Combustion Instability Studies for Application to Land-Based Gas Turbine Combustors

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Abstract

The current effort involves four tasks which address, respectively, (1) the development of a fiber-optic probe for fuel-air ratio measurements, (2) a study of combustion instability using laser-based diagnostics in a high pressure, high temperature flow reactor, (3) the development of analytical and numerical modeling capabilities for describing combustion instability which will be validated against experimental data, and (4) the preparation of a literature survey and establishment of a data base on practical experience with combustion instability. This task is intended to provide a mechanism for scaling the results of the laboratory and sub-scale studies to actual gas turbine engine applications.

Fiber-Optic Equivalence Ratio Probe

The accomplishments related to the fiber-optic equivalence ratio probe are: (i) the probe has been successfully tested for a second time in the 1atm.test rig at Westinghouse's test facility in Casselbury, Florida - radial profile measurements have been made at the exit of the fuel mixing passageway; (ii) several improvements have been made to the probe for ease of use in non-laboratory environments; and (iii) a modified version of the probe has been developed for use in liquid fueled combustors - preliminary tests have been conducted at Penn State to assess its capabilities and limitations.

Future plans involve the continued evaluation and testing of the probe for use in liquid fueled systems. In addition, planning has been initiated for testing the probe in a liquid fueled combustor at Westinghouse's test facility in Ontario, Canada.

High Pressure Flow Reactor Combustion Instability Studies

Efforts on the high pressure, high temperature flow reactor have focused on the investigation of combustion instabilities related to swirl injectors operating with natural gas at chamber pressures up to eight atmospheres. Operating conditions at which combustion instabilities occur have been experimentally determined and the type of instabilities carefully characterized. These correspond primarily to the first longitudinal mode of the combustion chamber with frequencies between 1100 and 2000 Hz. Phase-resolved CH chemiluminescence images of unstable flame have been taken and showed that heat release occurs when pressure oscillations are at a maximum. These results are encouraging and provide an excellent qualitative agreement with the Rayleigh criterion stating that combustion instability can be sustained only if pressure oscillations and heat release rates are in phase.

Modeling of Combustion Instability Mechanisms

A unified theoretical/numerical analysis has been established to investigate unsteady motions in cylindrical combustors with GE-DLN2 injectors. The analysis was established at two levels of detail in terms of formulation of flow motions. A numerical analysis was first conducted to obtain the flowfields and flame structures under steady-state conditions. The model was based on the complete conversion equations in three dimensions with finite-rate chemical kinetics and variable properties, and was solved numerically by means of a preconditioning technique. Turbulence closure was achieved using a modified k-ε two-equation scheme. Good agreement with experimental data has been obtained in terms of the flame shape and heat release distribution. The calculated steady-state solutions were then incorporated into an approximate analysis which treated the interactions between flame dynamics and local flor oscillations. The methodology established in this task can be effectively used to determine the stability characteristics of any gas-turbine injectors subject to longitudinal pressure disturbances.

The above framework was first applied to study the flame response to longitudinal acoustic oscillation for cases involving single injectors. Acoustic transmission and reflection properties for disturbances incident from both upstream and downstream regions have been obtained. This information is instrumental in identifying the salient variables for designing stable swirl-injectors. The same approach was extended to study the stability characteristics of a cylindrical combustor having four injectors. Special attention was given to the effect of mass flow distribution among the injectors on the stability characteristics of the combustor. Detailed results in terms of injector coupling may serve as a guideline for maintaining the stability of the combustor.

Acknowledgments

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Modelling of Combustion Instability Mechanisms

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- **Research Objective**

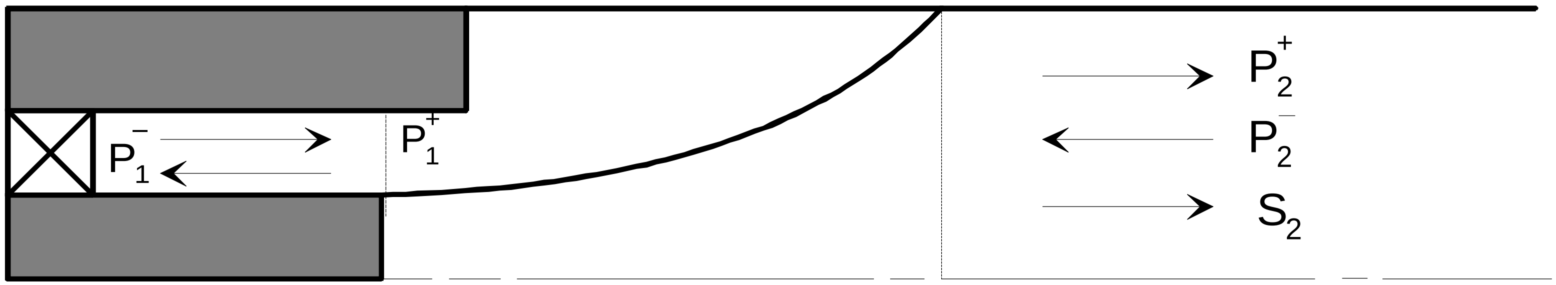
  - Establishment of a theoretical/numerical framework for analysis of steady and unsteady flow motions in a gas turbine combustor

- **Research Foci**

  - Fundamental understanding of interactions between flame dynamics and local flow oscillations
  - Investigation of the relationships between the linear and nonlinear characteristics of the unsteady motions

- **Methods of Approach**

  - Approximate analytical analysis of unsteady flow motions
  - Numerical simulation of steady-state flowfields in three dimensions



