COMBUSTION DIAGNOSTICS

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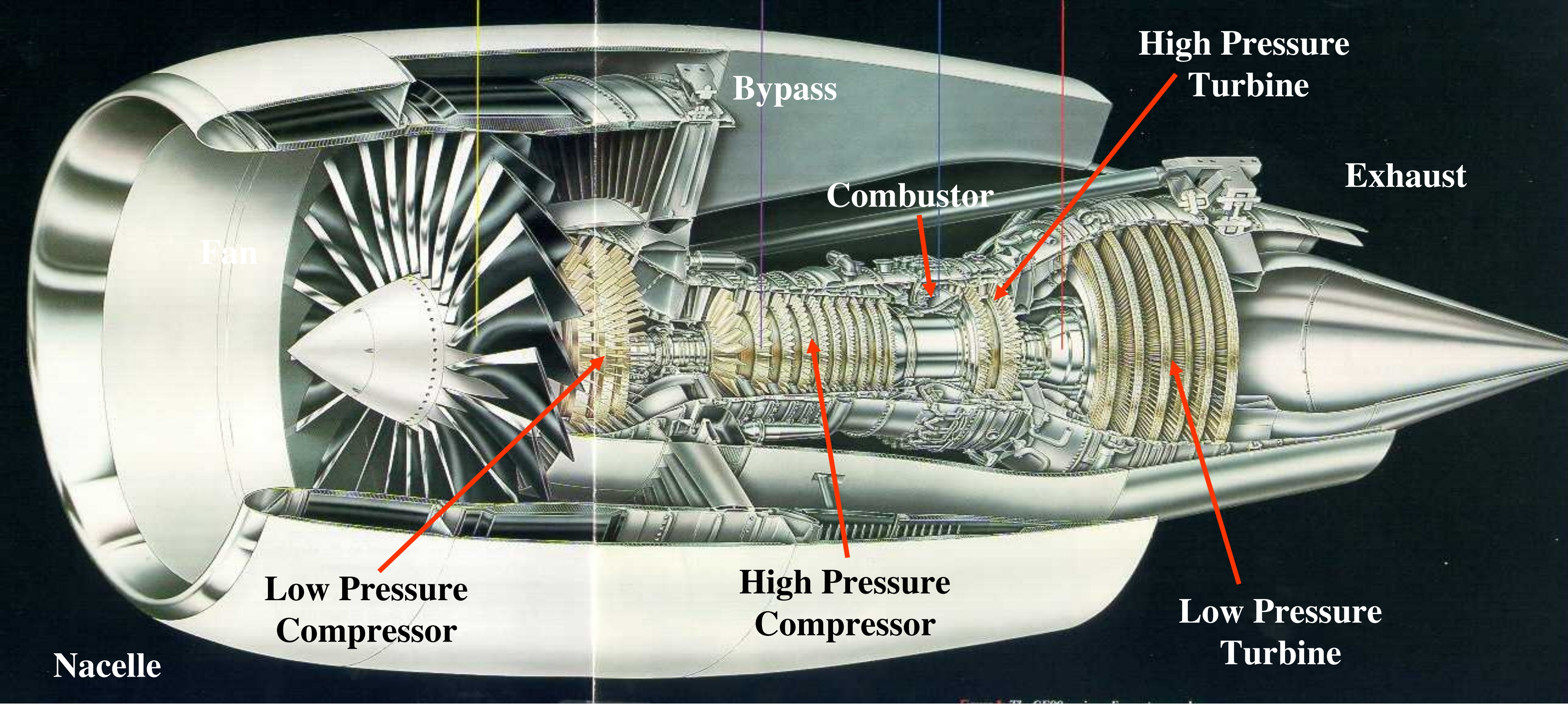
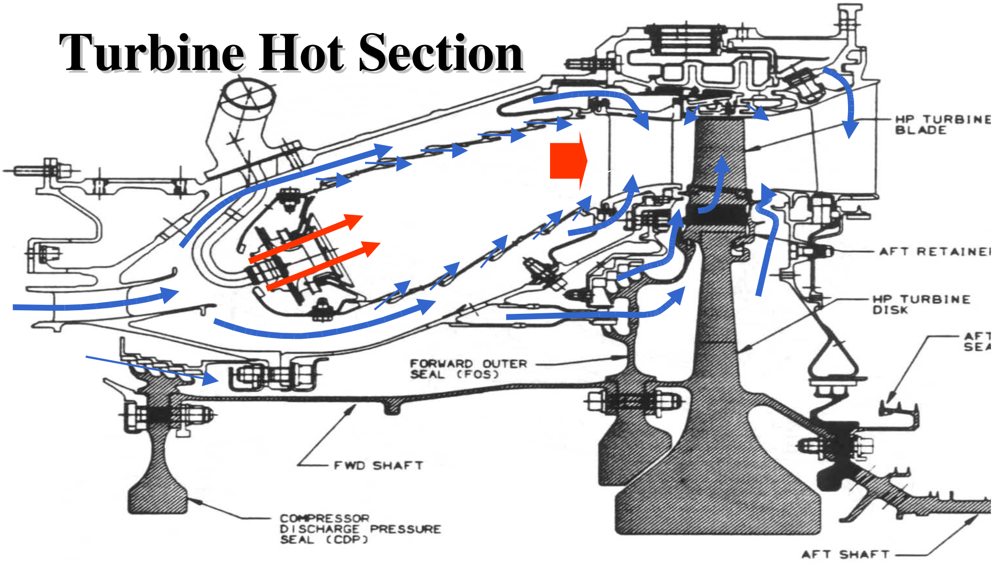
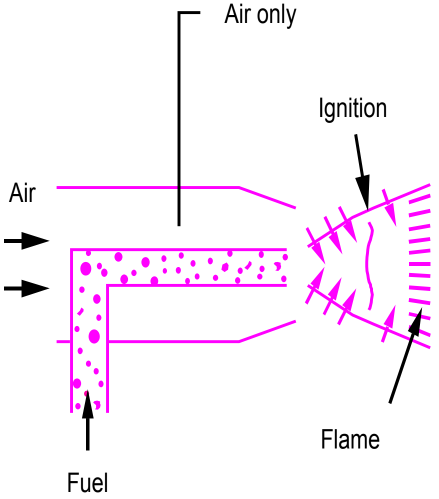


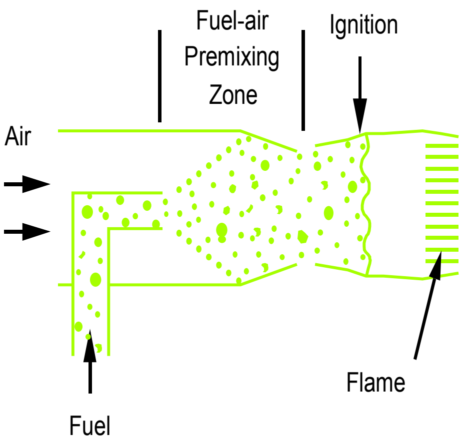
Turbine Hot Section



Diffusion Flame



Premixed Flame



PERFORMANCE METRICS

There are three basic performance metrics for a gas turbine combustor

- Fuel air mixing

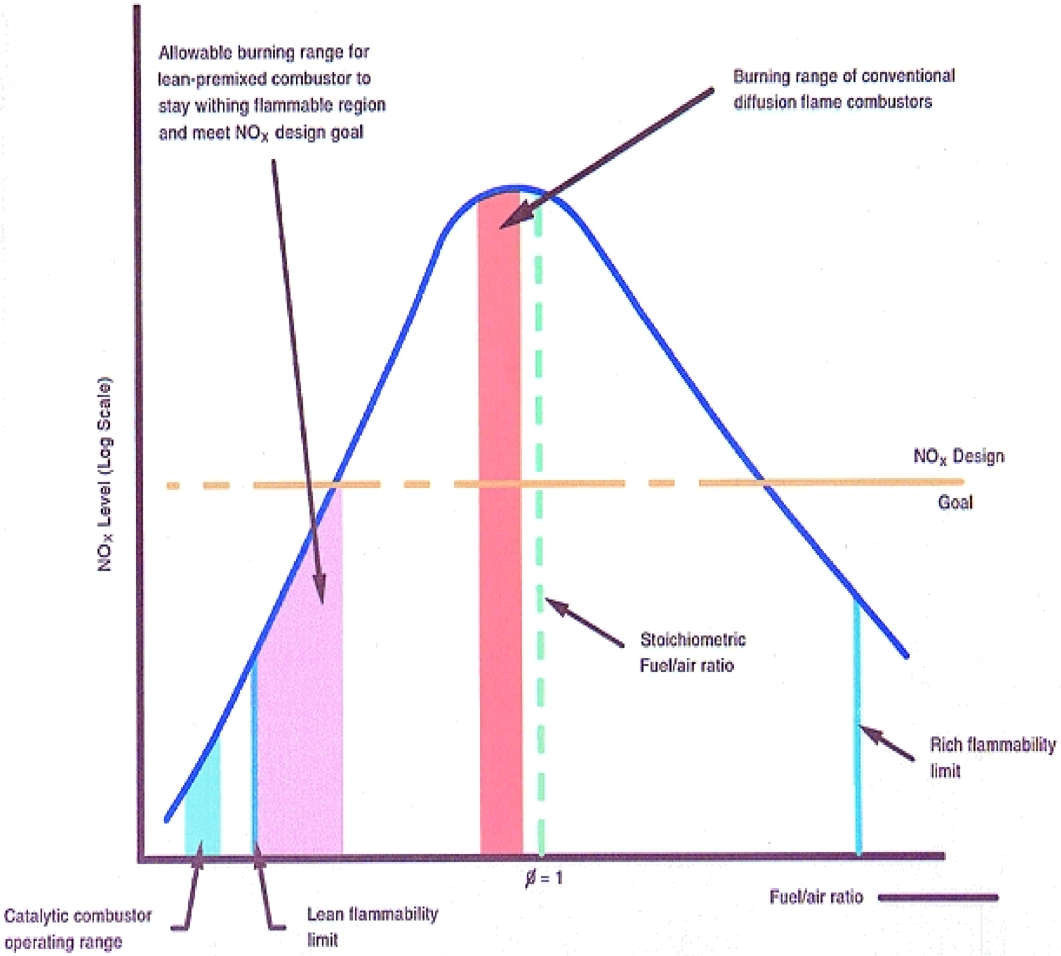
Fuel air mixing is often quantified by pattern factors which is a measure of uniformity of the temperature distribution. The lower the pattern factor the better the fuel air mixing.

- Volumetric heat release

Higher volumetric heat release enables the design of more compact combustors. Volumetric heat release is also closely related with mixing.

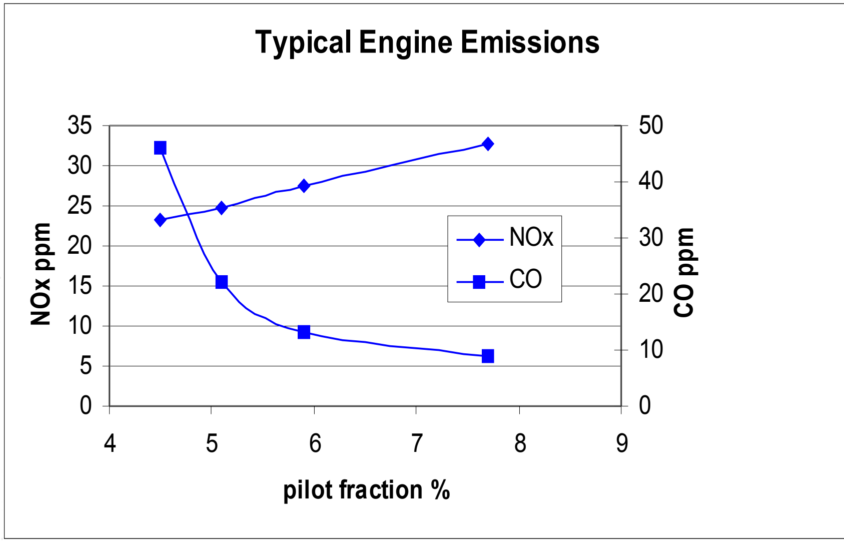
- Emissions (NOx, CO, UHC etc.)

Reducing emissions in order to meet legal criteria



Factors Affecting Emissions

- Stochiometry
- Reaction zone residence time
- Turbulence-chemistry interactions



Beneficial for NOx

- Low Flame Temperatures
- Uniform Fuel Air Mixtures
- Short Residence Times

Conflicting interests

Need to optimize

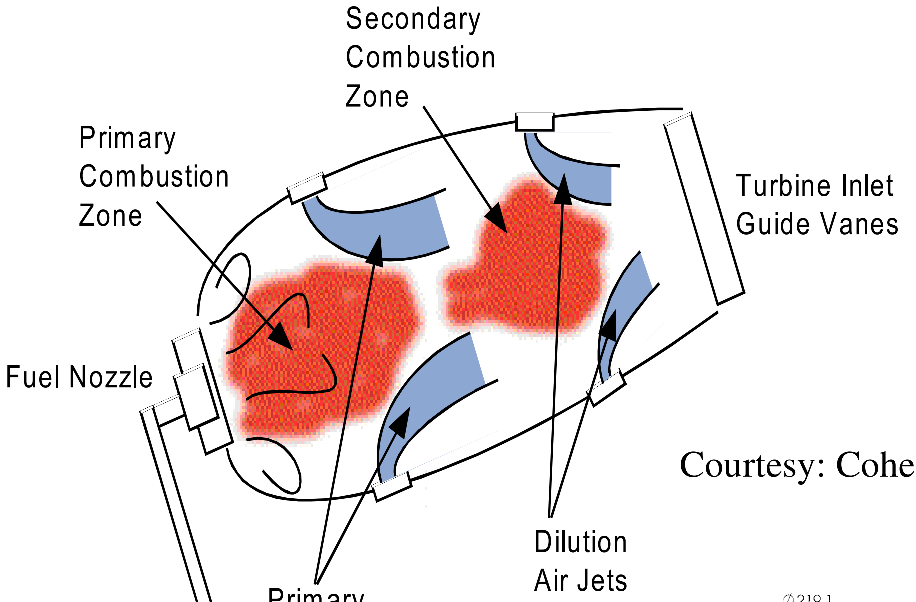
Beneficial for CO

- Long Residence Times
- High Flame Temperatures
- Excess Oxygen

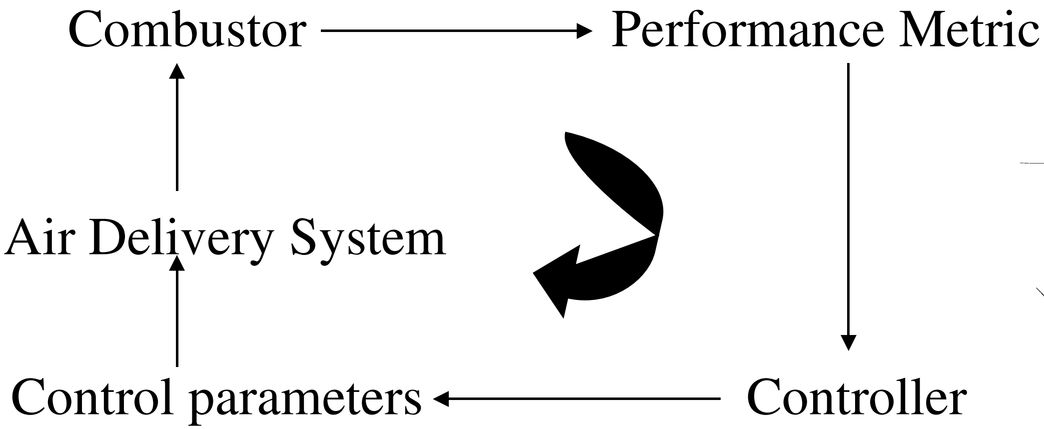
* Figures courtesy of Siemens-Westinghouse

ACTIVE CONTROL OF SIDE AIR JETS

- Control parameters
  - ➢ Modulation frequency
  - ➢ Blowing Ratio
  - ➢ Equivalence Ratio



Courtesy: Cohen et al.



