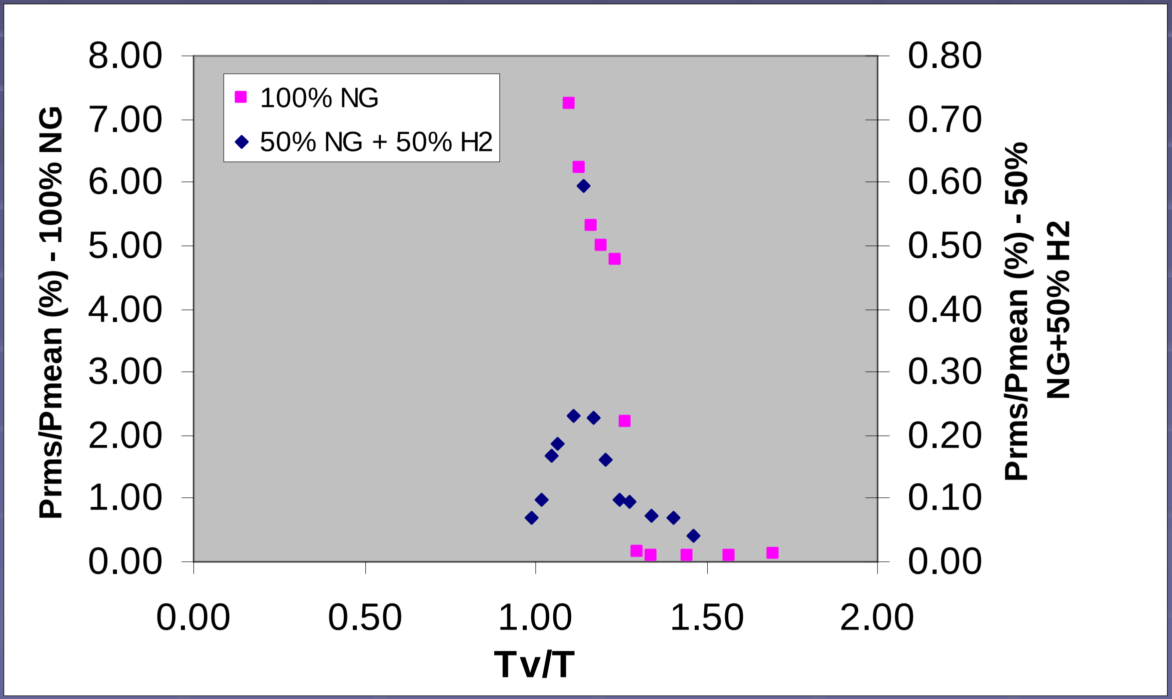
Use Vortex Time Lag Model to Predict Unstable Operating for 50% NG / 50% Hydrogen Fuel Mixture

- 100 % NG (f=0.7)and 50% NG+50 % H2 (f=0.525)

- where the distance to COM was 71 mm

- inlet velocity was 84 m/sec

- inlet temperature was 200 C



PENNSTATE 1855

Summary

- Lean blowout limits have been measured for a broad range of natural gas – hydrogen – carbon monoxide fuel mixtures.

- A stirred reactor model of combustion in the dump plane recirculation zone has given very encouraging predictions of the lean blowout limit and its dependence on fuel composition.

PENNSTATE
1 8 5 5

Summary (cont'd)

- The viability of making chemiluminescence-based heat release measurements during unstable combustion in the absence of equivalence ratio fluctuations has been demonstrated.

- A previously proposed strategy for making chemiluminescence-based heat release measurements during unstable combustion with equivalence ratio fluctuations has been assessed.

PENNSTATE 1855

Summary (cont'd)

- A flame-vortex time-lag model has been shown to be capable of predicting whether a combustor is stable or not for given operating conditions <u>and</u> fuel properties.

PENNSTATE 1855

Personnel

Jeff Lane (undergrad)

Jessica Ruehr (undergrad)

Helene Krenitsky (undergrad)

Esteban Gonzalez (MS student)

Tyler Morris (MS student)

Dr. Bryan Quay

Dr. Jongguen Lee

PENNSTATE 1855