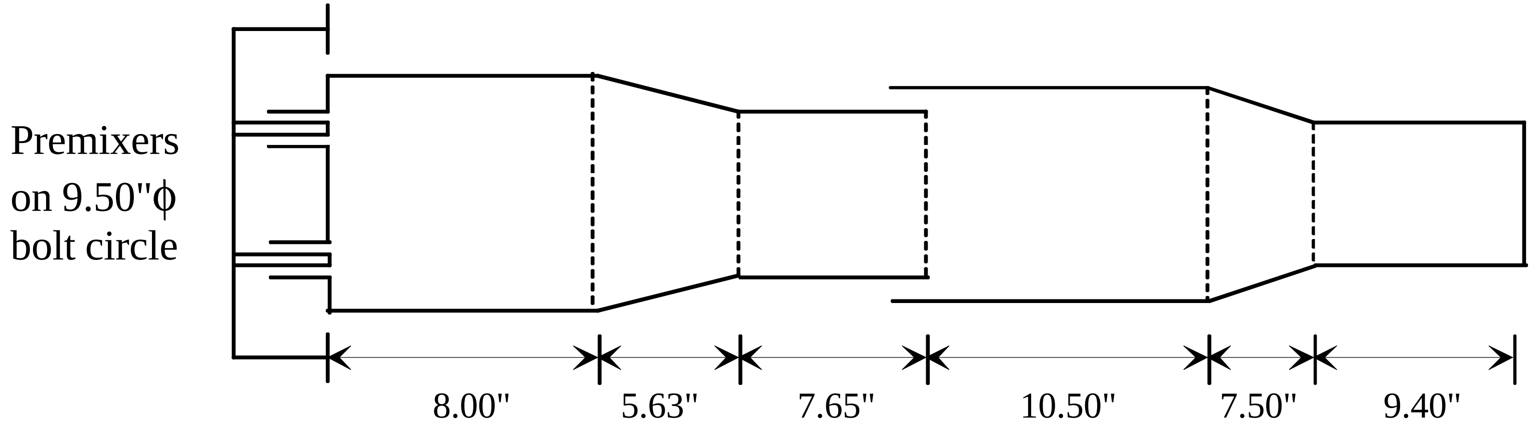
Approximate Analysis of Unsteady Flow Motions

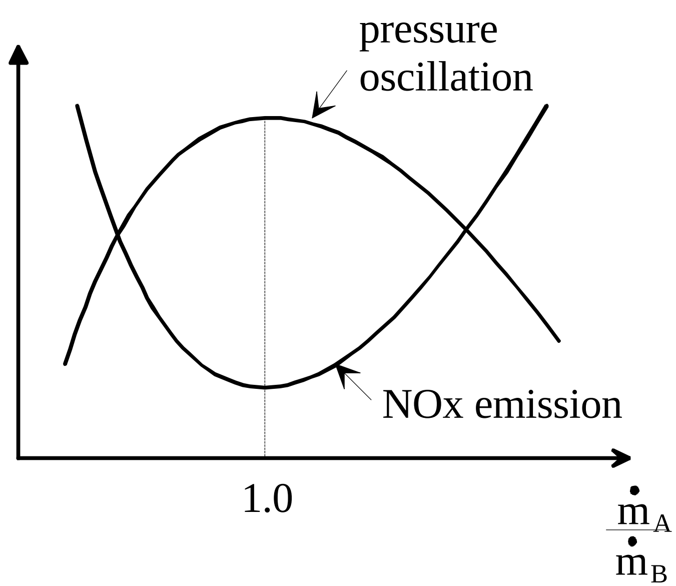
- Integral formulation of flow motions
- Unsteady flame dynamics to local disturbances
- Acoustic, entropy, and vortical oscillations

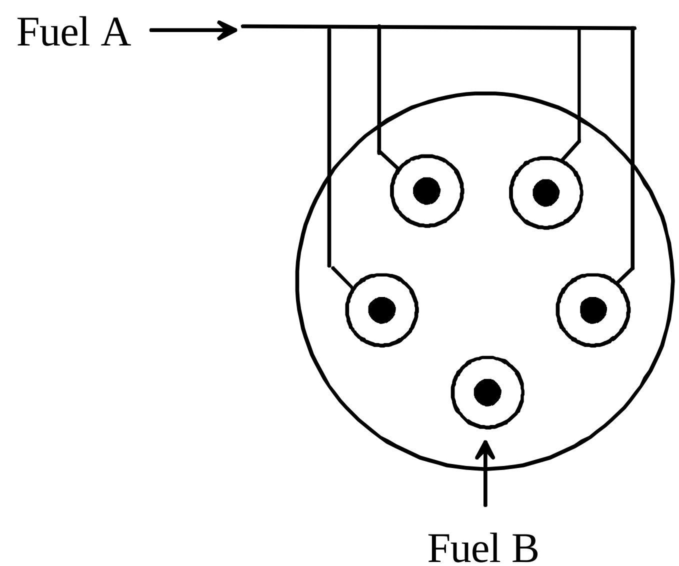
Numerical Simulation of Mean Flowfields

- Full conservation equations of mass, momentum, energy, species concentration in three dimensions
- Variable transport and thermodynamic properties
- Finite-rate chemical kinetics
- Turbulence closure by k-ε model

Investigation of Effect of Fuel-Biasing on Combustion Dynamics

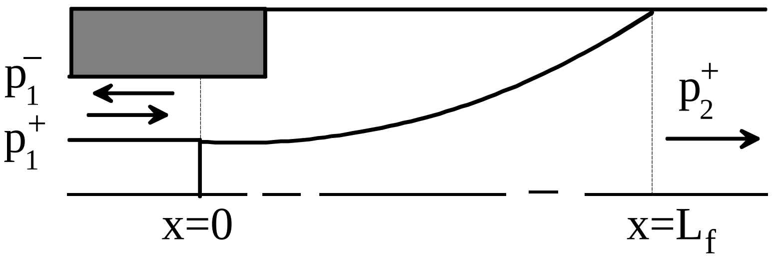






Dynamic Response of Single Injector Flame to Longitudinal Acoustic Disturbances

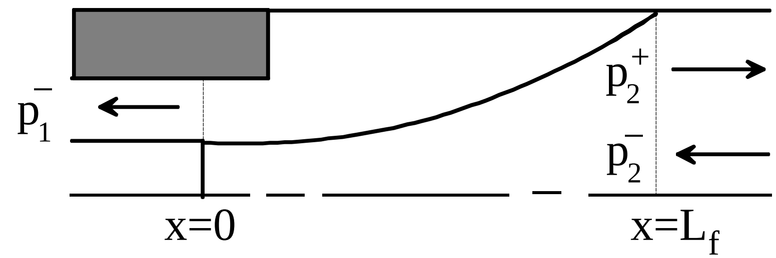
- Disturbance from upstream



$$\text{Transmission Coeffieicnt} = \frac{p_2^+}{p_1^+}$$

$$\text{Reflection Coeffieicnt} = \frac{p_1^-}{p_1^+}$$

- Disturbance from downstream



$$\text{Transmission Coeffieicnt} = \frac{p_1^-}{p_2^-}$$

$$\text{Reflection Coeffieicnt} = \frac{p_2^+}{p_2^-}$$

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Axial Velocity Contour and Streamlines in Four-Injector Combustor

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Temperature Contour and Streamlines