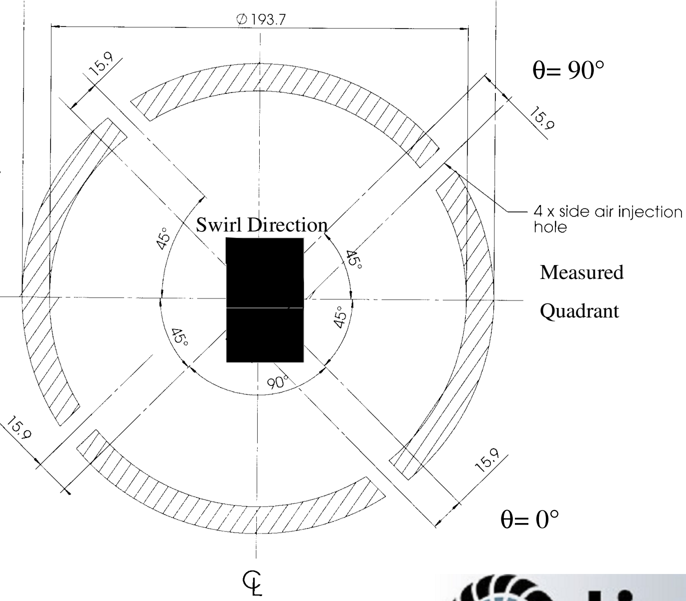
Combustor → Performance Metric

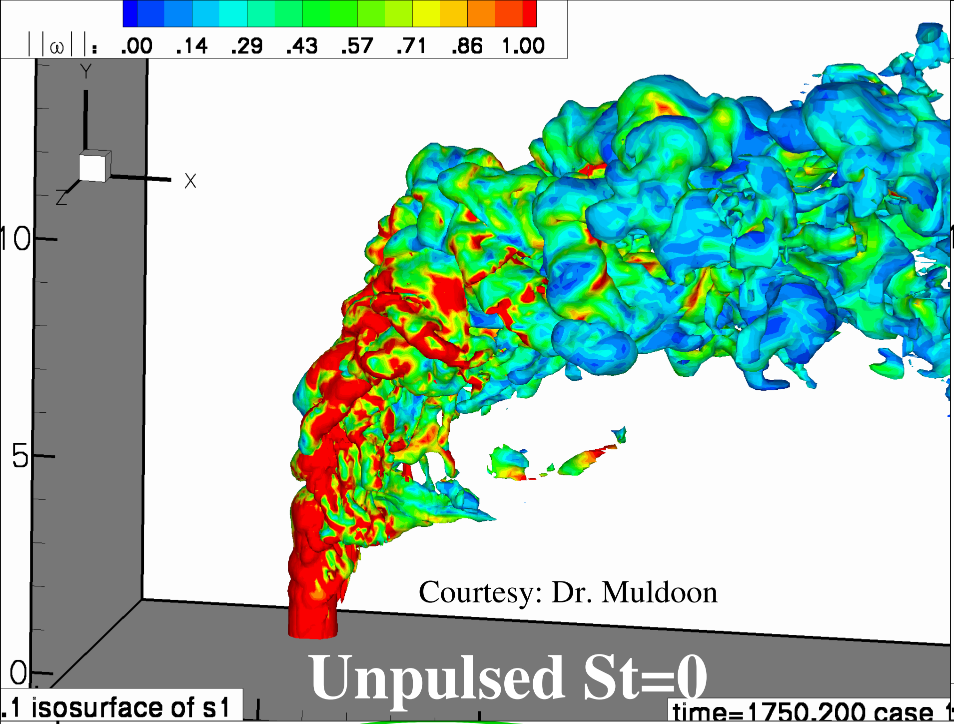
Performance Metric → Controller

Controller → Control parameters

Control parameters → Air Delivery System

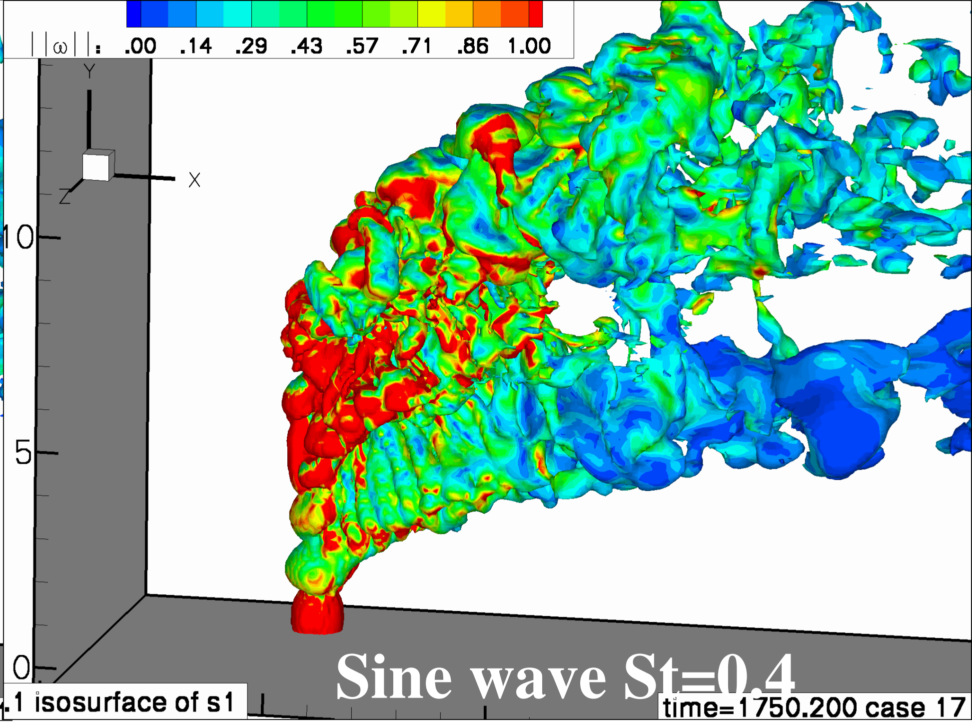
Air Delivery System → Combustor



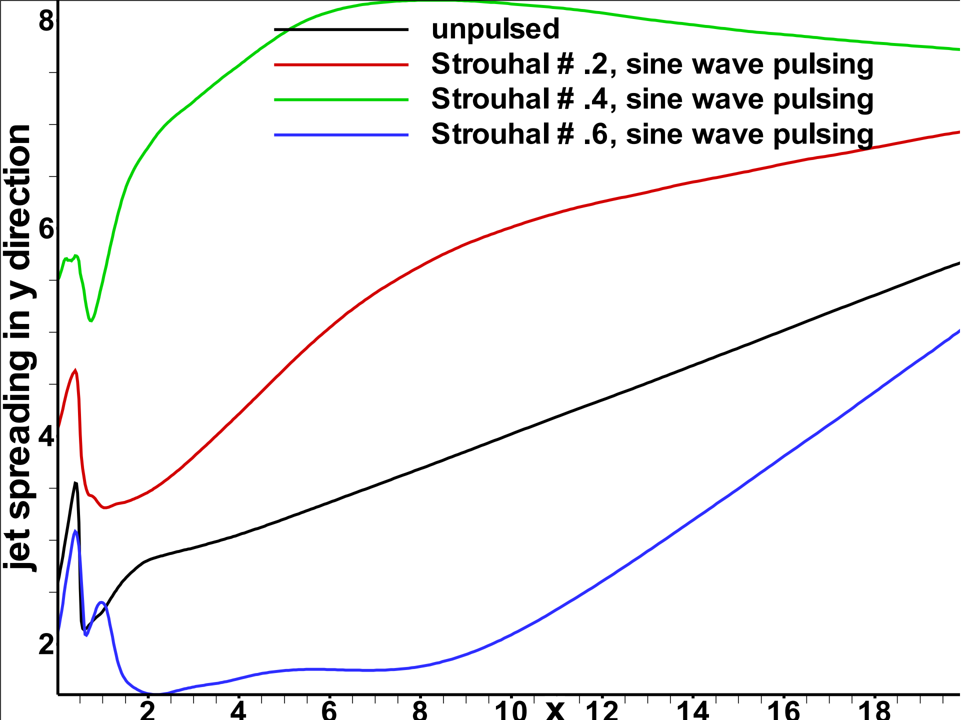


Courtesy: Dr. Muldoon

Unpulsed St=0



Sine wave St=0.4

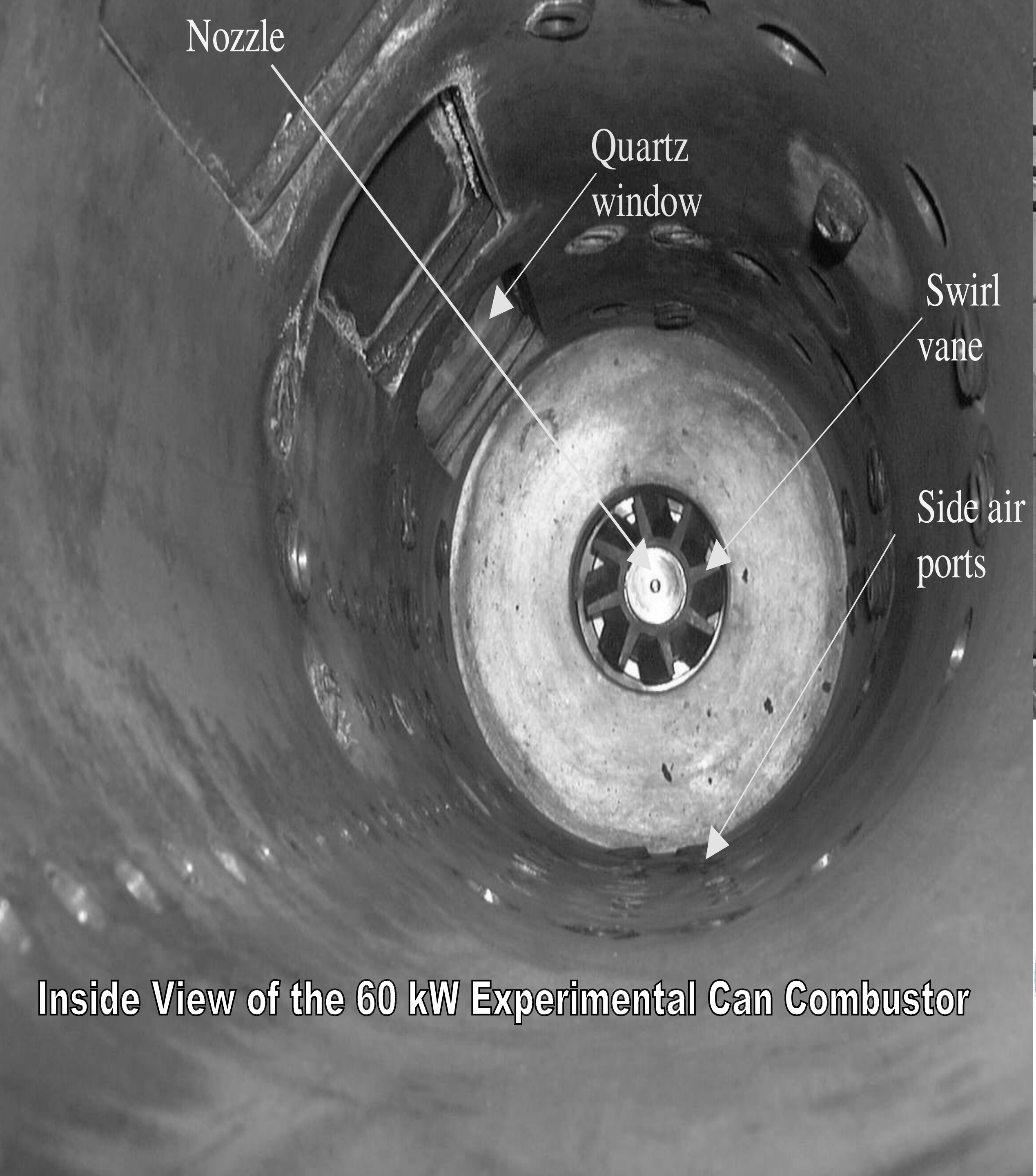


Some examples of <u>experimental</u> evidence on mixing enhancement of transverse jets due to forcing;

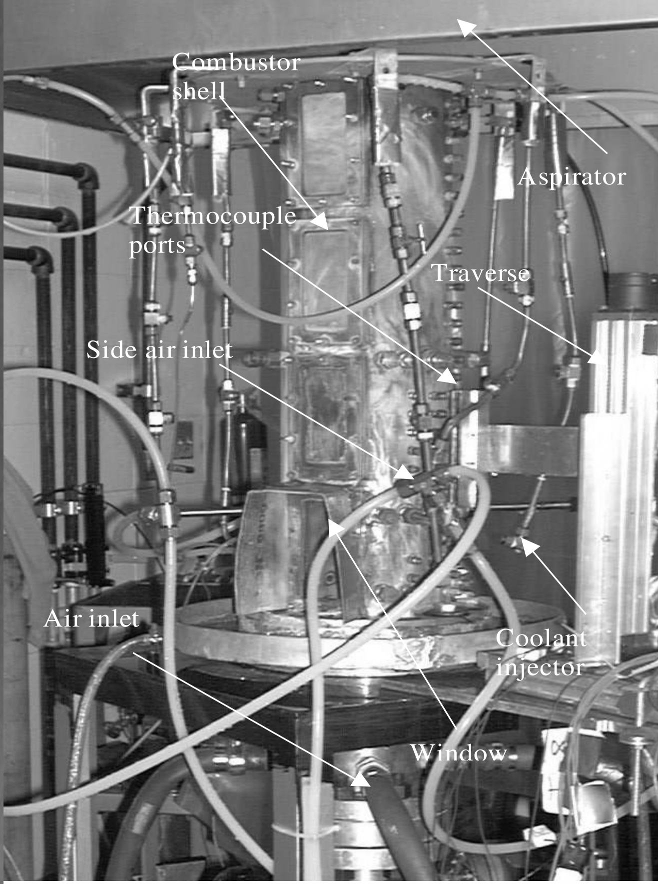
❖Vermeulen, P. J., Yu, W. K. (1985) An Experimental Study of Mixing by an Acoustically Pulsed Axisymmettrical Air Jet, ASME Paper No. 85-GT-49

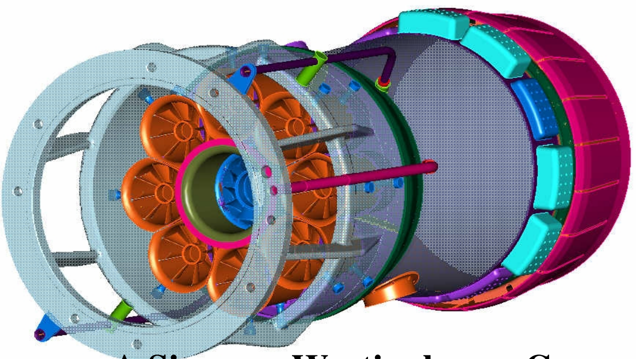
❖Karagozian, A. R., M’Closkey, R. T., King, J. M., Cortelezzi, L. (2002) The Actively Controlled Jet in Crossflow, J. Fluid Mech., **452**, pp. 325-335

❖Johari, H., Pacheco-Tougas, M. and Hermanson, J. C. (1999) Penetration and Mixing of Fully Modulated Turbulent Jets in Crossflow, AIAA Journal, **37**(7), pp. 842-850

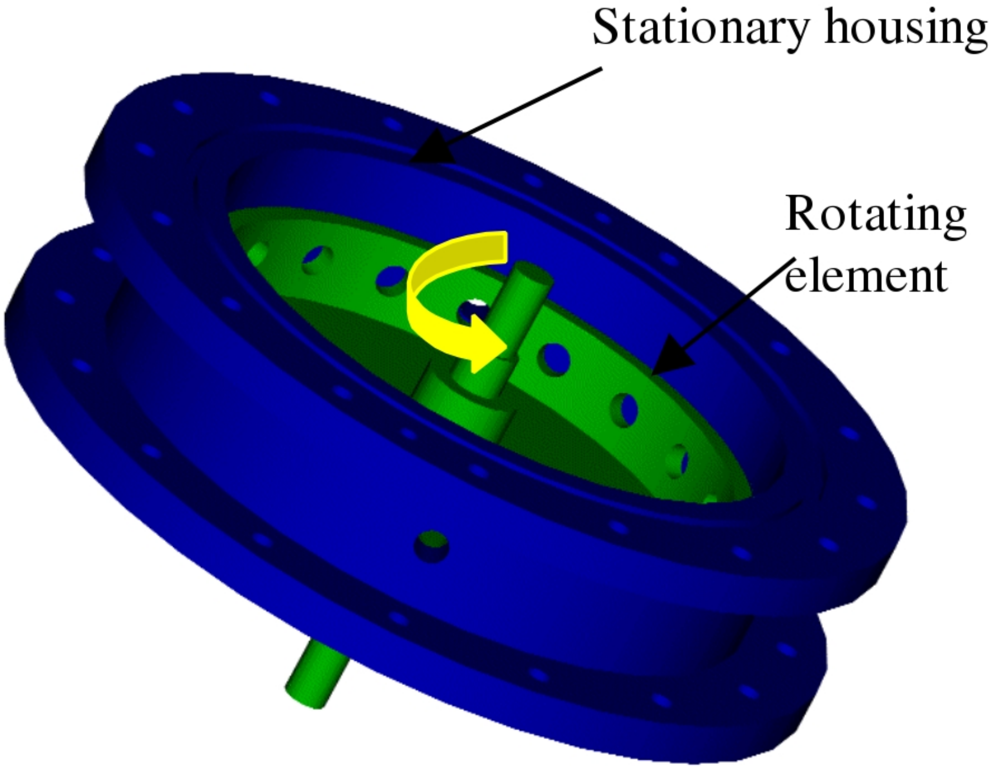


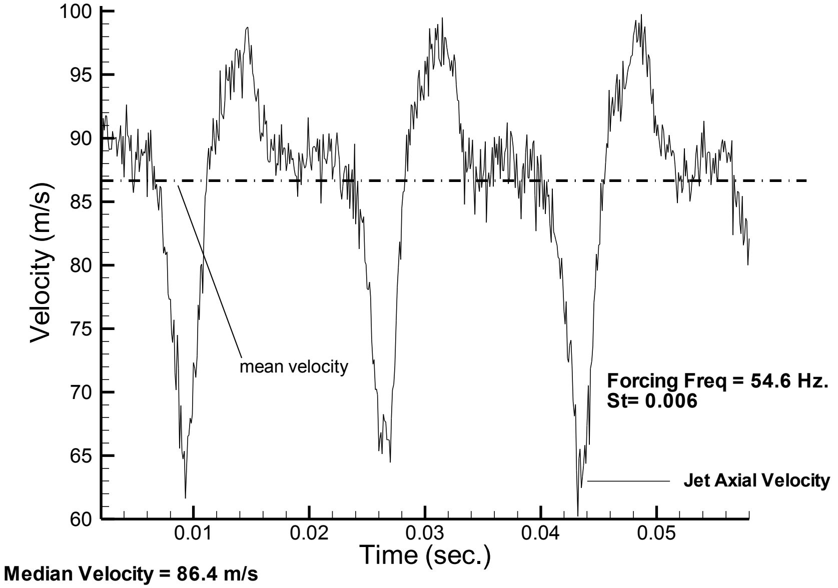
Inside View of the 60 kW Experimental Can Combustor