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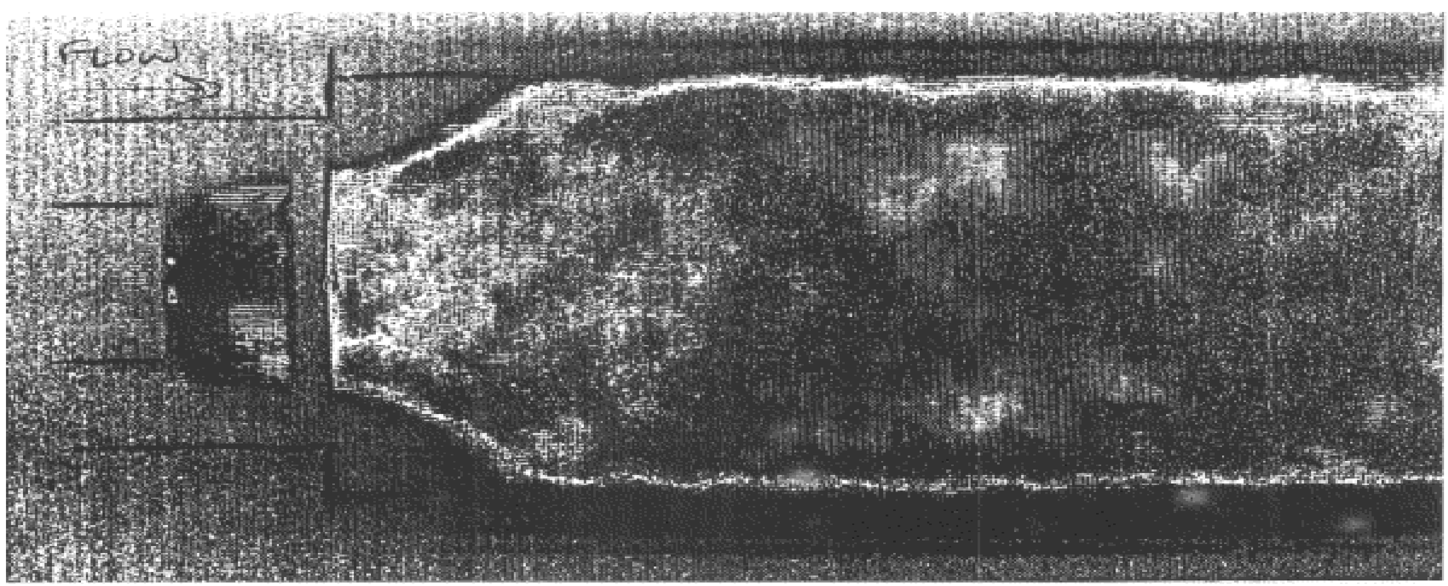
CH Image of the Flame



EXPERIMENTAL STUDIES OF COMBUSTION DYNAMICS

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The Pennsylvania State University

Objectives

- Provide an understanding of the effects of combustor design and operating parameters on combustion instability under low emissions and high performance conditions.
- Develop a predictive capability for gas turbine combustion stability which is based on an extensive experimental data base.

Approach

- Develop empirical map of stable/unstable operating regimes.

  Test variables:

Fuel-air ratio	Level of premixing
Chamber length	Inlet air temperature
Injector geometry	Swirl level

- Obtain *in-situ* measurements of key combustion parameters.
- Interpret data using combustion response model.

Operating Conditions

Inlet Air Temperature: $315 < T_o$ (° C)< 455

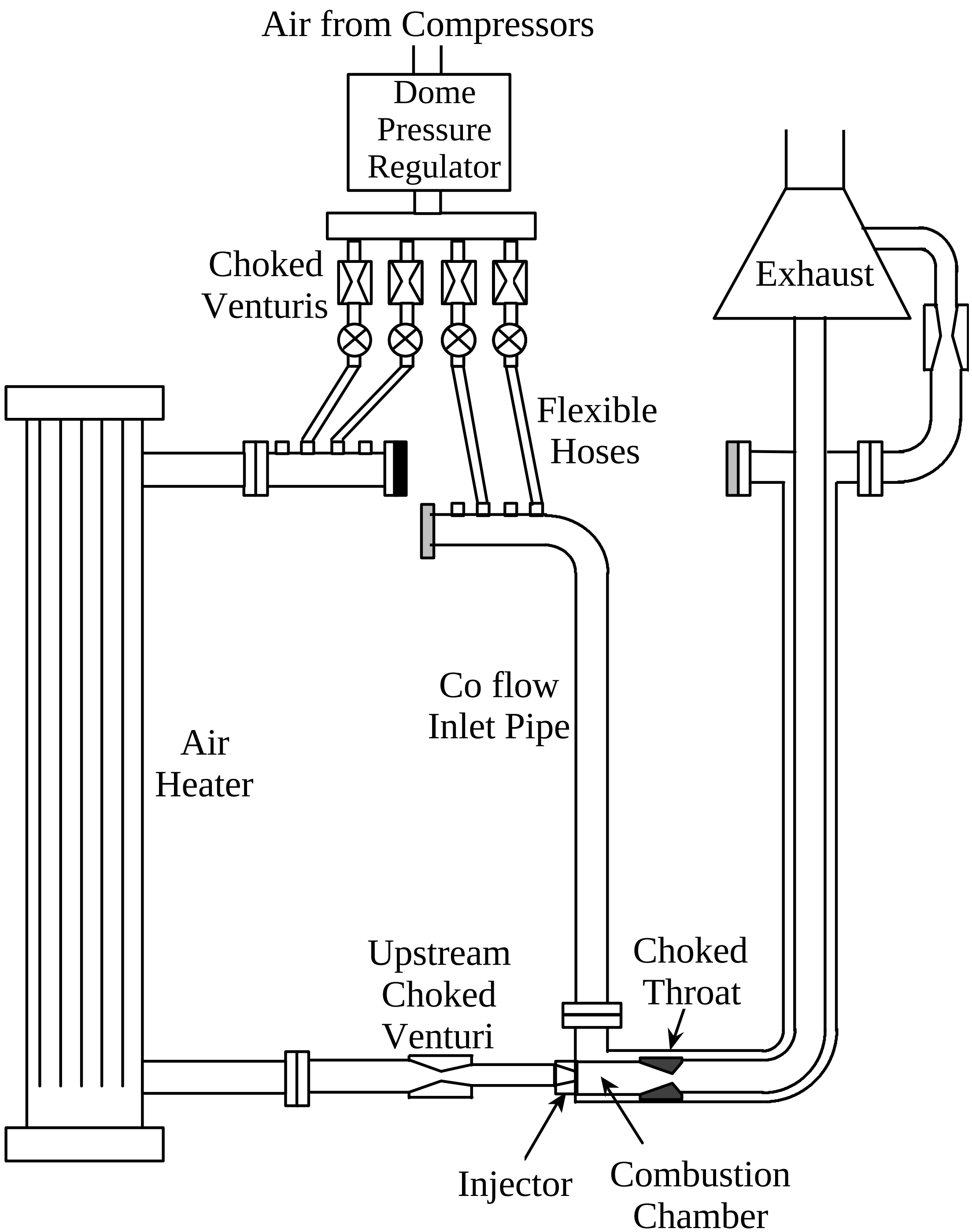
Equivalence Ratio: $0.50 < \phi < 0.80$

Air Flow Rate: $30 < \dot{m}_a$ (g/s) < 70

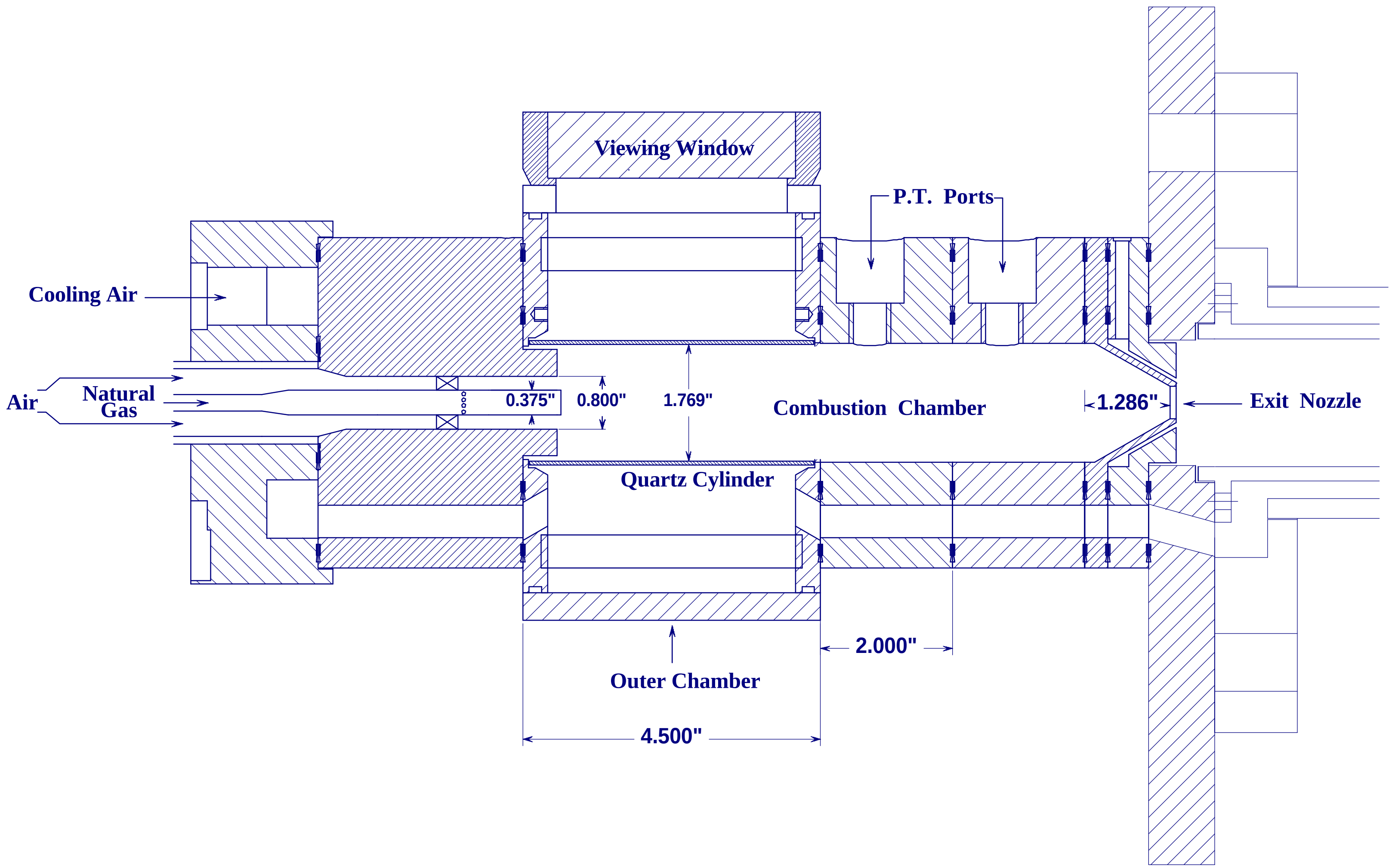
Chamber Pressure: 3 atm.$< P_c <$ 7 atm.

Average Inlet Velocity (Unburned): $V_u \cong 13$ m/s

Average Velocity in Combustor (Burned): $V_b \cong 45$ m/s



Schematic of Experimental Setup
(Non-Regenerative Mode)