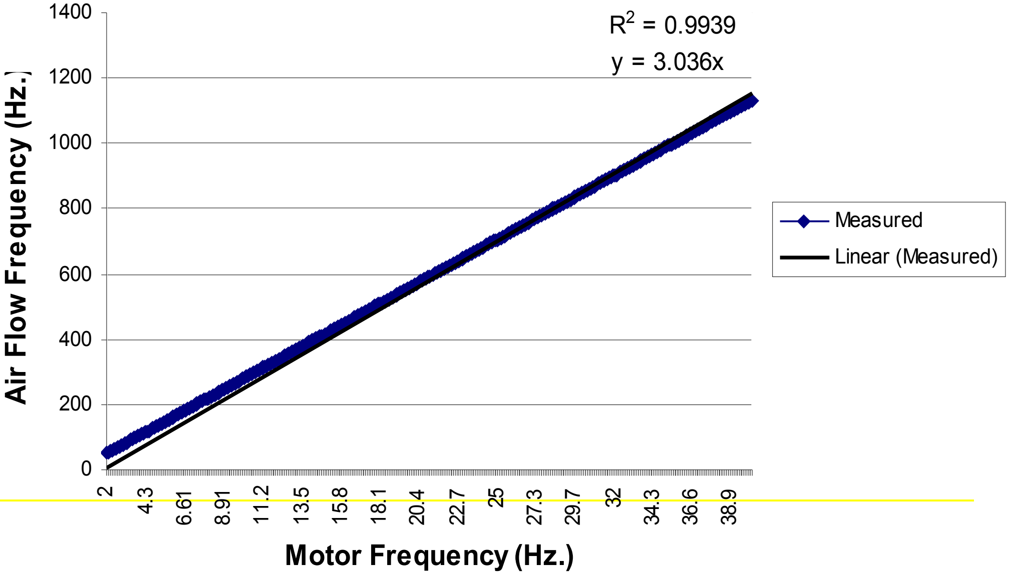


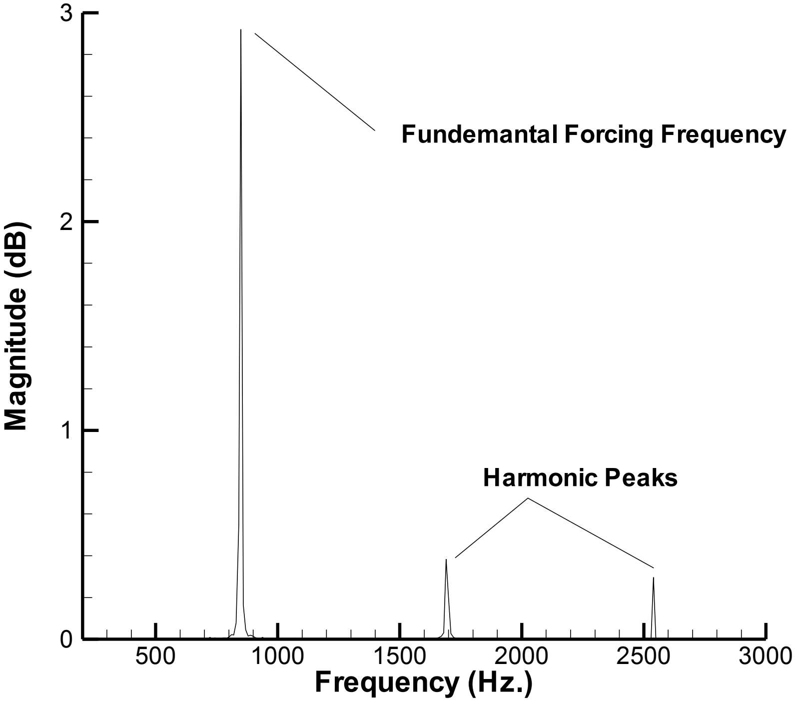


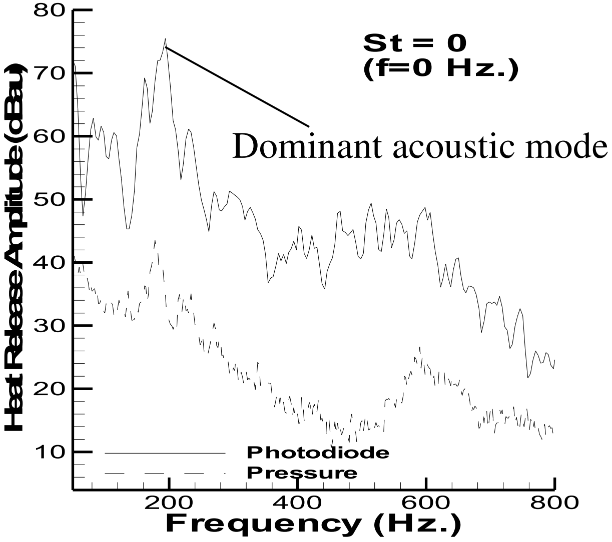
A Siemens-Westinghouse Can Annular Combustor

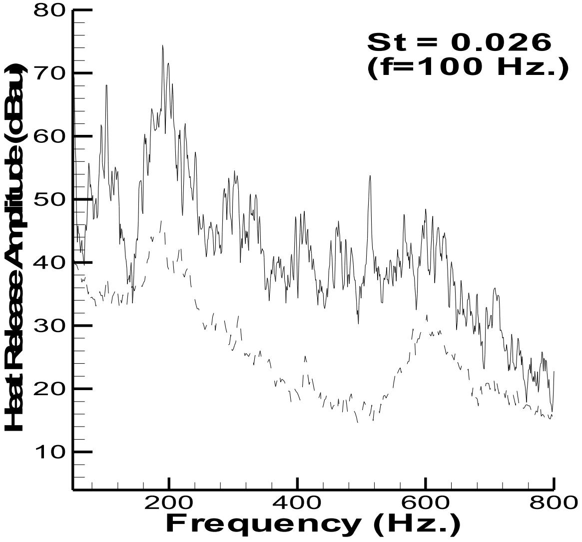

Stationary housing
Rotating element

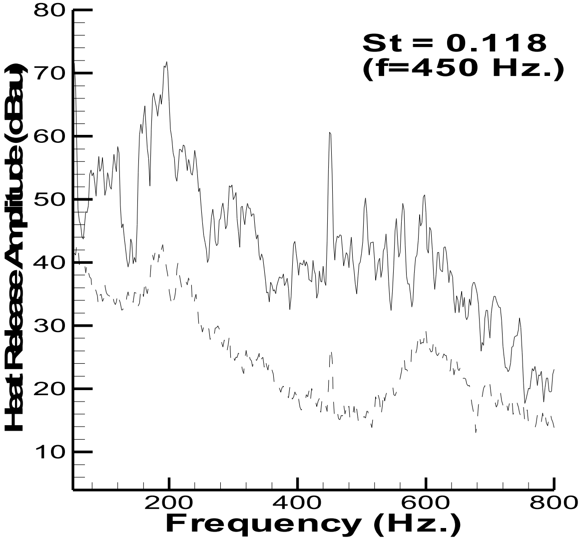

100
95
90
85
80
75
70
65
60
Velocity (m/s)
0.01
0.02
0.03
0.04
0.05
Time (sec.)
mean velocity
Forcing Freq = 54.6 Hz.
St= 0.006
Jet Axial Velocity
Median Velocity = 86.4 m/s

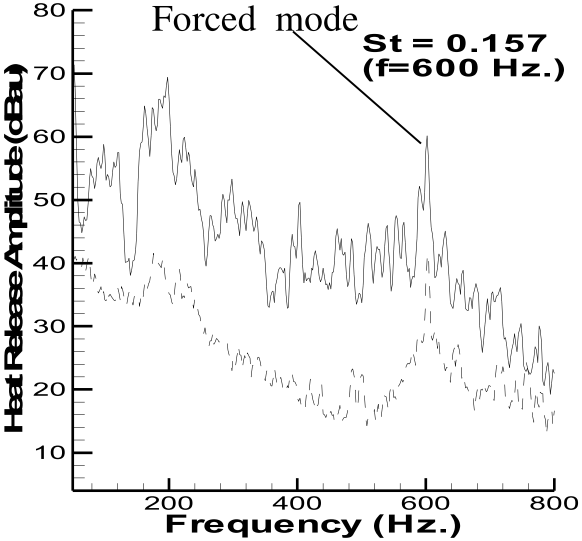

1400
1200
1000
800
600
400
200
0
Air Flow Frequency (Hz.)
$R^2 = 0.9939$
y = 3.036x
Measured
Linear (Measured)
2
4.3
6.61
8.91
11.2
13.5
15.8
18.1
20.4
22.7
25
27.3
29.7
32
34.3
36.6
38.9
Motor Frequency (Hz.)

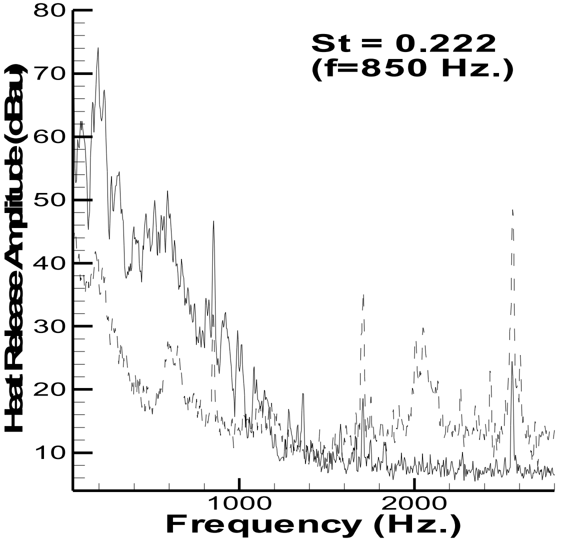

3
2
1
0
Magnitude (dB)
Fundemantal Forcing Frequency
Harmonic Peaks
500
1000
1500
2000
2500
3000
Frequency (Hz.)