Cutaway View of the Combustion Chamber

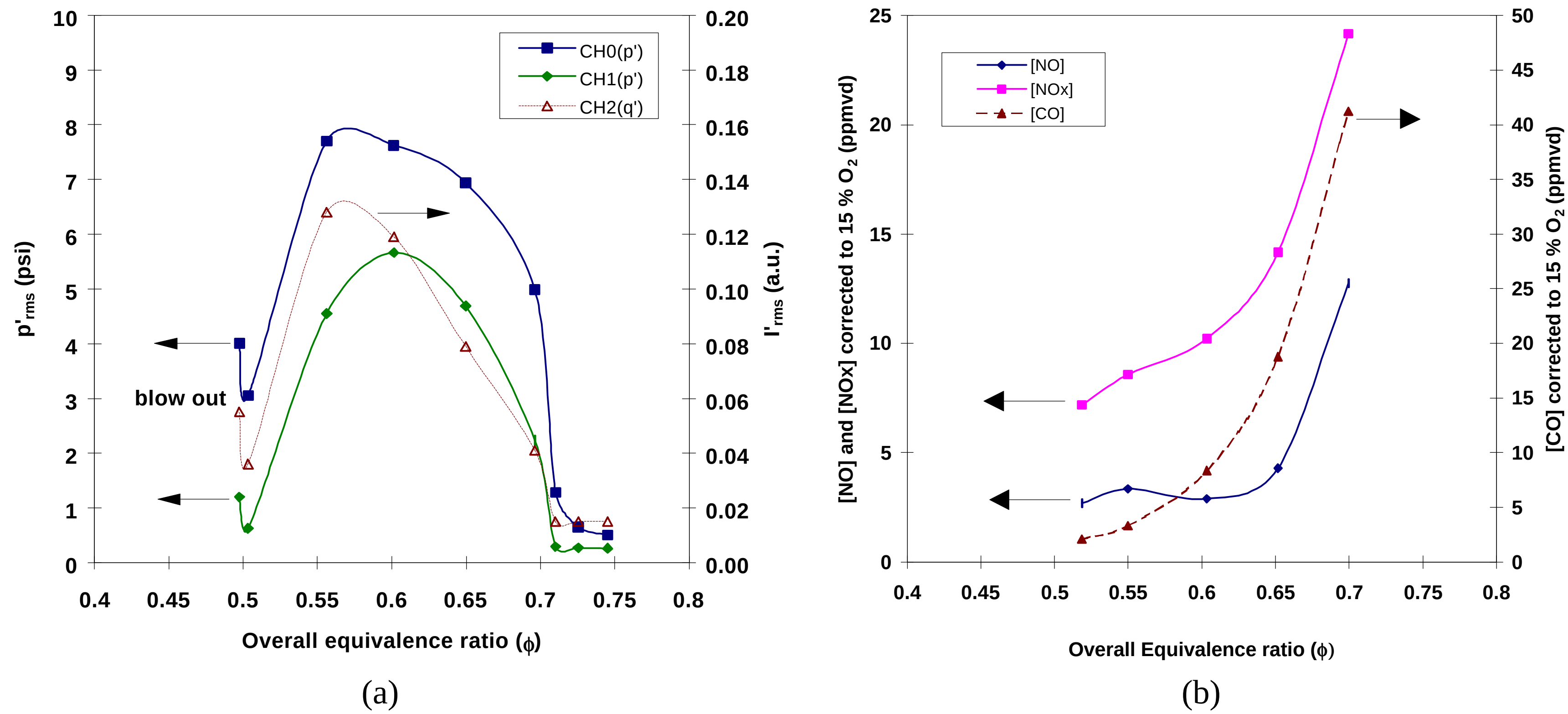
Stability Map

Conditions for unstable flame:

- $T_o > T_{omin} \cong 400°C\ (750°F)$
- $0.50 < \phi < 0.70$

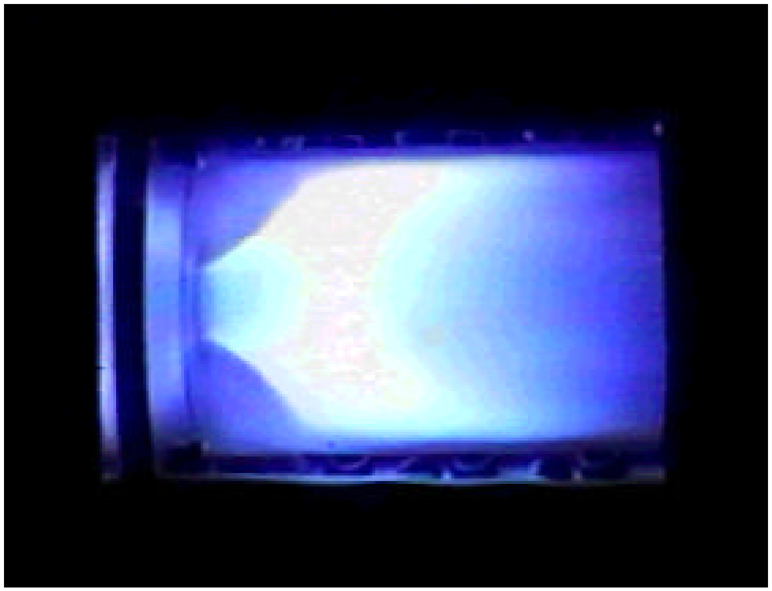
Important Trends:

- T_o's higher than T_{omin} do not alter strength of instability
- Instabilities strongest around $\phi = 0.60$
- Longer chambers produce much stronger instabilities
- Effect of higher pressures (Pc =7 - 8 atm.) on T_{omin} ?

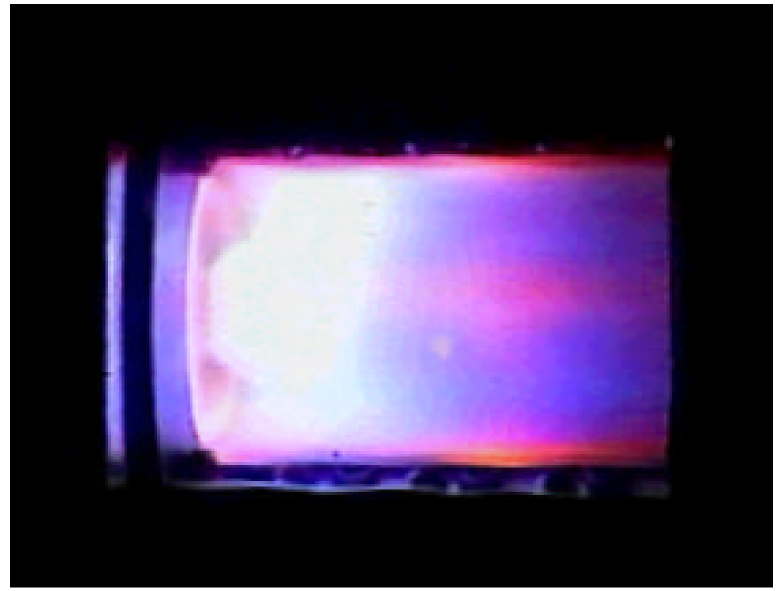


(a) RMS of pressure and CH chemiluminescence signal fluctuations as a function of equivalence ratio at P_c=4.57 atm