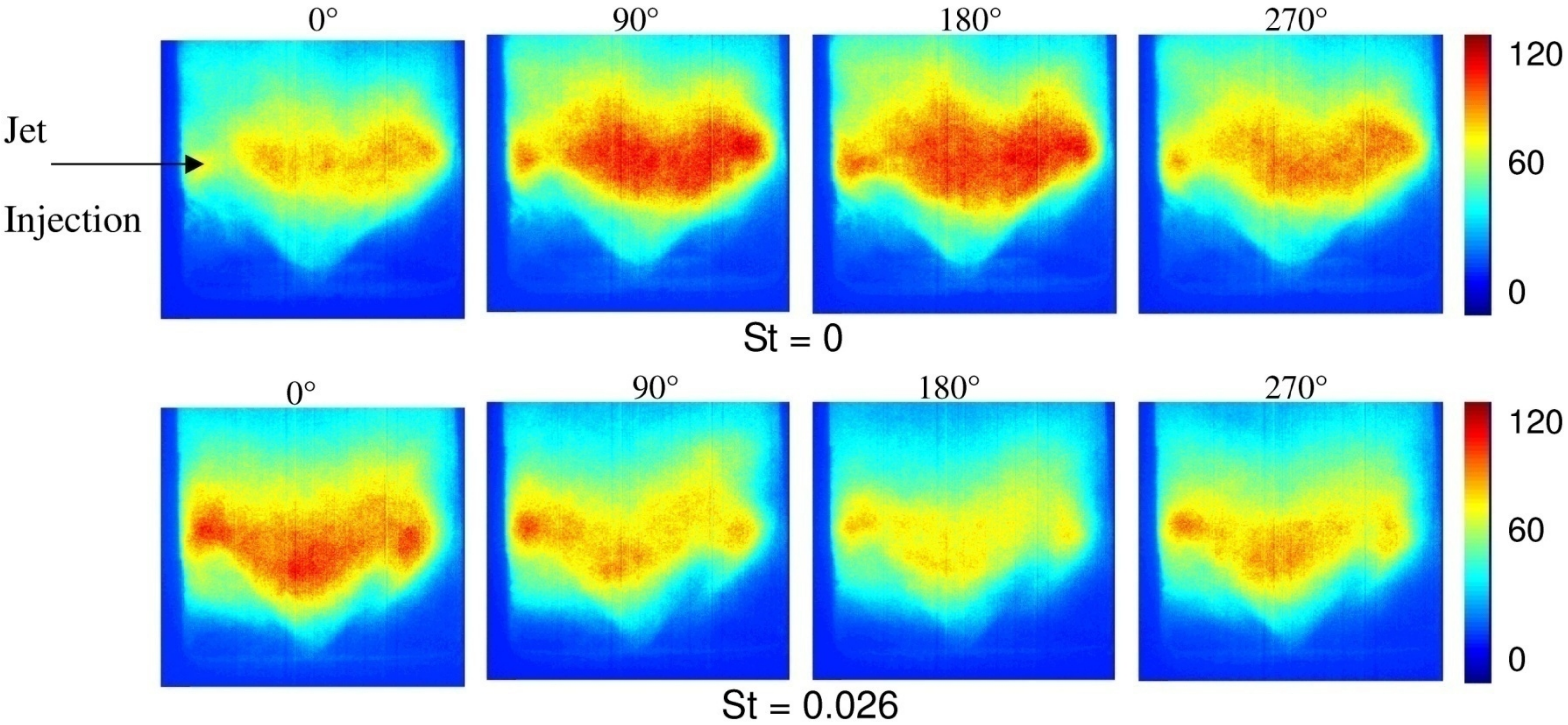
For the dominant quarter-wave mode

$$\lambda = 4H$$

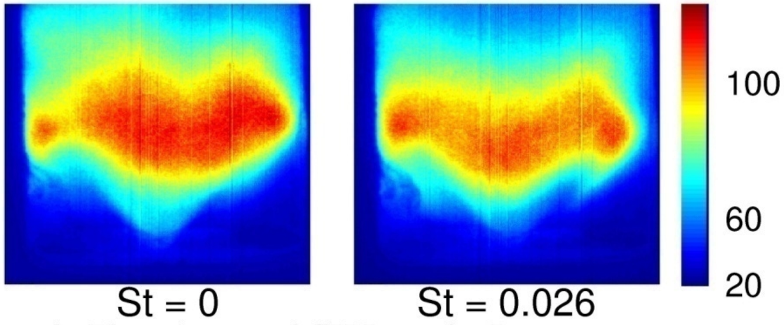
$$f_{1/4} = {}^{c}\!/_{4H}$$

$$c = \sqrt{\gamma R T}$$

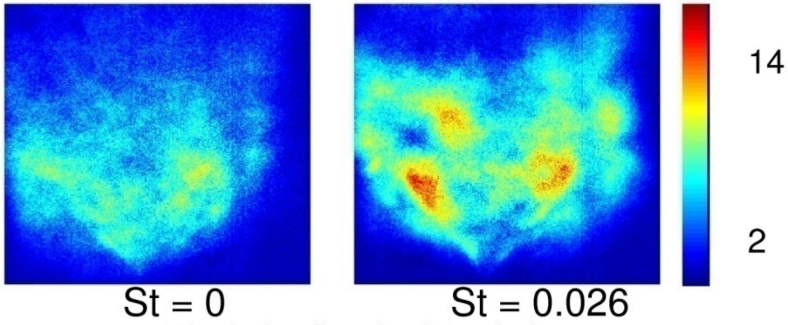
Pressure & Heat Release Spectra



a. Phase Averaged CH Intensity

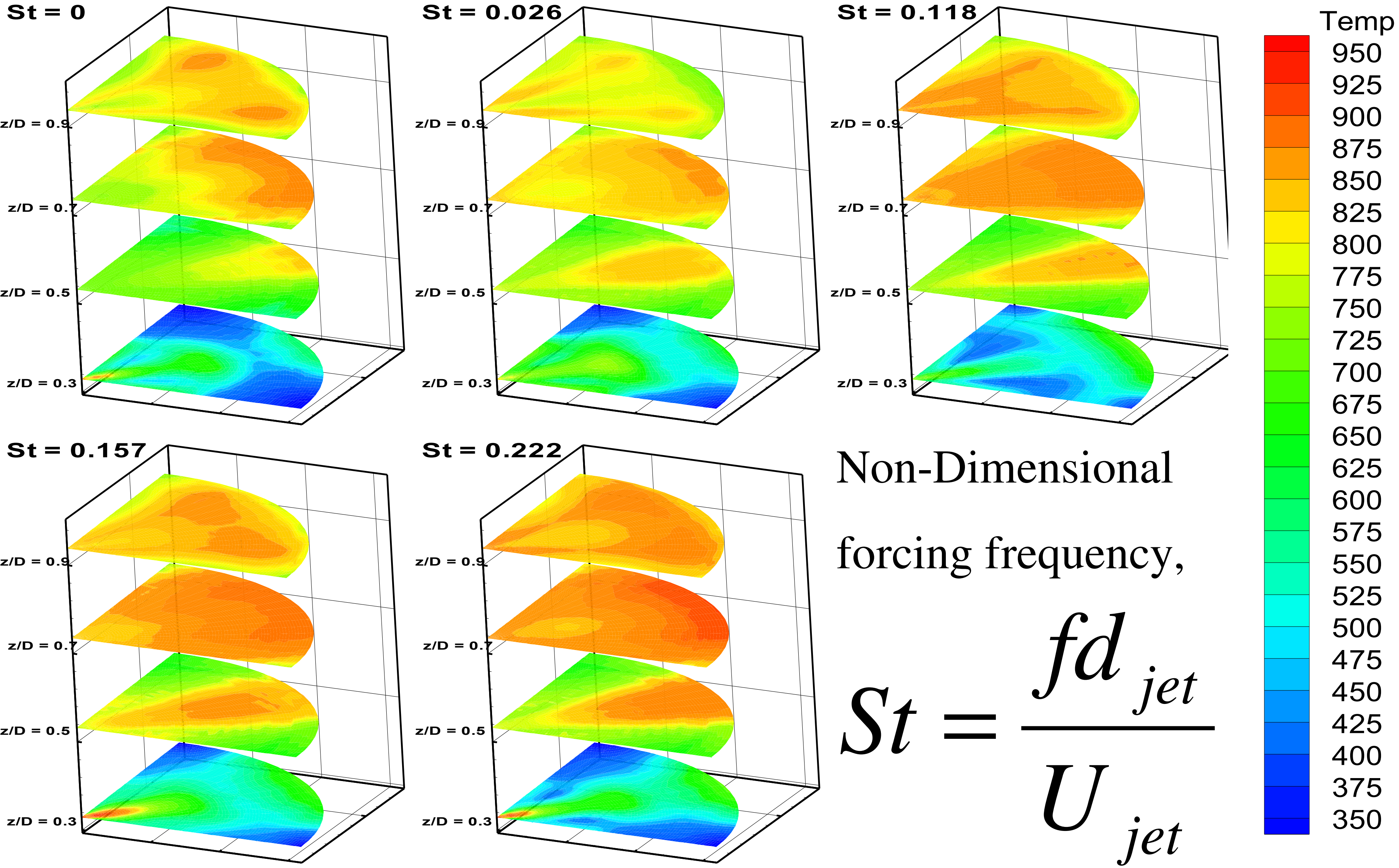


b. Time Averaged CH Intensity Images



c. Pixelwise Standard Deviation

CH Radical Images

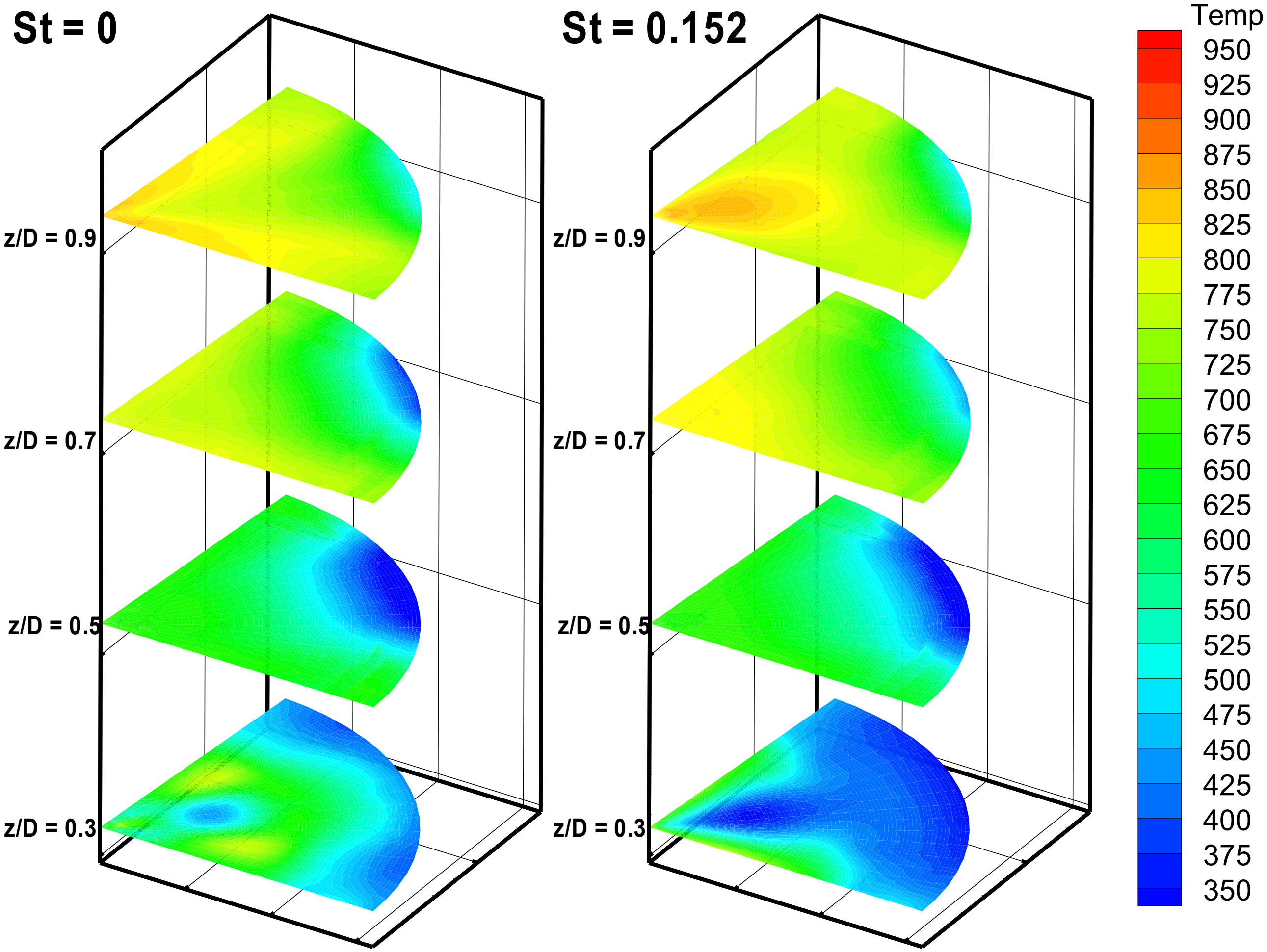


Non-Dimensional forcing frequency,

$$St = \frac{fd_{jet}}{U_{jet}}$$

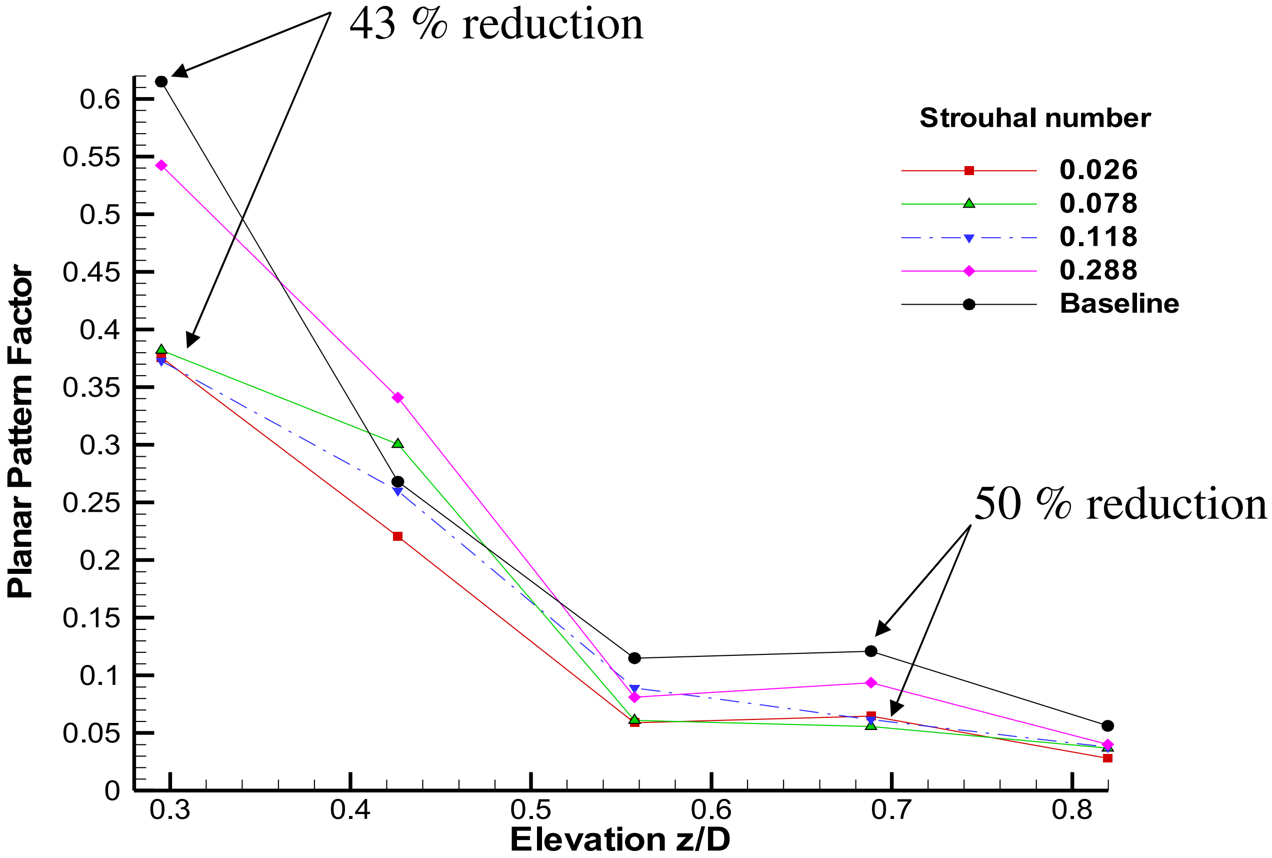
3-D Temperature Profiles as a Function of Forcing Frequency

$\Phi=0.9$, R=15


St = 0
St = 0.152
z/D = 0.9
z/D = 0.7
z/D = 0.5
z/D = 0.3
z/D = 0.9
z/D = 0.7
z/D = 0.5
z/D = 0.3
Temp
950
925
900
875
850
825
800
775
750
725
700
675
650
625
600
575
550
525
500
475
450
425
400
375
350

Φ=0.9, R=10

Define pattern factor as, $PF(z) = \dfrac{T_{\max}(z) - \overline{T}(z)}{\overline{T}(z) - T_o}$ where, $\overline{T}(z) = \dfrac{\iint T(r,\theta,z)\,r\,dr\,d\theta}{\iint r\,dr\,d\theta}$

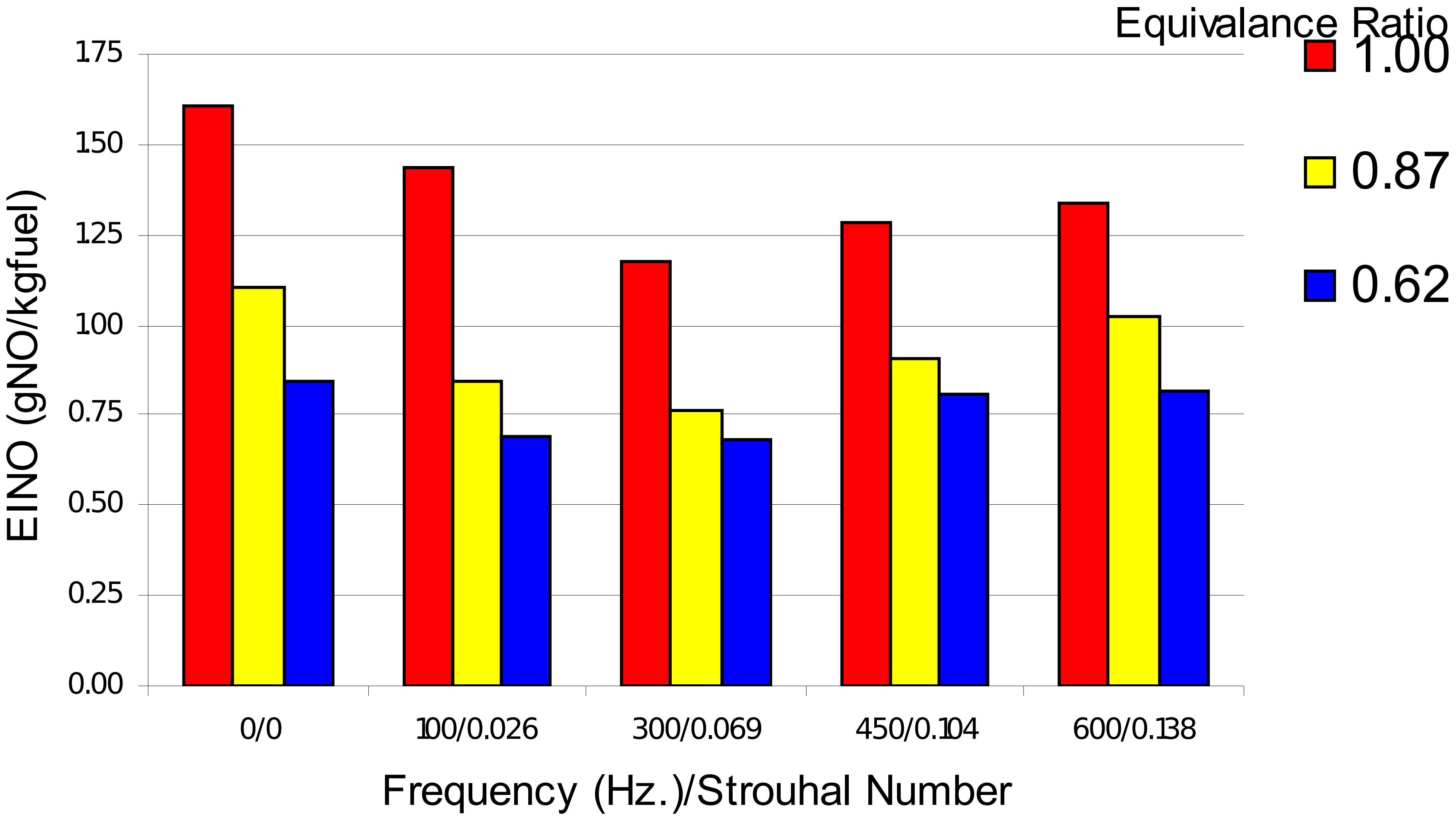


43 % reduction

50 % reduction

R=15 (Blowing Ratio)

Pattern Factor as a Function of Elevation

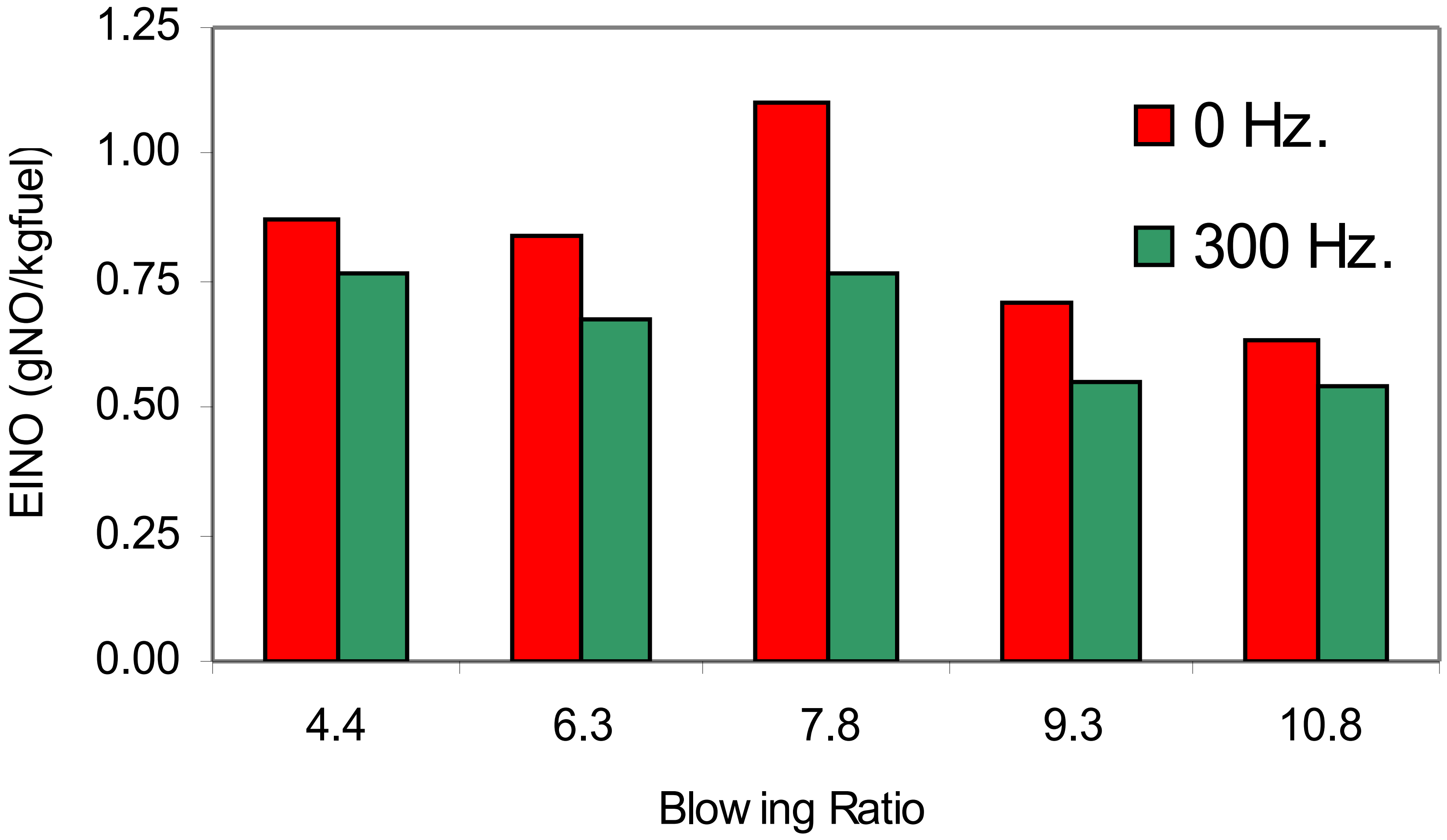


Emissions Index as a Function of Forcing Frequency

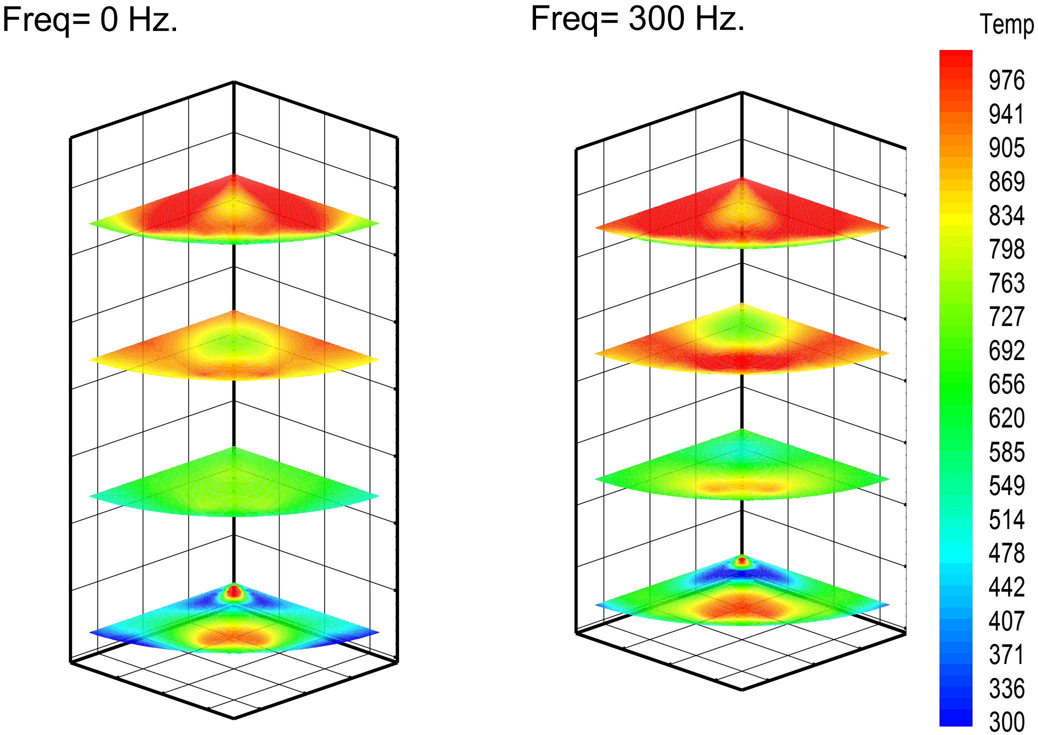
<u>Definition:</u> Emissions index is defined as the grams of nitric oxide generated per kilogram of fuel burnt

<u>Note:</u> Emissions measurements were made using K1 grade kerosene as liquid fuel.

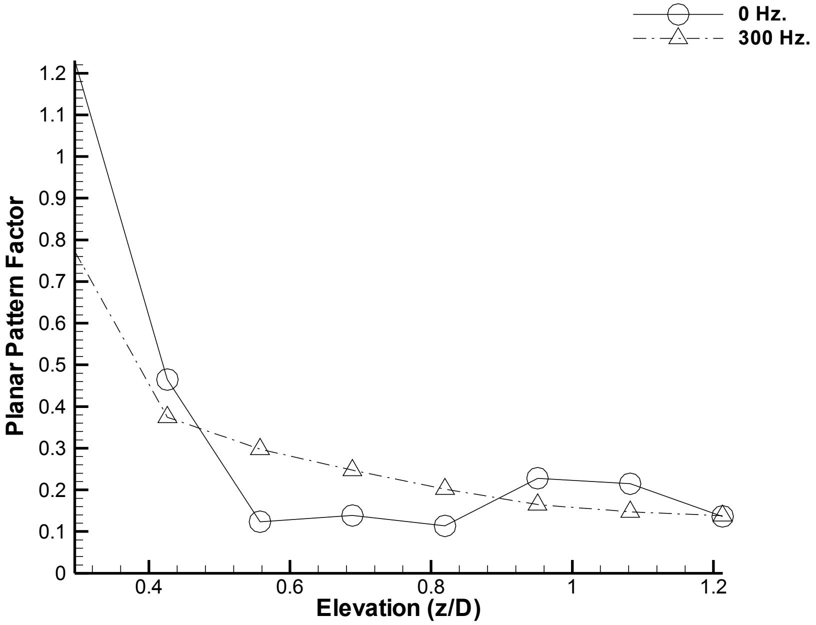
K1 grade kerosene is very close to Jet-A fuel in chemical composition.



Emissions Index as a Function of Blowing Ratio



Temperature Contours at R=7.8 and Φ=0.87
(Temperatures in °C)



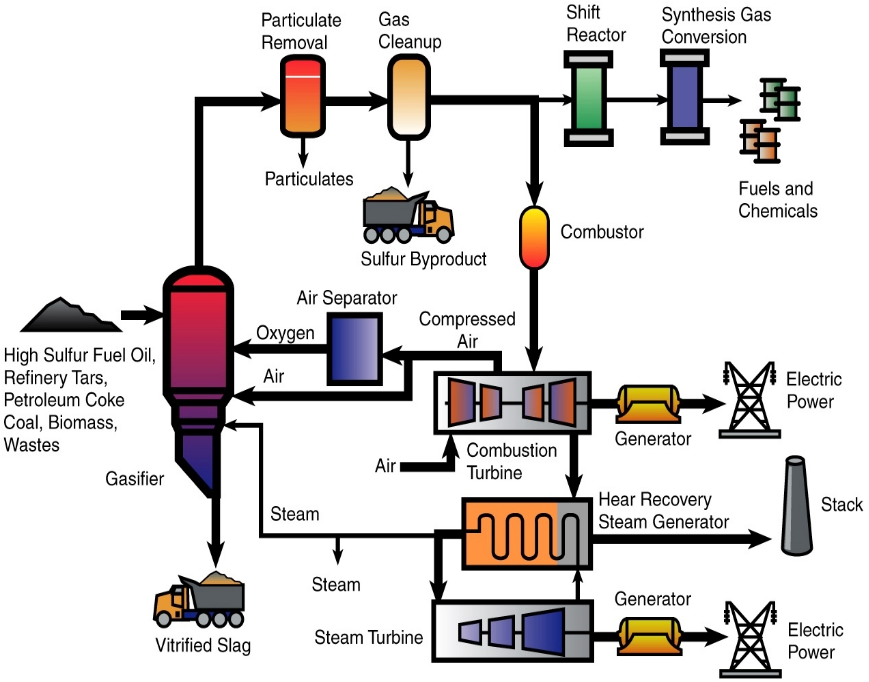
Planar Pattern Factor as a Function of Elevation at R=7.8 and Φ=0.87

Syngas Combustion

- ➢Synthesis gas (syngas) is a variable mixture of H2 and CO and other some gases in trace amounts
  - ➢Mostly used in combined cycles (IGCC) to increase efficiency
- ➢Can be produced from the gasification of coal or biomass
- ➢Composition depends on the gasification process

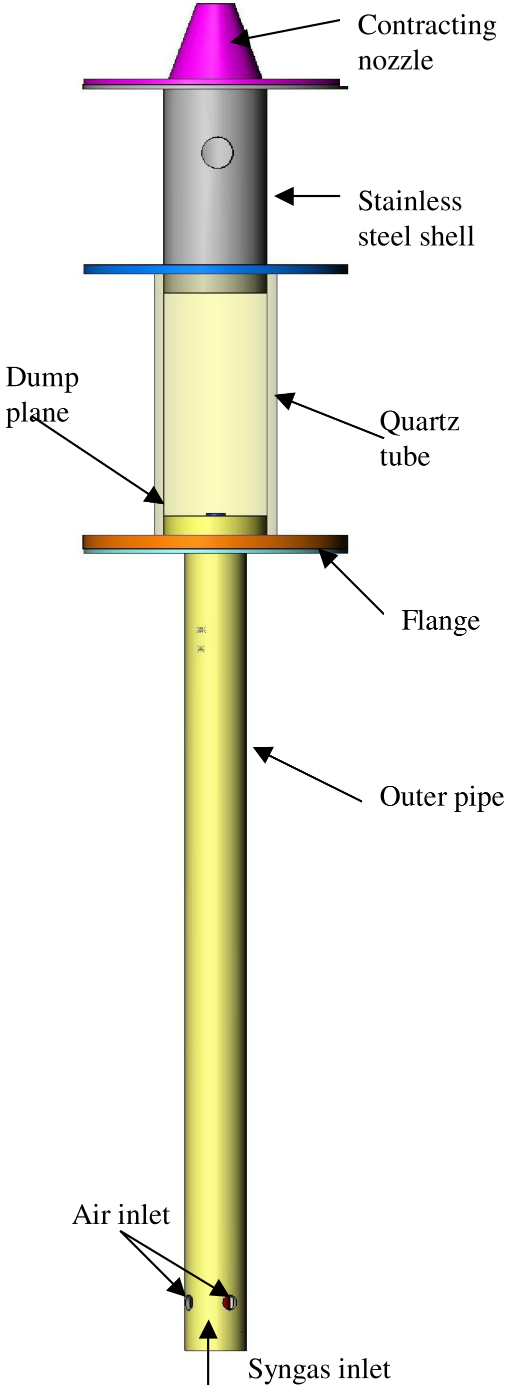
Important Issues

- •Flame flashback
- •Auto-ignition
- •Emissions



Motivation for Work

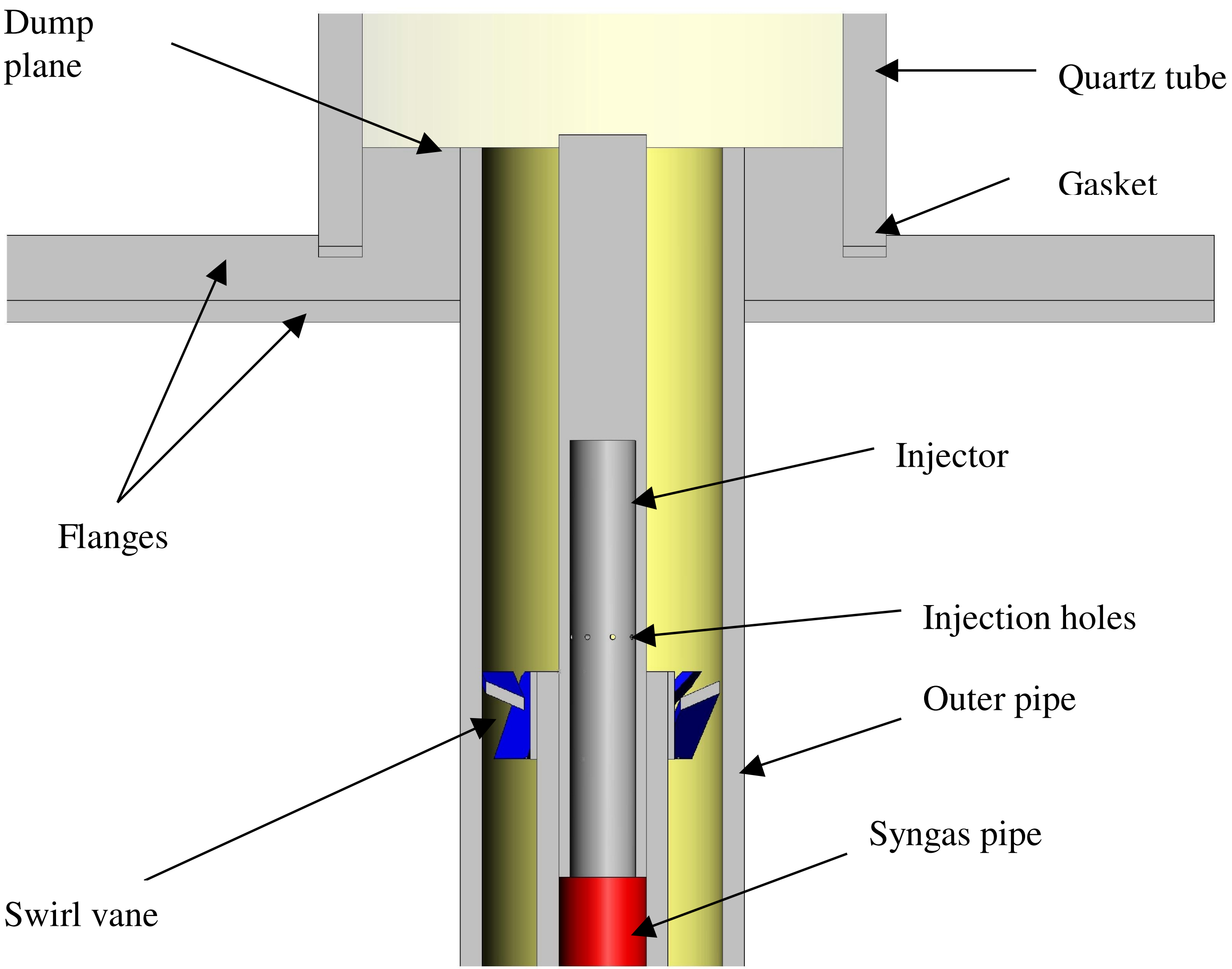
- Present low emissions technology mainly focuses on burning natural gas
- Natural gas cannot be relied upon as the exclusive source for fueling the clean power plants in the future
- Increasing demand due to new installations has caused substantial price volatility
- Concerns about future supplies
- Concern about energy security have motivated interest in utilizing coal-derived syngas or fuels from other sources, such as biomass, landfill gas, process gas and others.
- Technologies like integrated gasification combined cycle (IGCC) plants enable the combustion of coal and other solid or liquid fuels, while still maintaining aggressive emissions targets and high efficiency



Reasons Causing Flame Flashback

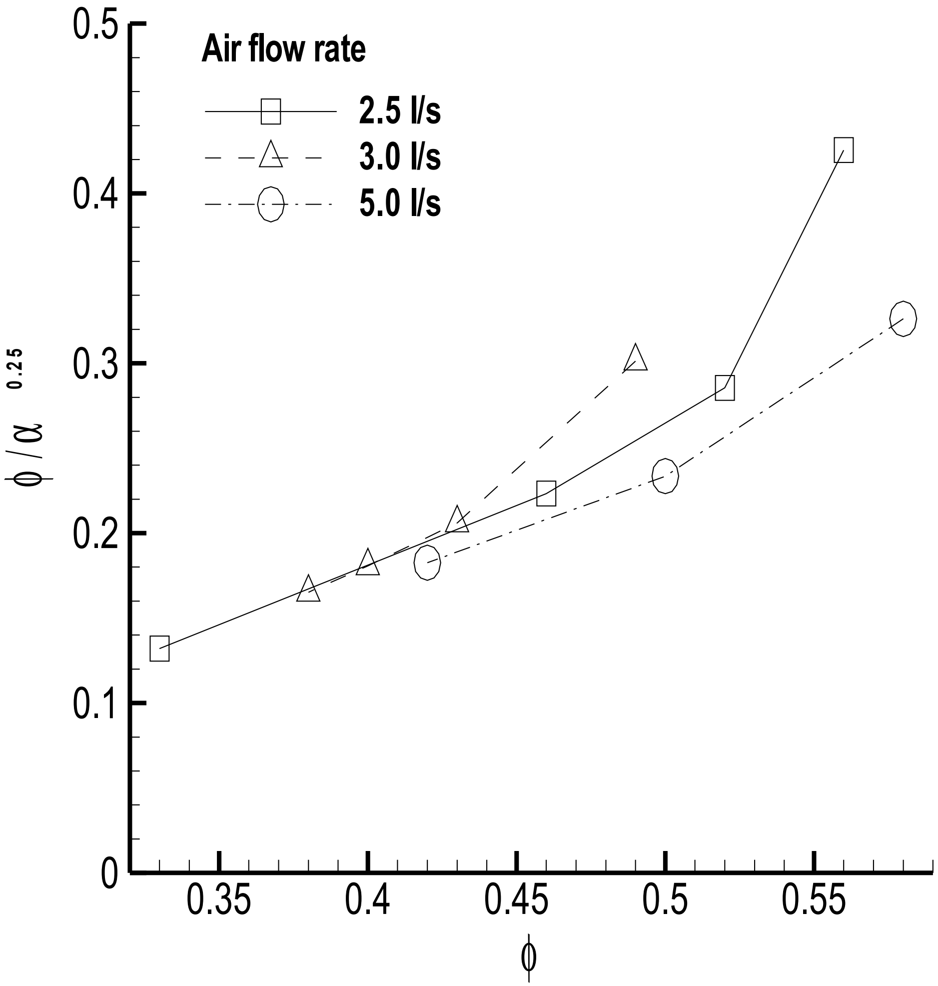
- ❖Low local speeds in the premixing section
- ❖Boundary layer propagation
- ❖Thermo-acoustic instability
- ❖Combustion induced vortex breakdown (CIVB)

- Challenge with syngas is high flame speeds associated with the hydrogen content of the mixture