(b) NO, NO_x, and CO dry concentrations at P_c=6.3 atm and T_o=390^{o}C

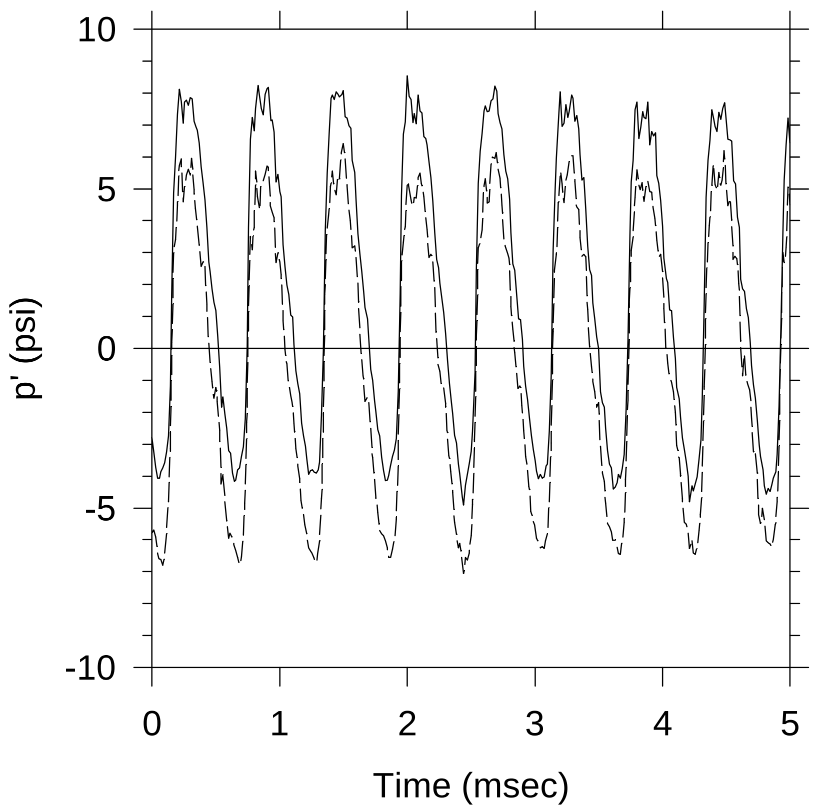


Stable Flame

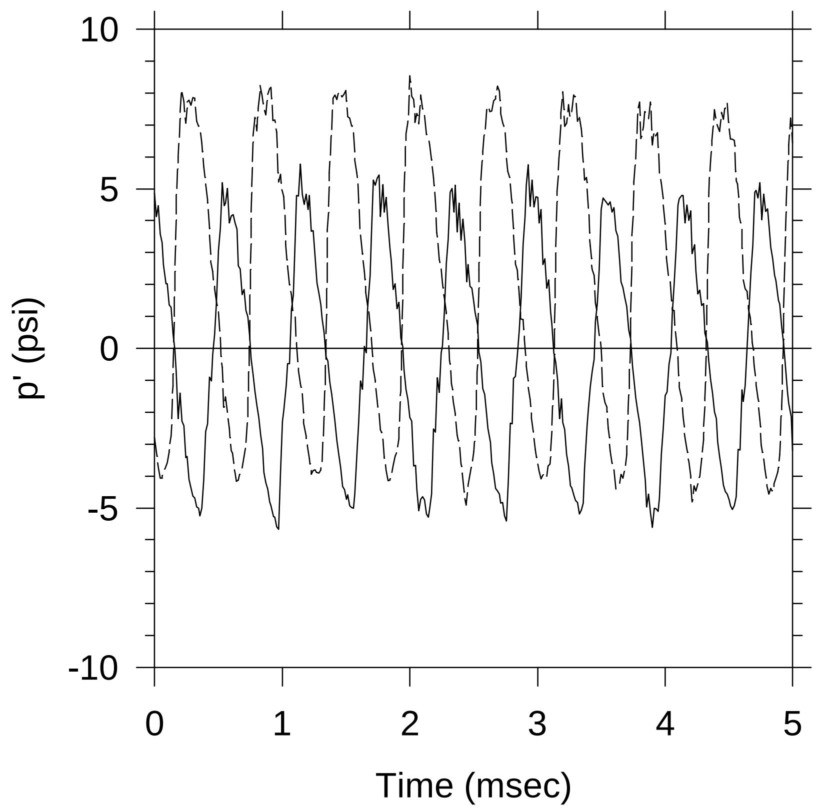


Unstable Flame

Typical Photographic Views of Stable and Unstable Flames

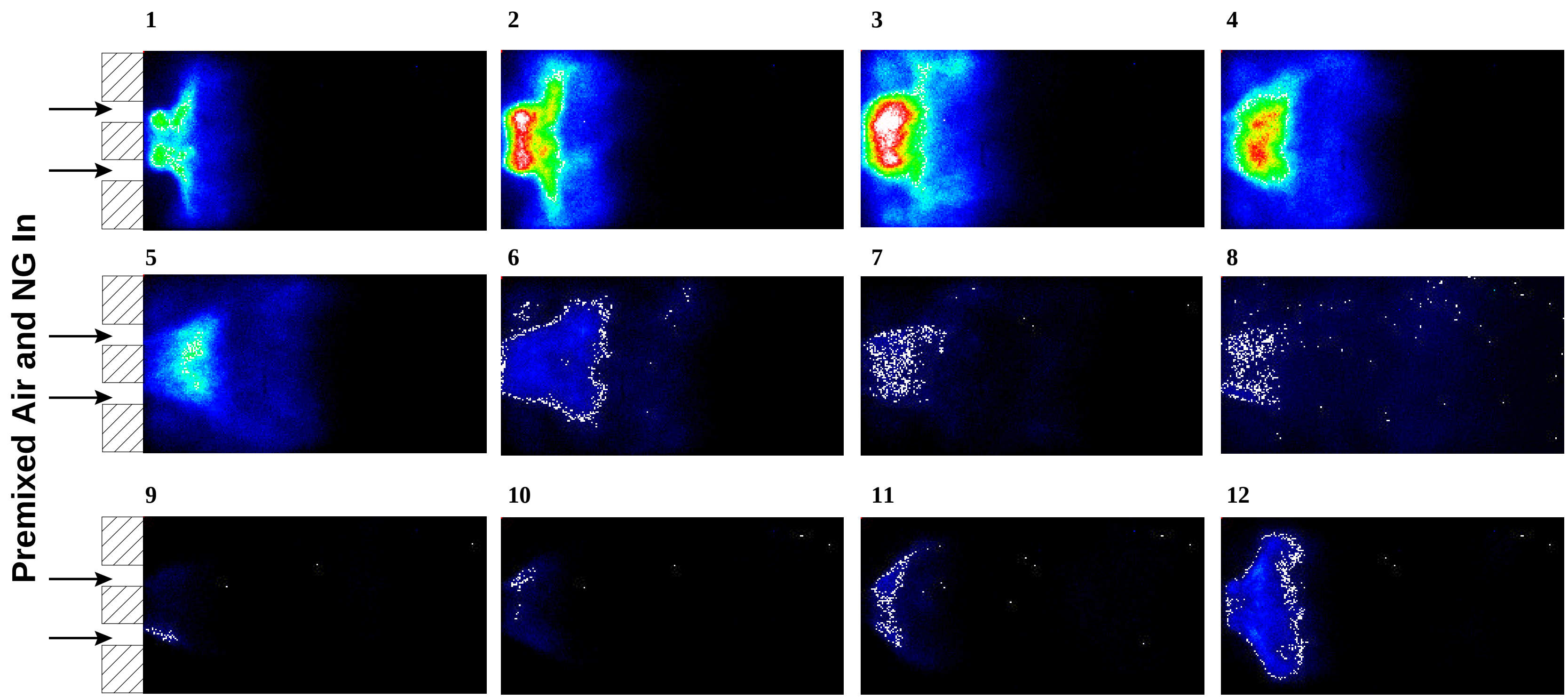


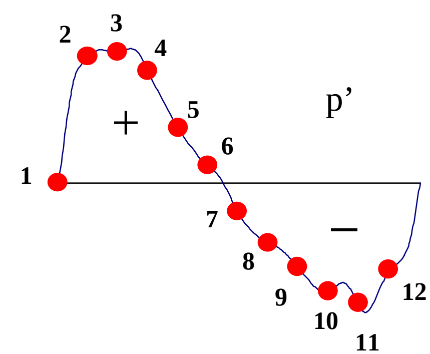
Pressures in phase: same x, different angle



Pressures out of phase: different axial location x

Identification of Combustion Instability:
1L Mode of Combustor at F ≅ 1800 Hz





Phase-resolved CH chemiluminescence Images of Unstable Flame at T_o=750 °F and $\phi_{overall}$=0.52

Fiber Optic Probe for Primary Zone Fuel Distribution Measurements in Actual Gas Turbine Combustors

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- **Objective**

Development of fiber-optic probes for measurement of the *equivalence ratio distribution* in an *actual turbine combustor* under typical operating conditions