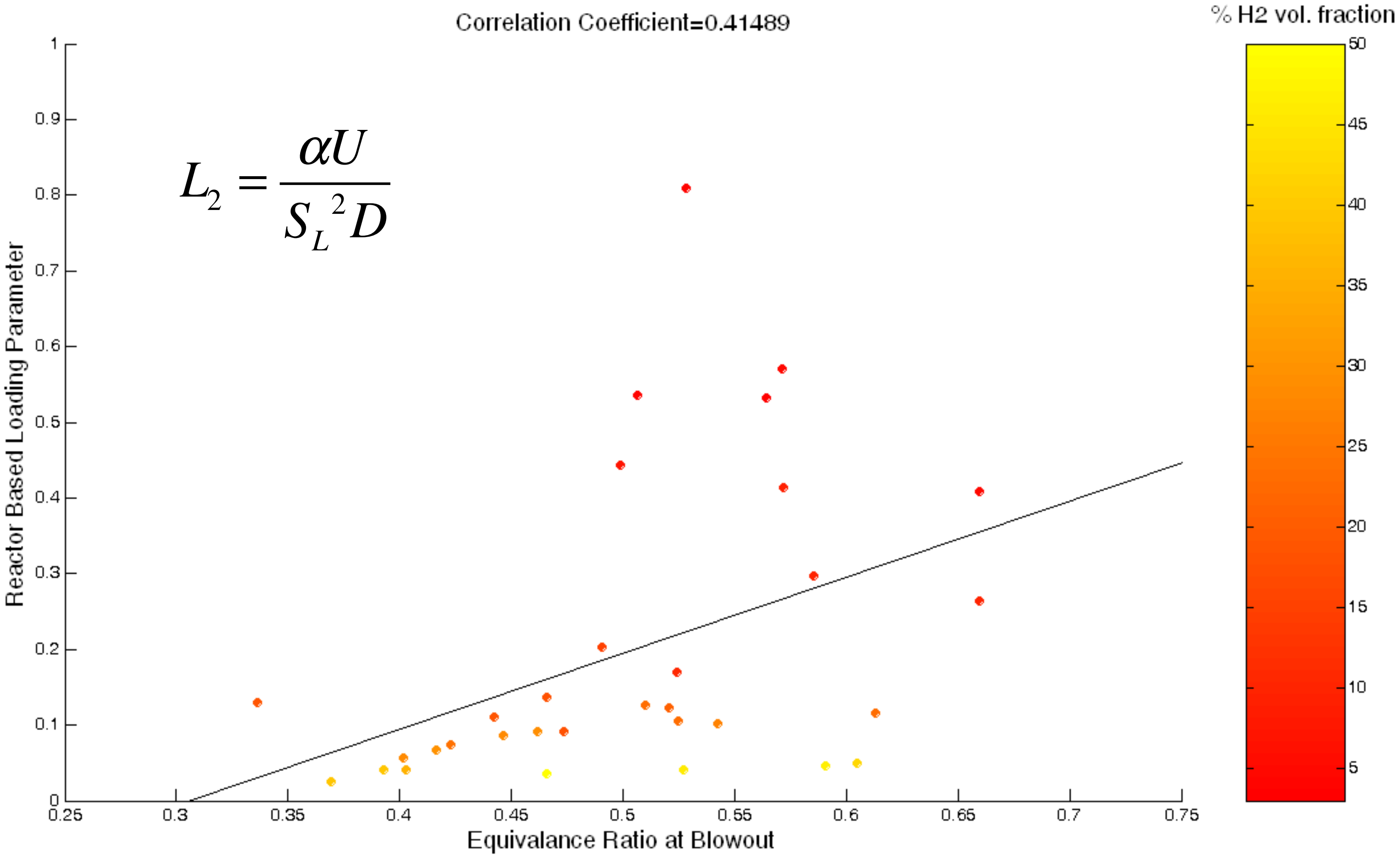


Schematic View of Fuel Delivery System

HYDROGEN ENRICHED COMBUSTION STUDIES



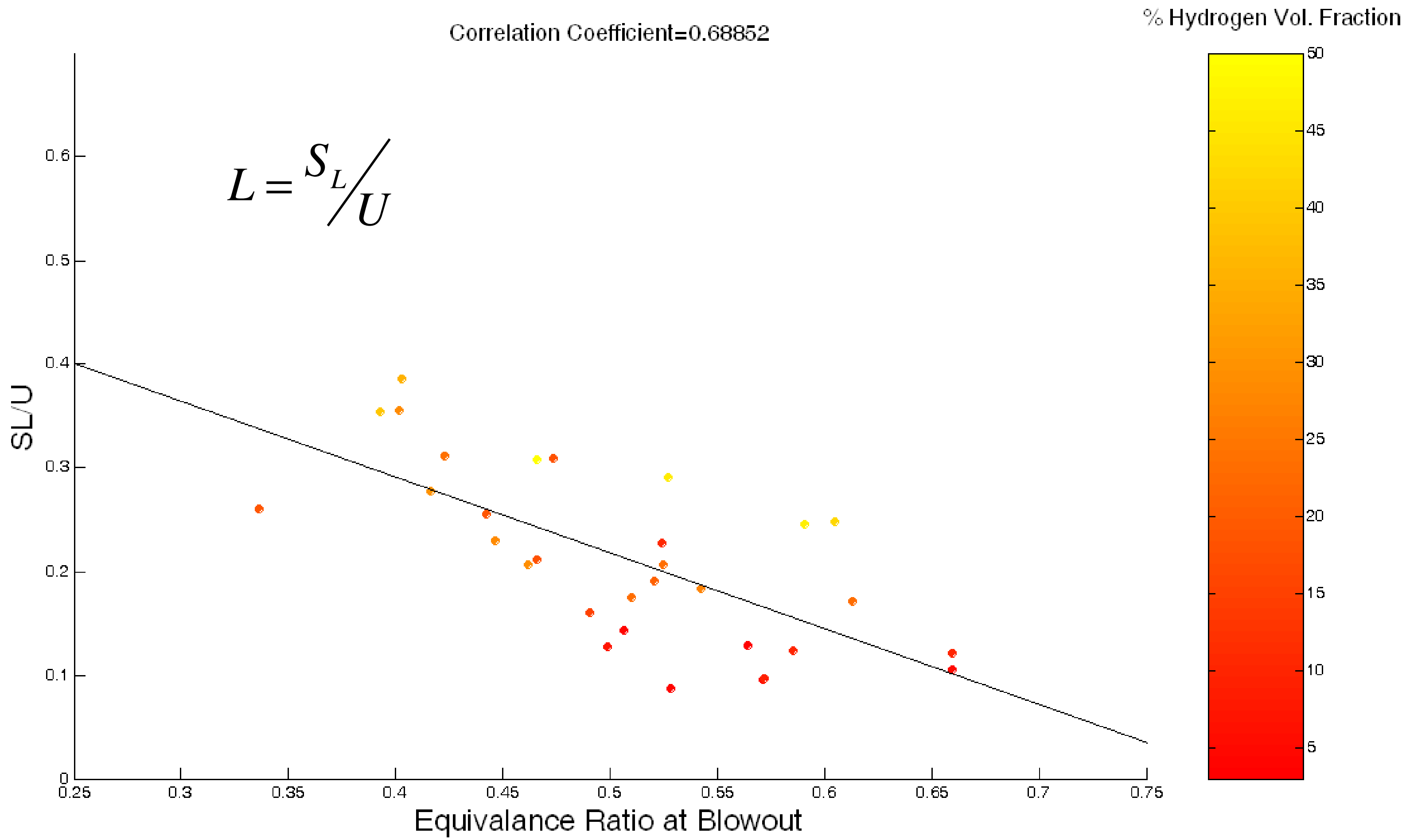
$$\phi = \frac{C_F / \left(C_A - C_H / \left(C_H / C_A \right)_{st} \right)}{\left(C_F / C_A \right)_{st}}$$



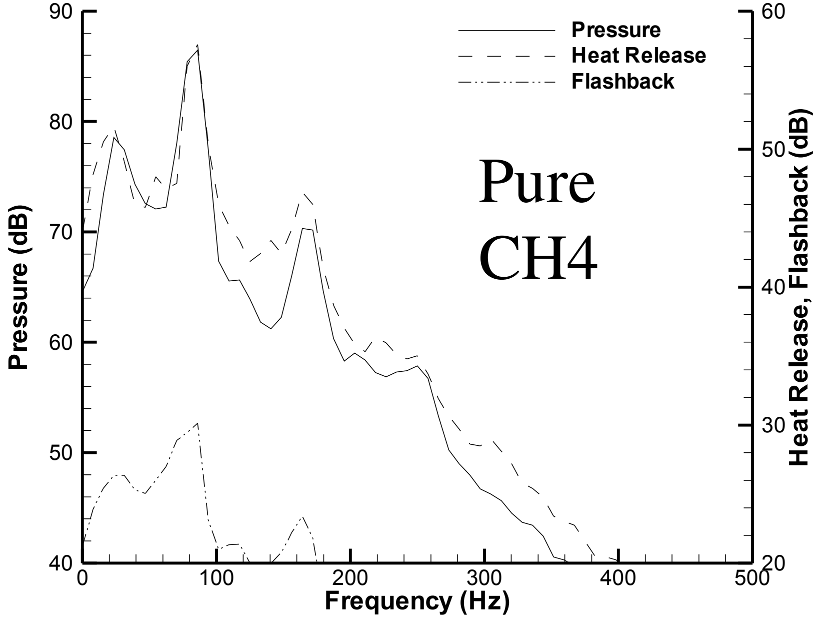
$$L_2 = \frac{\alpha U}{{S_L}^2 D}$$

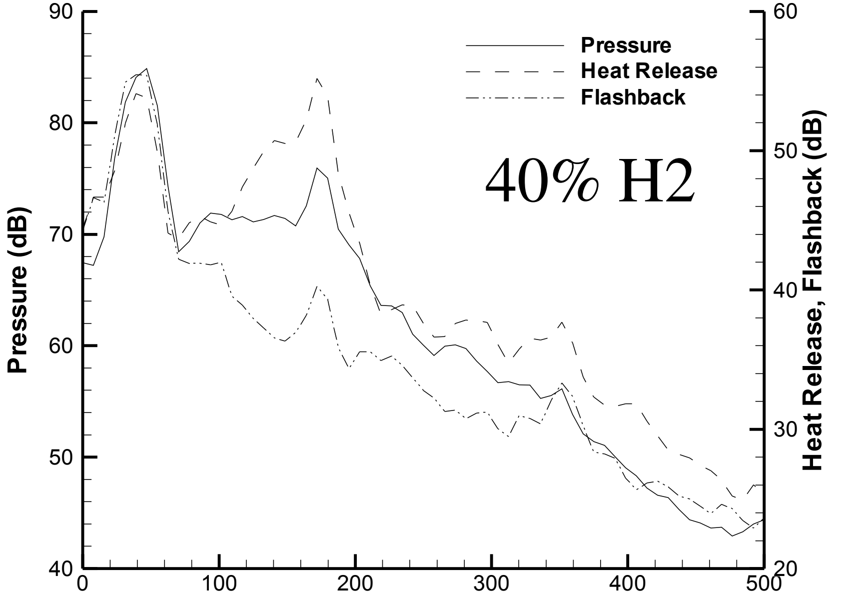
Relationship Between Blowout Equivalence Ratio and Reactor Based Loading Parameter

$$S_L = \frac{C_F}{C_F + C_H} S_{L,CH_4,\phi} + \frac{C_H}{C_F + C_H} S_{L,H_2,s}$$

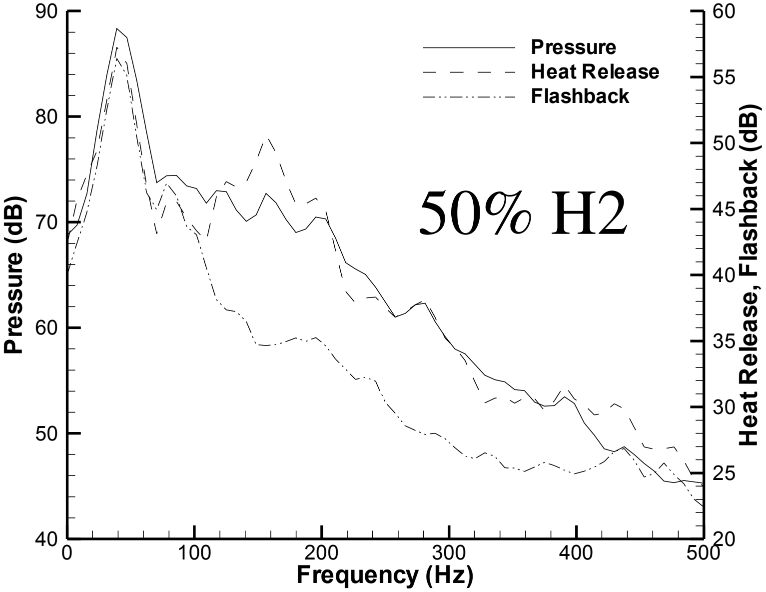


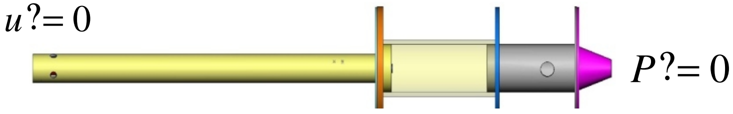
Relationship Between Blowout Equivalence Ratio and Flamelet Based Loading Parameter

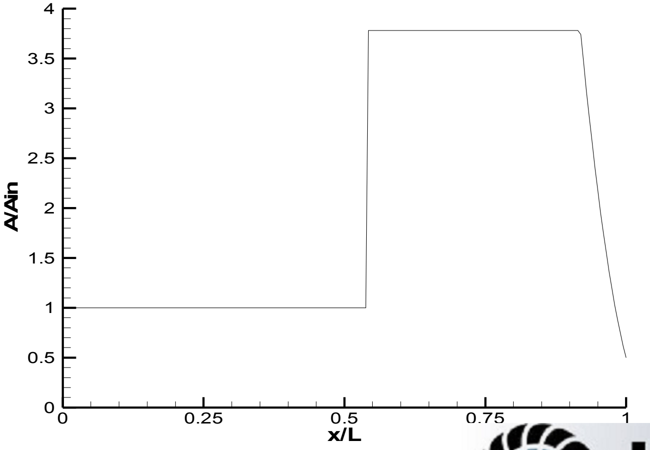


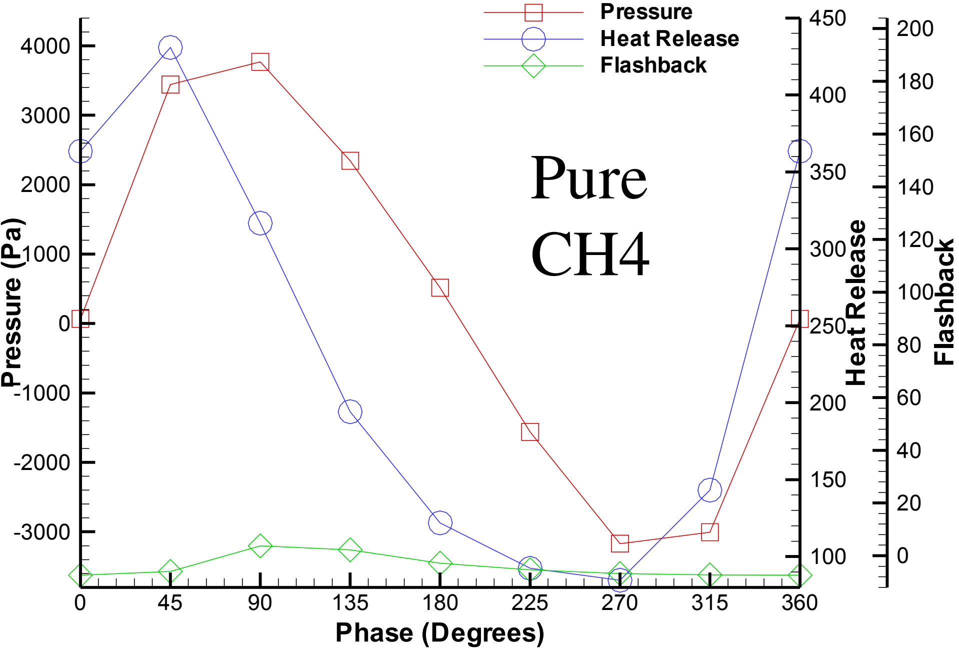


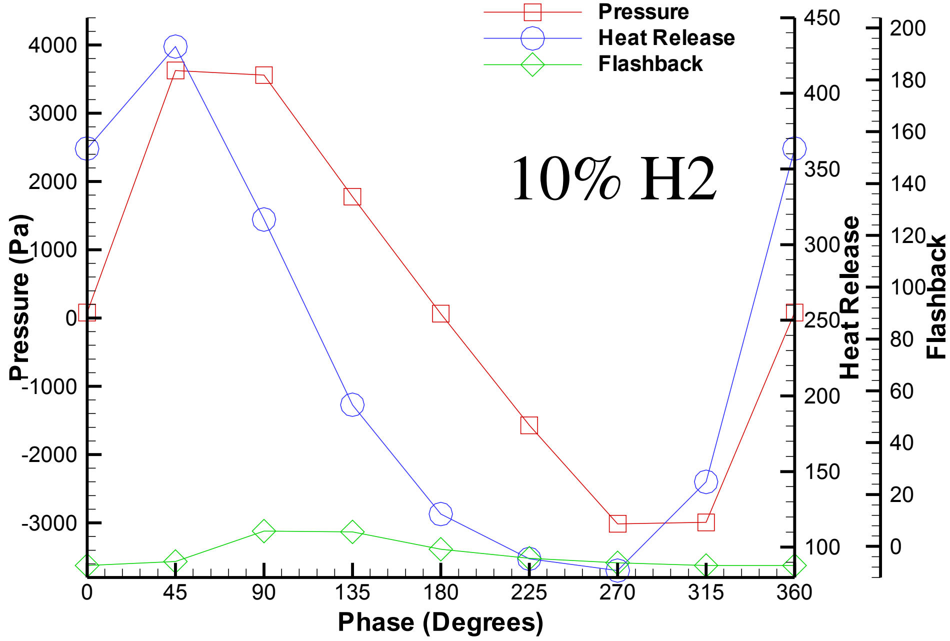
Pressure, Heat Release & Flashback Spectra

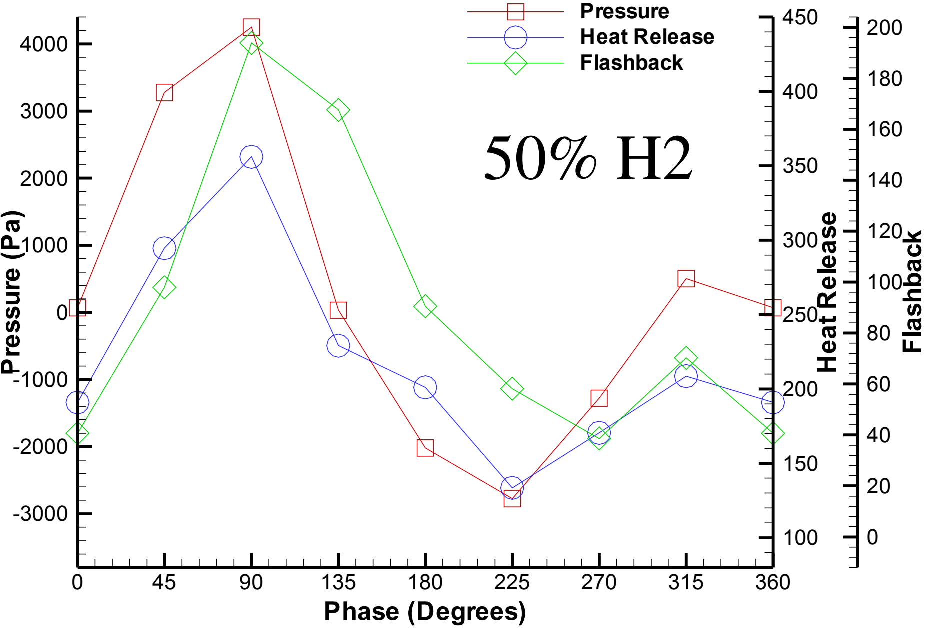






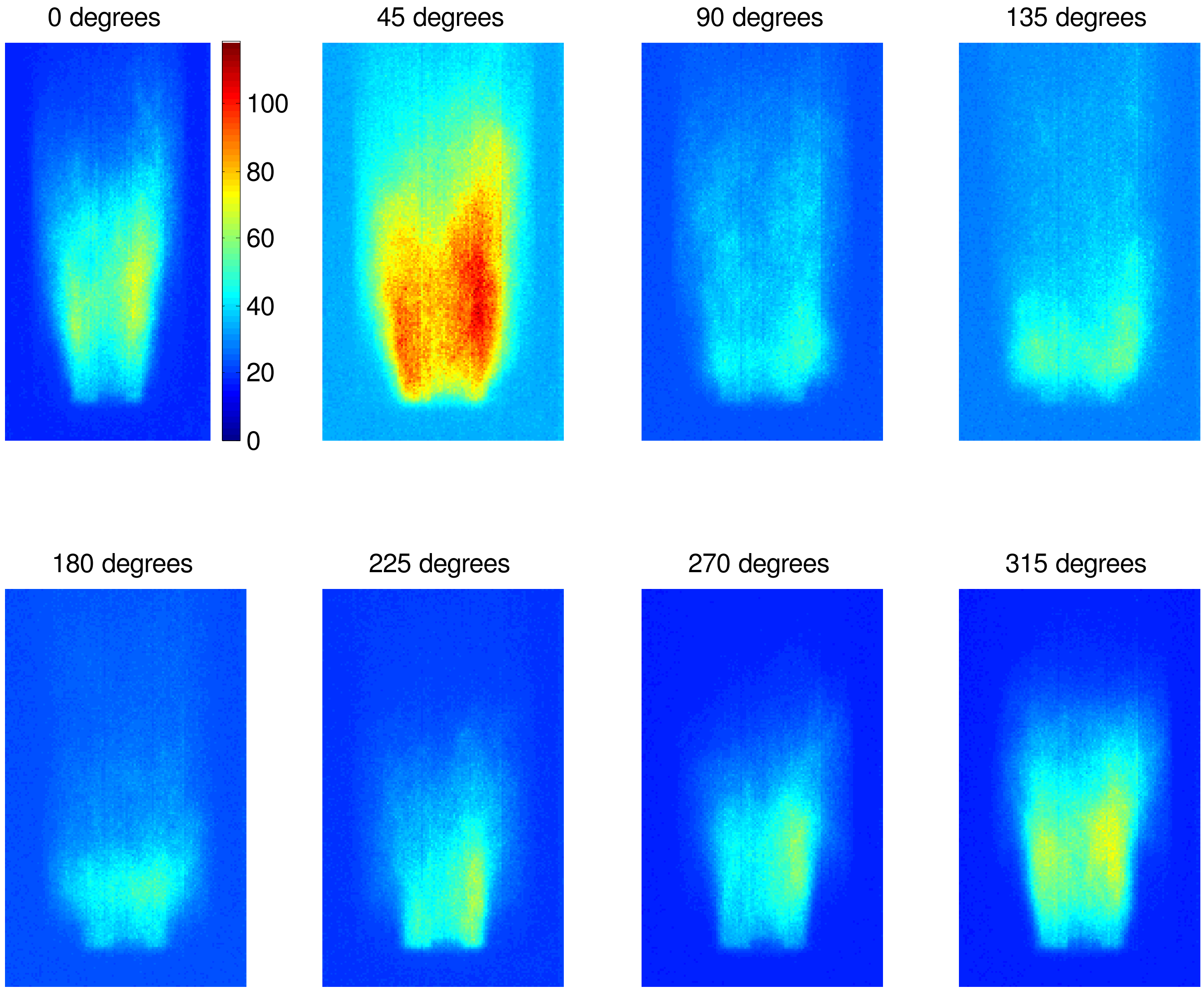






Phase Averaged Pressure, Heat Release & Flashback Signals

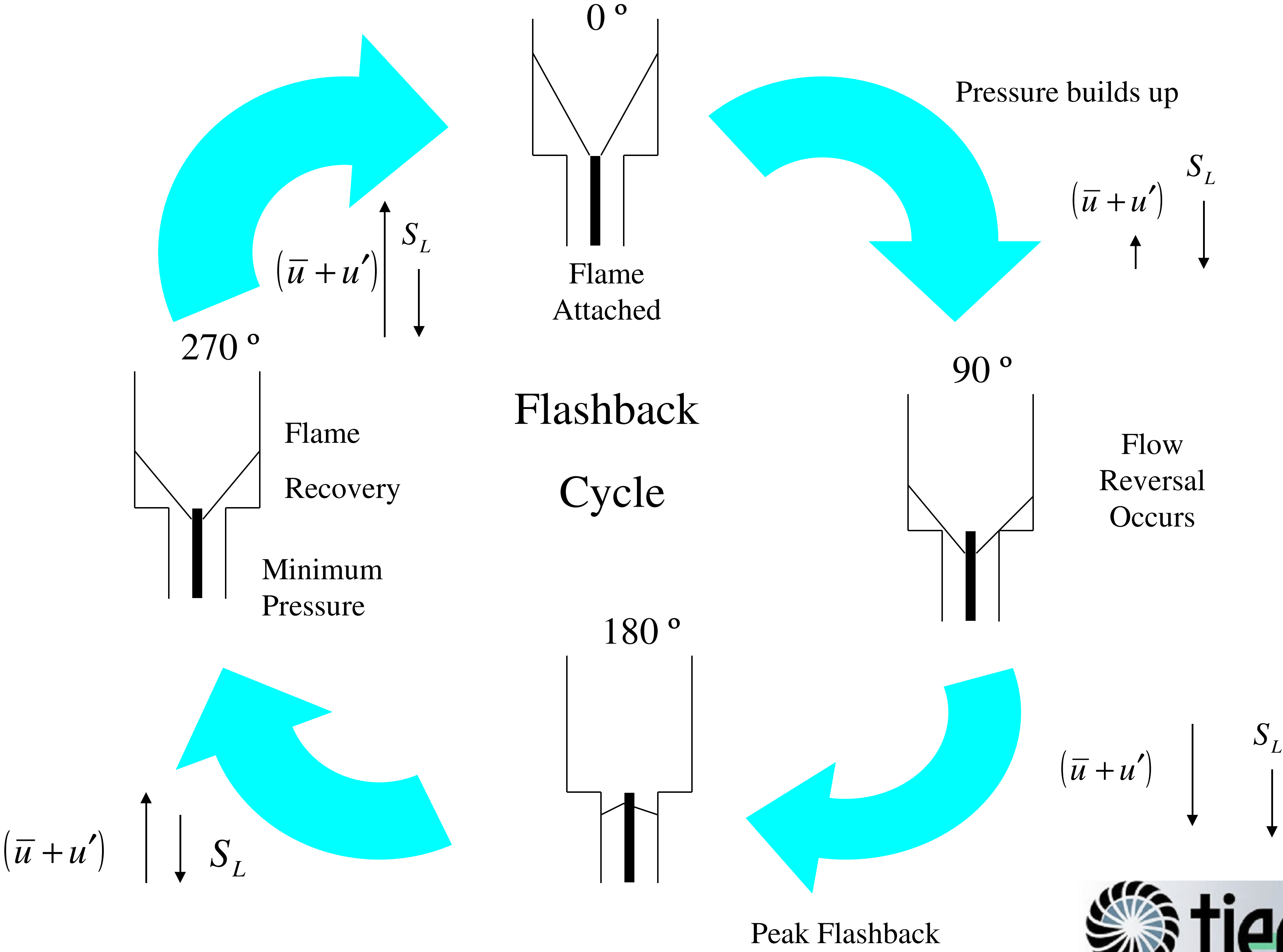
Qair = 6.2 l/s, $\Phi = 0.7$



Qair = 5.7 l/s, $\Phi = 0.7$, 40% Hydrogen by Volume

Phase averaged CH radical images with Flashback

Flashback Cycle



0 °

Flame Attached

Pressure builds up

$(\bar{u} + u')$ $\uparrow$ S_L $\downarrow$

90 °

Flow Reversal Occurs

$(\bar{u} + u')$ $\downarrow$ S_L $\downarrow$

180 °

Peak Flashback

$(\bar{u} + u')$ $\uparrow$ $\downarrow$ S_L

270 °

Flame Recovery

Minimum Pressure

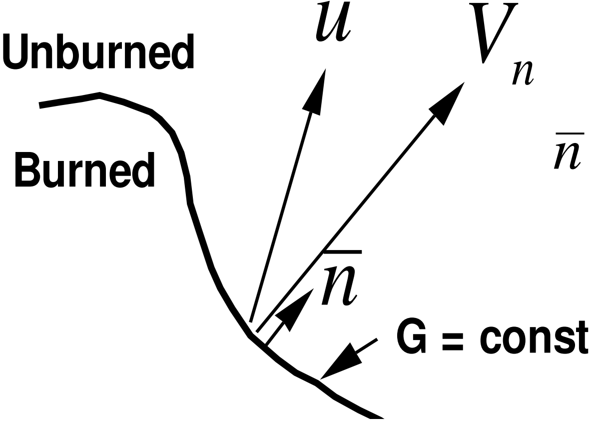
$(\bar{u} + u')$ $\uparrow$ S_L $\downarrow$

Flamelet Modeling

Many models based on "G-equation" (Kerstein et al. 1987)

Any curve of G = C is a flame front (G < C burned; G > C burned)

Flame advances by self-propagation and advances or retreats by convection



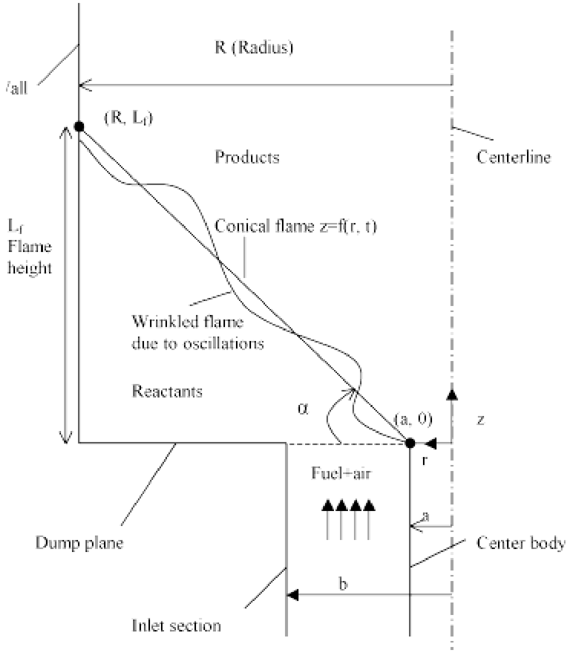
$$\bar{n} = \text{unit normal to front} = \frac{-\left(\frac{\partial G}{\partial x}\hat{i} + \frac{\partial G}{\partial y}\hat{j}\right)}{\sqrt{\left(\frac{\partial G}{\partial x}\right)^2 + \left(\frac{\partial G}{\partial y}\right)^2}} = \frac{-\nabla G}{|\nabla G|}$$

$$V_n = \text{flame speed in lab frame} = \frac{\partial G/\partial t}{|\nabla G|}$$

$$V_n - \bar{u} \bullet \bar{n} = \text{flame speed in lab frame}$$

$$-\ \text{flow speed} = S_L$$

$$\frac{\partial G/\partial t}{|\nabla G|} + \frac{\bar{u} \bullet \nabla G}{|\nabla G|} = S_L \text{ or } \frac{\partial G}{\partial t} + \bar{u} \bullet \nabla G = S_L|\nabla G|$$



Combustor Acoustics

$$\frac{\partial^2 P}{\partial t^2} + c^2 \nabla^2 P = \left(\gamma - 1\right)\frac{\partial q'}{\partial t}$$

Acoustic field inside the gas turbine combustor can be assumed to be one-dimensional (i.e. wavelength of acoustic waves much larger than combustor diameter)

$$\frac{\partial^2 P}{\partial t^2} + c^2 \frac{\partial^2 P}{\partial x^2} = \left(\gamma - 1\right)\frac{\partial q'}{\partial t}$$

$$u'\left(x,t\right)\Big|_{x=0} = 0$$

Boundary condition at the closed inlet. Acoustic velocity is zero since particles adjacent to a wall cannot move

$$P'\left(x,t\right)\Big|_{x=L} = 0$$

Boundary condition at the open outlet. Particles are free to move (i.e. zero acoustic pressure, maximum velocity)

$$P = \bar{P}\eta\left(t\right)\Psi\left(x\right)$$

$$u = \dot{\eta}\left(t\right)\Psi'\left(x\right)k^{-2}$$

$$\left.\frac{\partial \psi}{\partial x}\right|_{x=0} = 0$$ Inlet $$\psi\Big|_{x=L} = 0$$ Outlet

$$\ddot{\eta} + \omega^2 \eta = \frac{\left(\gamma - 1\right)}{\bar{P}} E^{-1} \psi\left(x_f\right)\frac{dq'}{dt}$$

Governing oscillator equation $$E = \int_0^L \psi^2\left(x\right)dx$$

A sudden jump occurs in properties before and after the flame such that,

$$T(x) = \begin{array}{ll} ?\,T_{in} & x\ ?\ x_f \\ ? & \\ ?\,T_{ad} & x > x_f \\ ? & \end{array}$$

$$c(x) = \begin{array}{ll} ?\,c_u & x\ ?\ x_f \\ ? & \\ ?\,c_d & x > x_f \\ ? & \end{array}$$

Associated change in the speed of sound

Therefore while solving for the mode shape one must consider the matching condition the interface

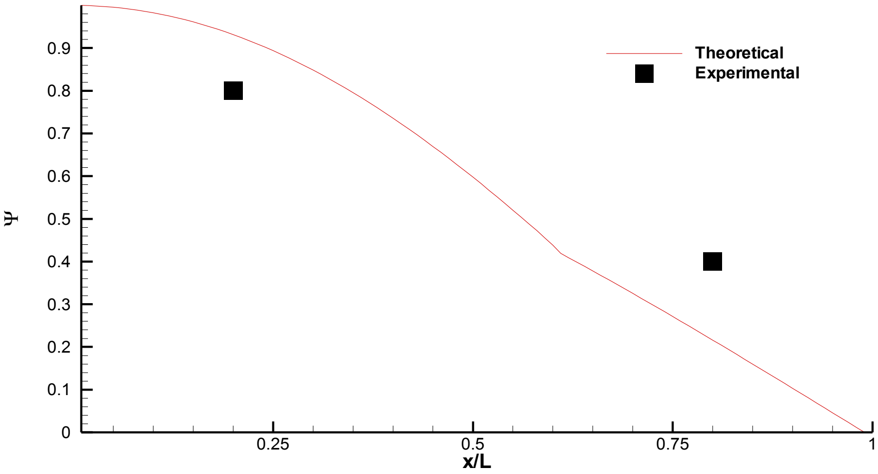
$$\psi\left(x_f{}^{+}\right) = \psi\left(x_f{}^{-}\right)$$

$$\psi(x) = \begin{cases} \cos\left(\dfrac{\omega x}{c_u}\right) & x \le x_f \\ \dfrac{\cos(\alpha)}{\sin(\beta)}\sin\left(\dfrac{\varpi(L-x)}{c_d}\right) & x > x_f \end{cases}$$

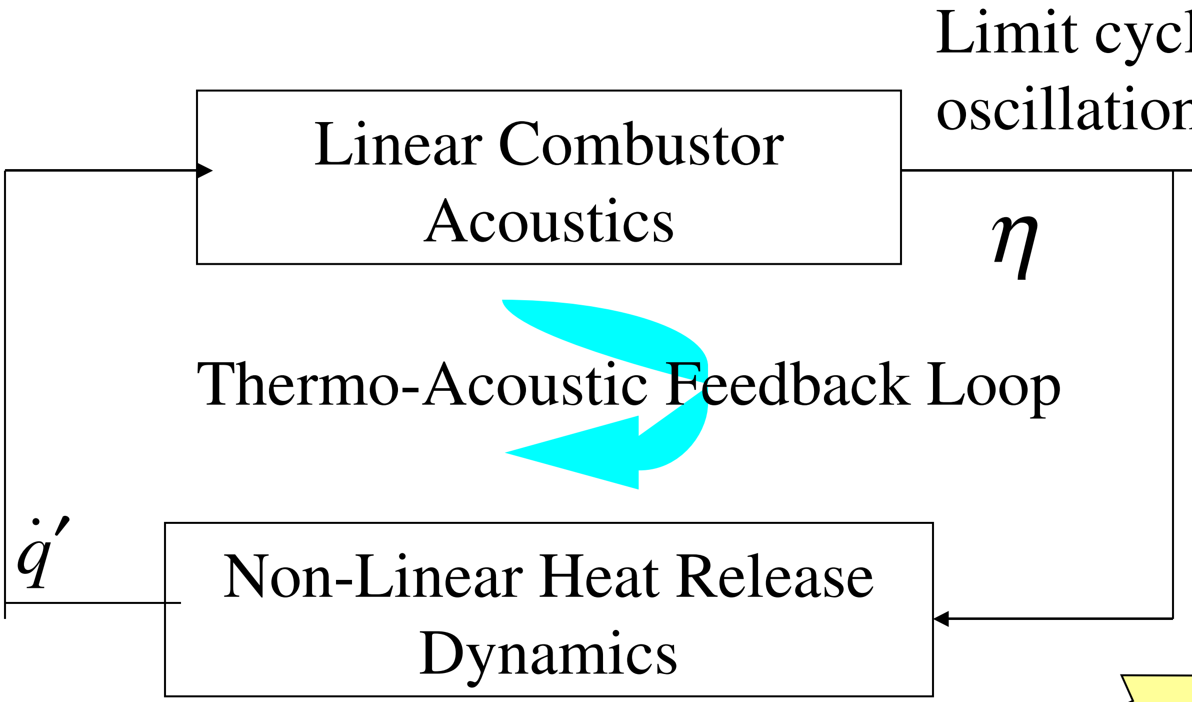
$$\alpha = \varpi\, x_f / c_u \qquad \beta = \varpi\left(L - x_f\right)/c_d$$

Solve for frequency w from the roots of,

$$\tan\alpha \tan\beta = \left(\rho_u c_u\right)/\left(\rho_d c_d\right)$$



Acoustic Mode Shape Along the Length of the Combustor



Limit cycle oscillations

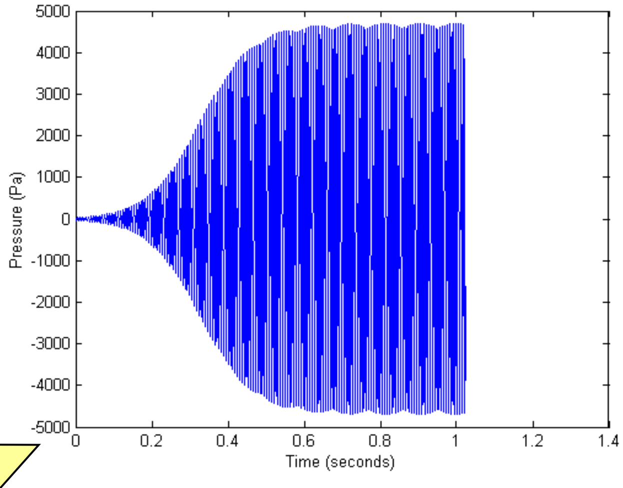
Linear Combustor Acoustics

η

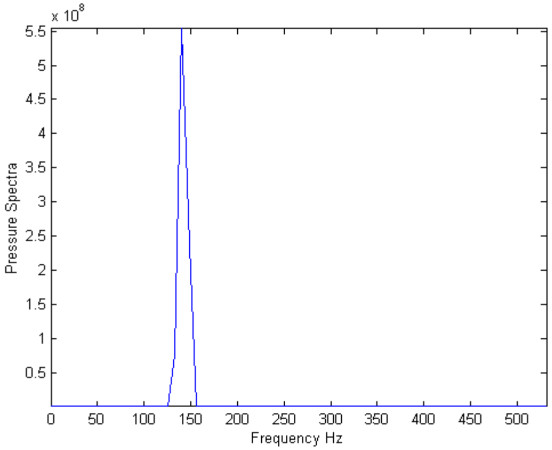
Thermo-Acoustic Feedback Loop

$\dot{q}'$

Non-Linear Heat Release Dynamics



Development of Limit Cycle Pressure Oscillations from an Arbitrary Initial Condition (ϕ=1.0, Q=540 lt/min at x/L=0.85)



Corresponding Pressure Spectrum

Heat Release Dynamics

In order to close the thermo-acoustic feedback loop one needs to specify the heat release dynamics

Linear heat release model (Annaswamy et. al., 2002) derived from linearizing a well-stirred reactor model for the flame front with single step chemical kinetics

$$\dot{q}'(s) = \frac{\beta}{s+\alpha}\dot{m}'(s)$$

Response of heat release fluctuations to mass flow rate perturbations (due to velocity fluctuations)