- **Approach**

- *Optical fibers* are used as light guides
- *Laser Induced Fluorescence* (LIF) with a *fluorescence seed* is used for *gas-fueled* combustors
- *Simultaneous measurement of LIF and Mie-scattering* is used for *liquid-fueled* combustors

‘ **Summary of Accomplishments in Natural Gas Fueled Systems**

[1] *Turbulent axisymmetric jet* (Penn State)

[2] *Plexiglass RQL Combustor* (Westinghouse STC, Pittsburgh, PA)

[3] *Combustor #1*(Westinghouse Electric PGBU, Orlando, FL)

- at 1 atm and preheat temperature of 400 ^{o}C *without and with combustion* ($\phi_{primary}$=0.6)

[4] *Combustor #2* (Westinghouse Electric PGBU, Orlando, FL)

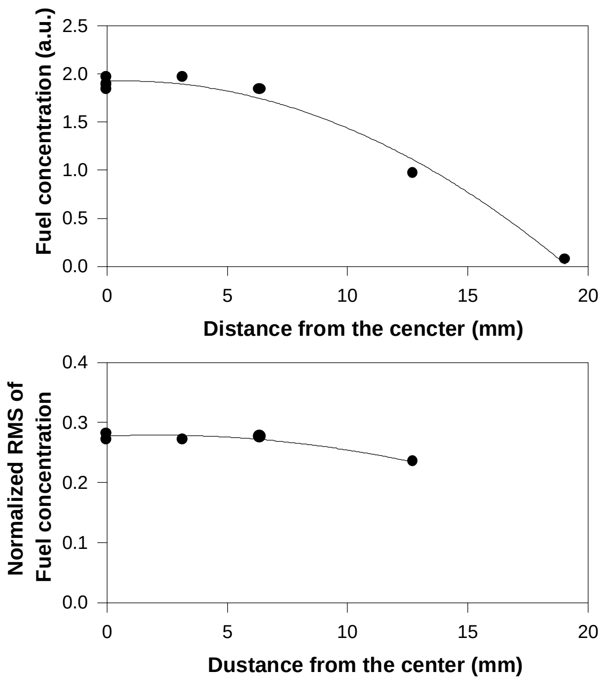
- at 1 atm and preheat temperature of 400 ^{o}C *with combustion*

- concentration of acetone : *1 %* (volume basis) *in the fuel stream*

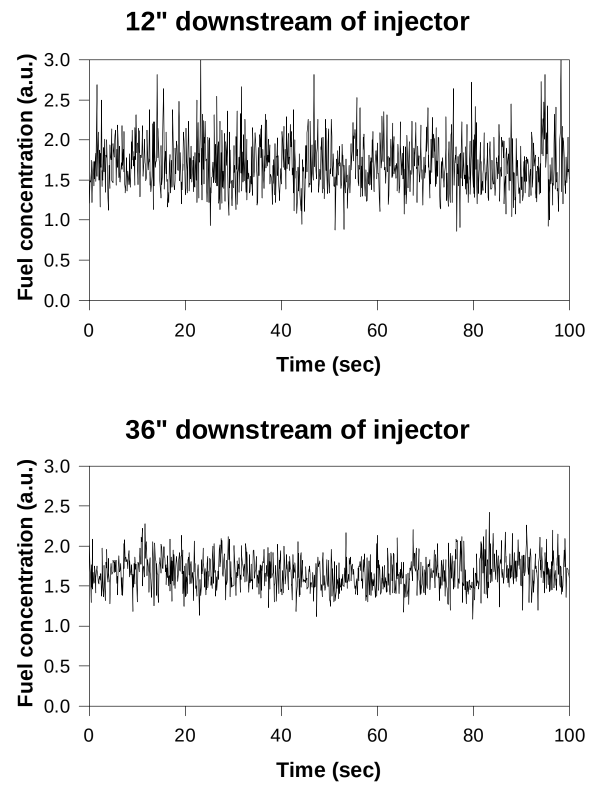
[5] *Low emission Combustor in LECTR* (FETC, Morgantown, WV)

- at *10 atm* and preheat temperature of 400 ^{o}C *without combustion*

- concentration of acetone : *1 %* (volume basis) *in the fuel stream*



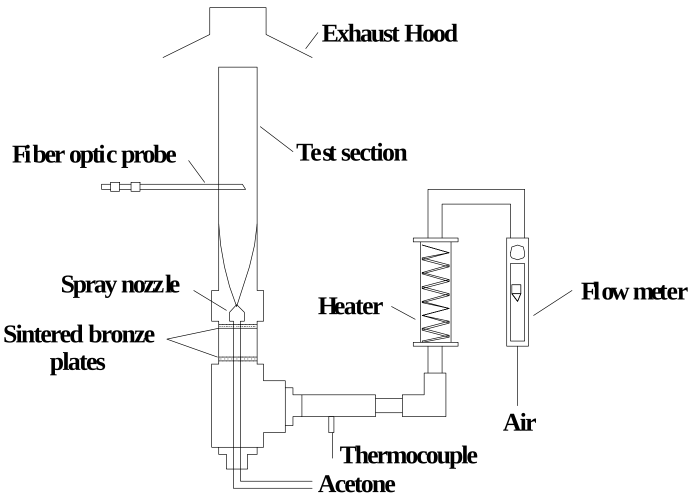
Spatial distribution **of fuel concentration and it's RMS along the radius of a cannular combustor (Combustor #2), Westinghouse)**



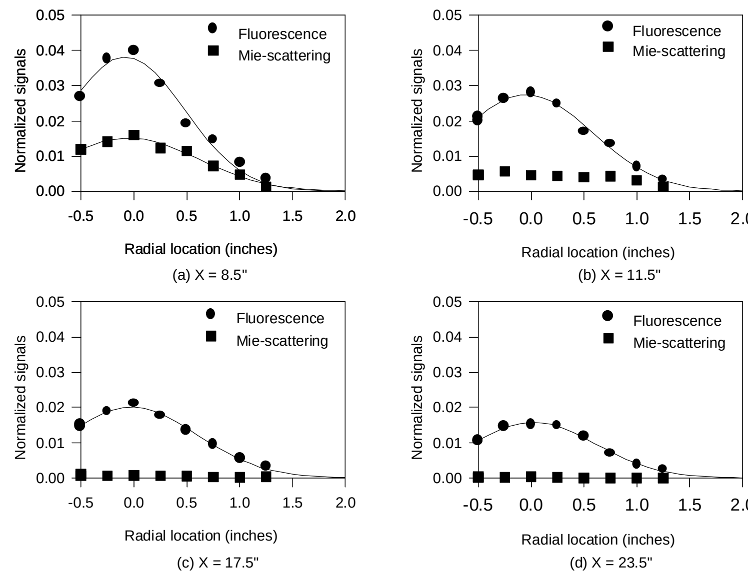
Temporal fluctuation **of fuel concentration (LECTR, FETC)**

‘ **Application to Liquid Fueled Systems**

- *simultaneous measurement* of *fluorescence* from fuel droplets and vapor and *Mie-scattering* from liquid fuel droplet)

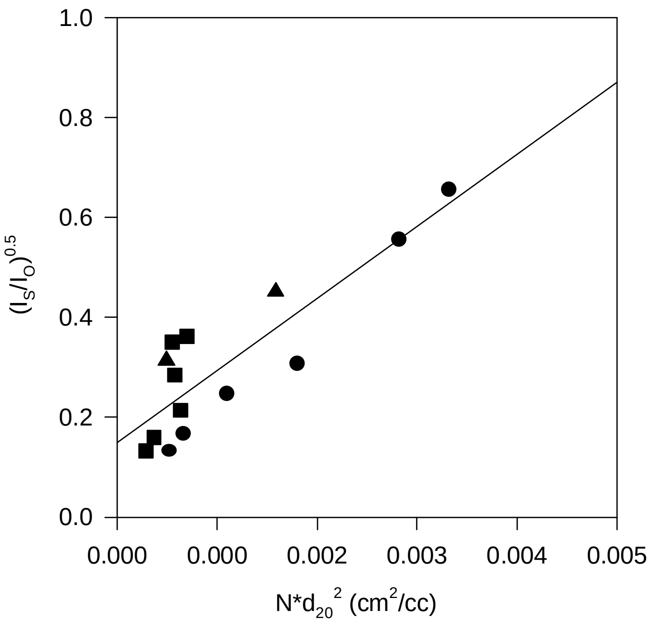


Schematic drawing of flow system for preliminary tests

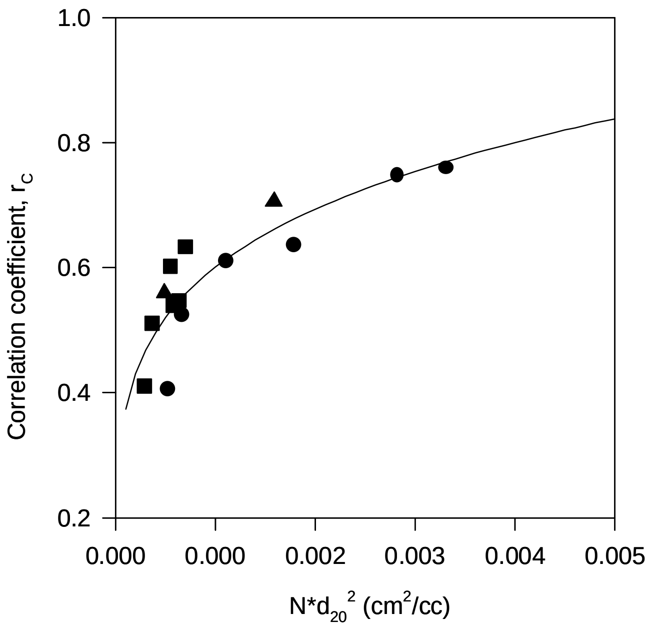


Radial distribution of fluorescence and Mie-scattering signals at different axial locations

Approaches for extracting information on fuel droplet from the simultaneous measurement of Mie-scattering and fluorescence



$N* d_{20}^2$ vs. $(I_S/ I_O)^{0.5}$



$N* d_{20}^2$ vs. Correlation coefficient

‘ **Conclusions**

- LIF-based *optical probe* has been developed for primary zone fuel distribution measurements in actual gas turbine combustors

- The applicability of the probe to *liquid-fueled turbine combustor* has been assessed

‘ **Future work**

- Evaluate methods for *interpreting* and *calibrating* measurement in *liquid-fueled system* using PDPA (Phase Doppler Particle Analyzer)

- Test with Jet-A fuel at Penn State

- *Test in a liquid-fueled combustor* at an *industrial test facility* (discussions with Westinghouse have been initiated)