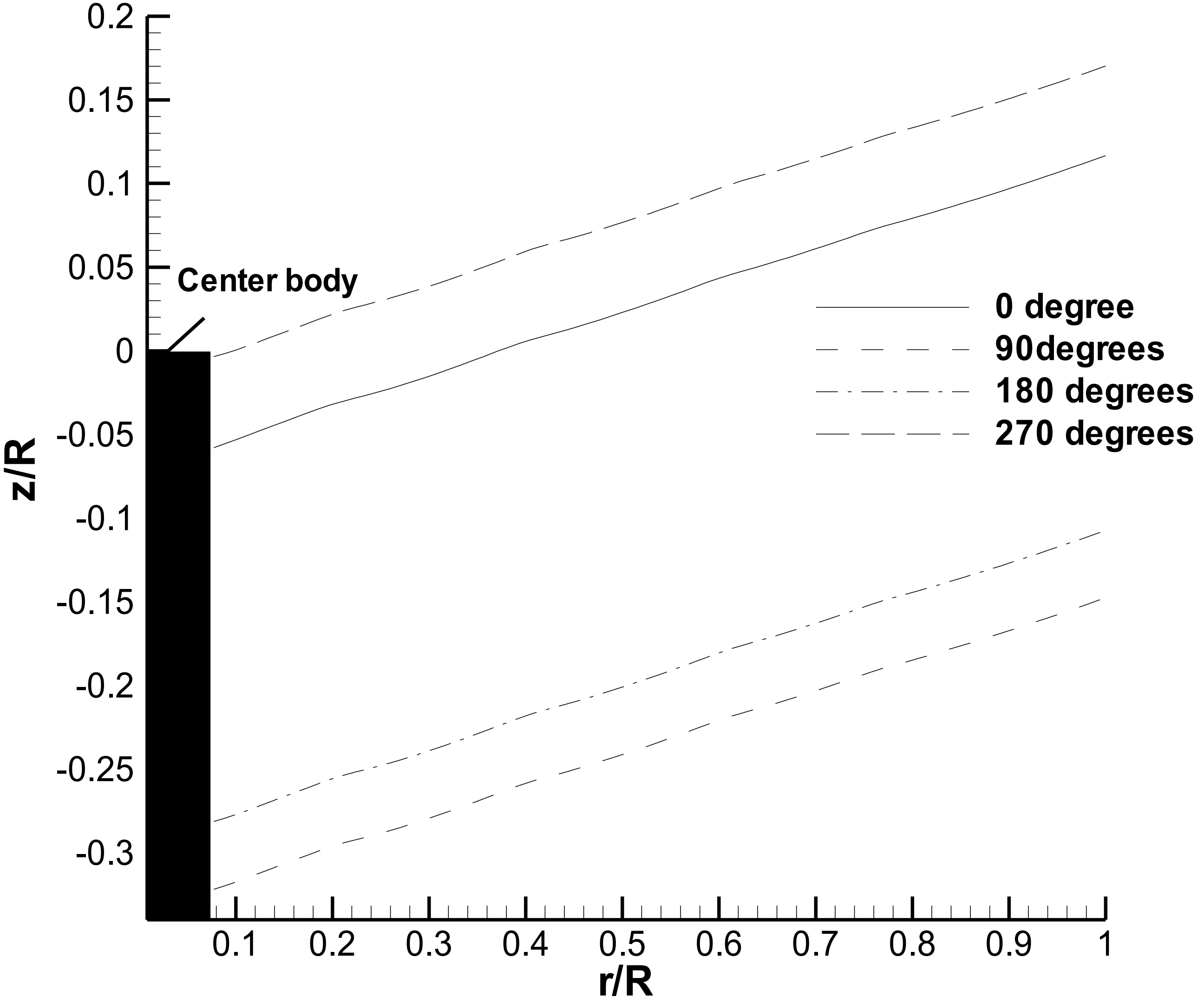
This linear model predicts linear stability characteristics of the flame but will not yield in a non-linear limit cycle. Instead for unstable conditions system output grows to infinity without an upper bound.

However, it is experimentally observed that heat release saturates as the amplitude of input grows. One can incorporate that non-linear saturation effect as follows,

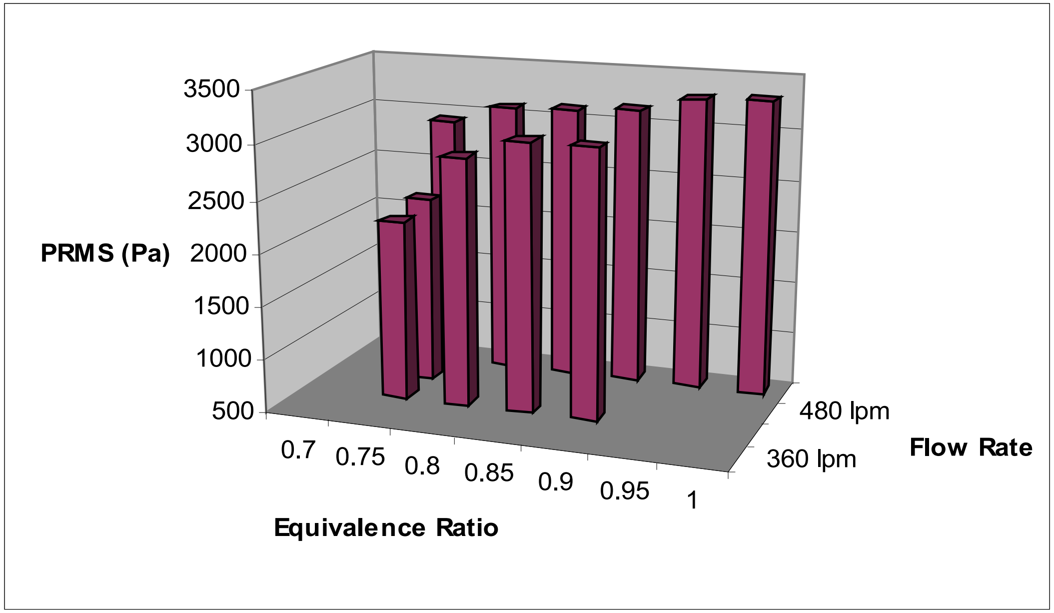
$$\dot{q}'(s) = \frac{\beta}{s+\alpha}\dot{m}'(s)\left(1-\left|\frac{\dot{m}'(s)}{\bar{\dot{m}}}\right|\right)$$

Non-linear response of heat release fluctuations to mass flow rate perturbations

The amount of heat release must be bounded by the amount of fuel available to be burnt. Heat release saturation occurs due to this fuel consumption effect

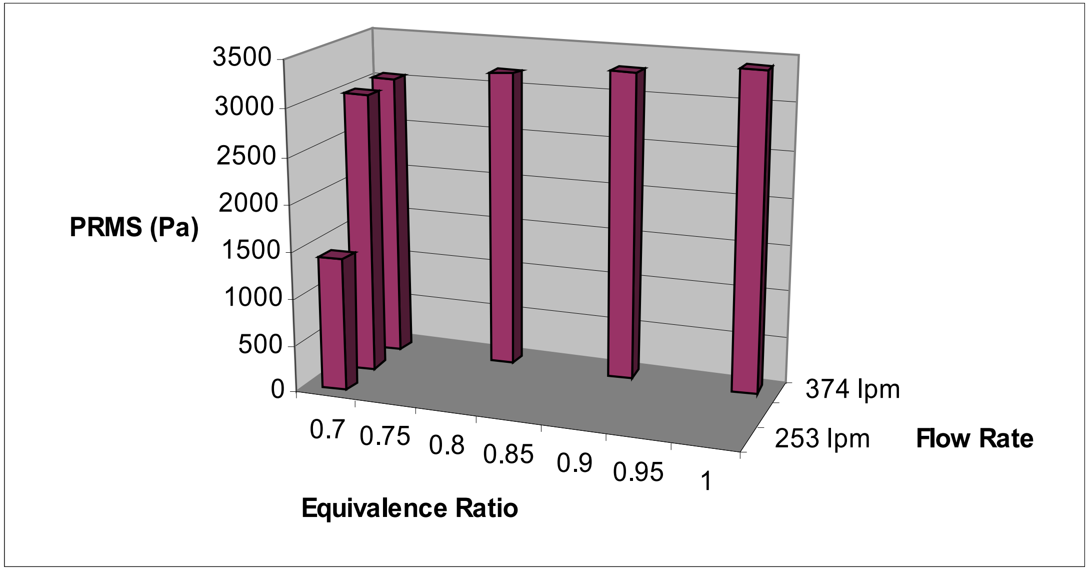


Flame Front Movement with Respect to Thermo-acoustic Instability Cycle
Position of the Flame front Phase Locked with Pressure



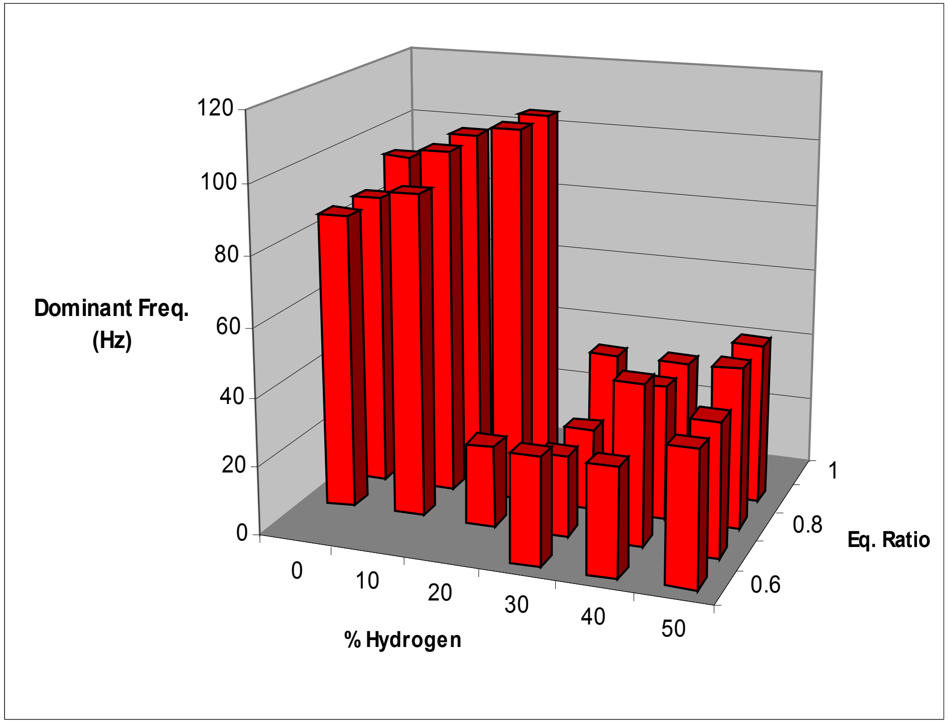
RMS Amplitude of Limit Cycle Pressure Fluctuations

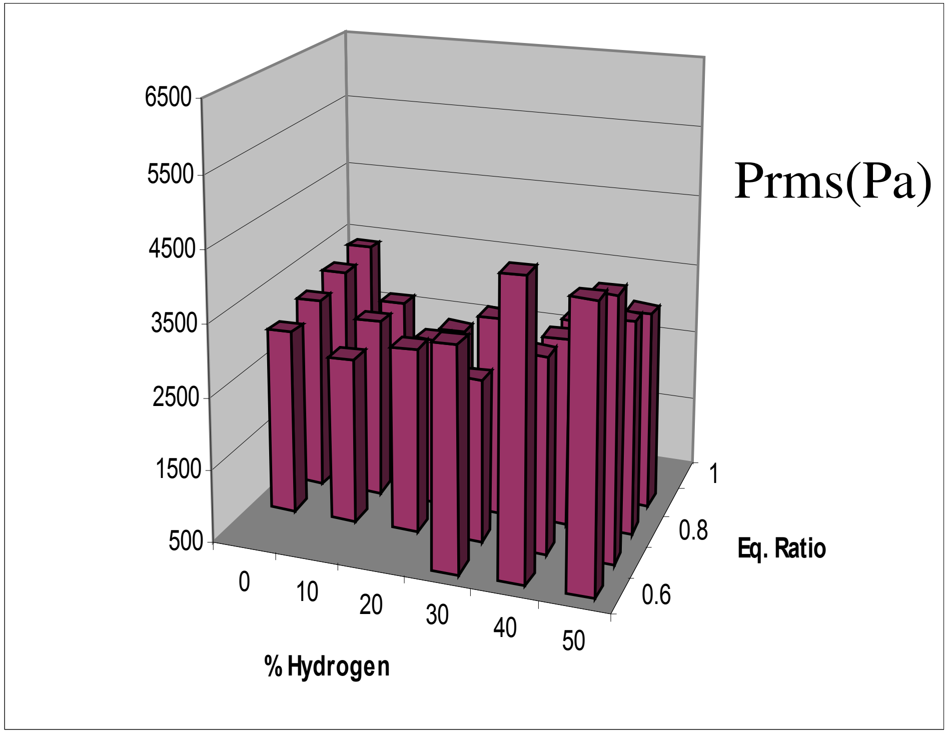
Obtained From Simulations as a Function of Air Flow Rate and Equivalence Ratio (Pure Methane, x/L=0.80)



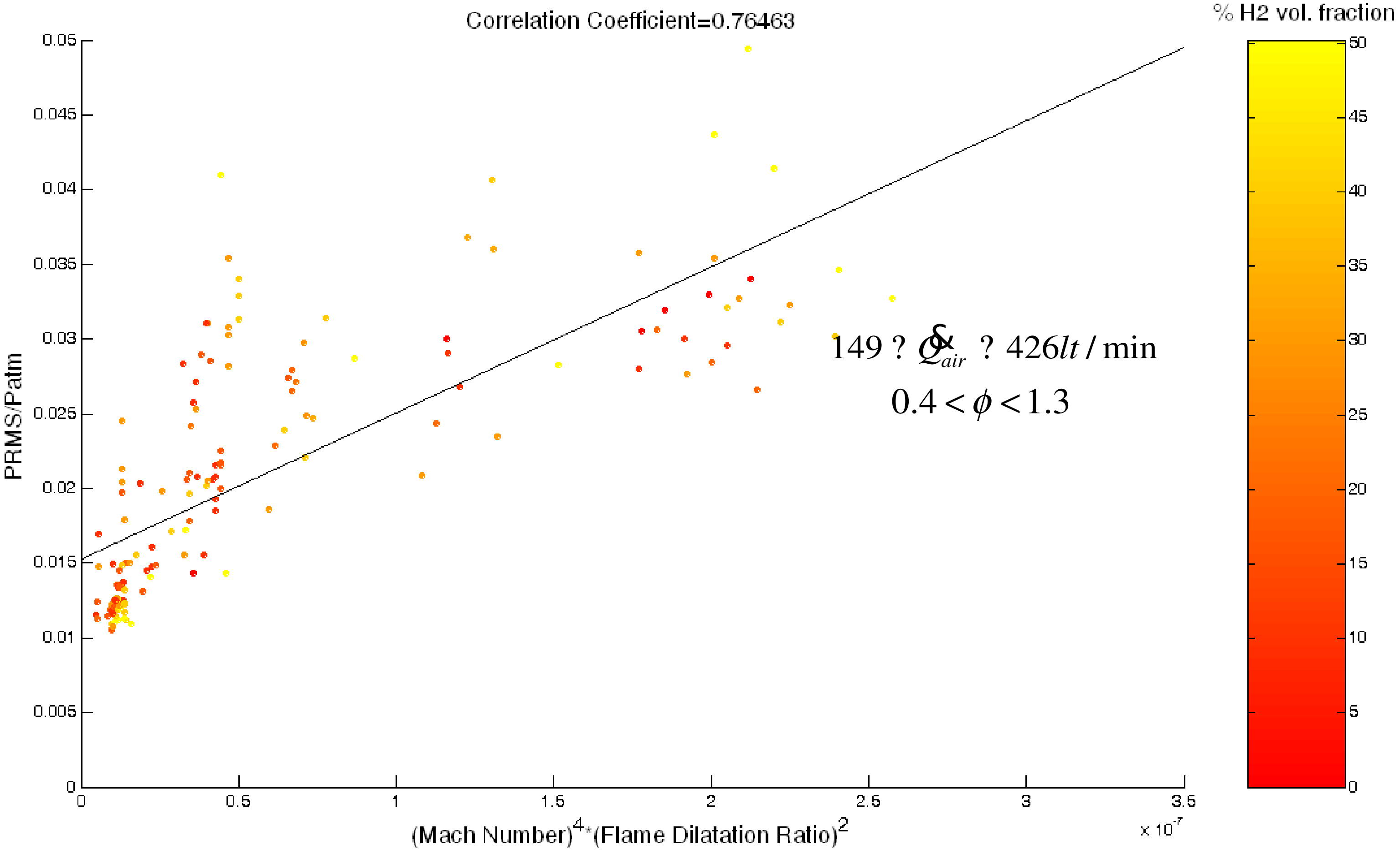
RMS Amplitude of Limit Cycle Pressure Fluctuations

Obtained From Experiments as a Function of Air Flow Rate and Equivalence Ratio (Pure Methane, x/L=

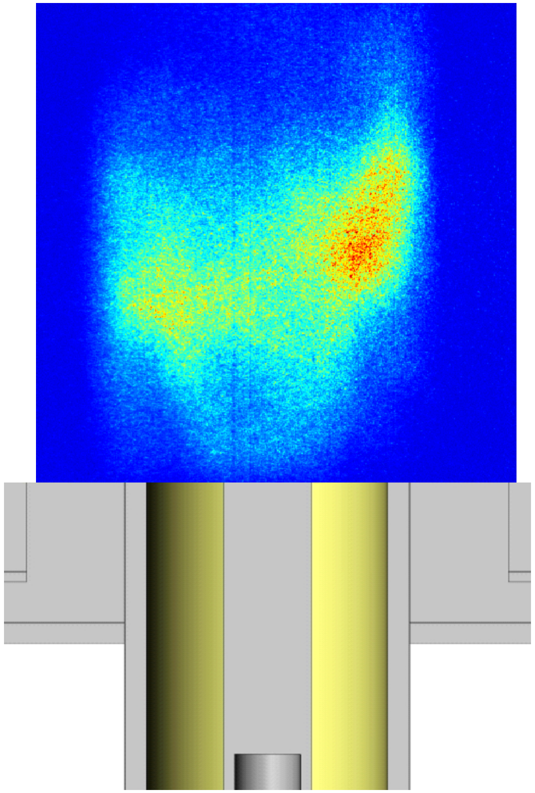




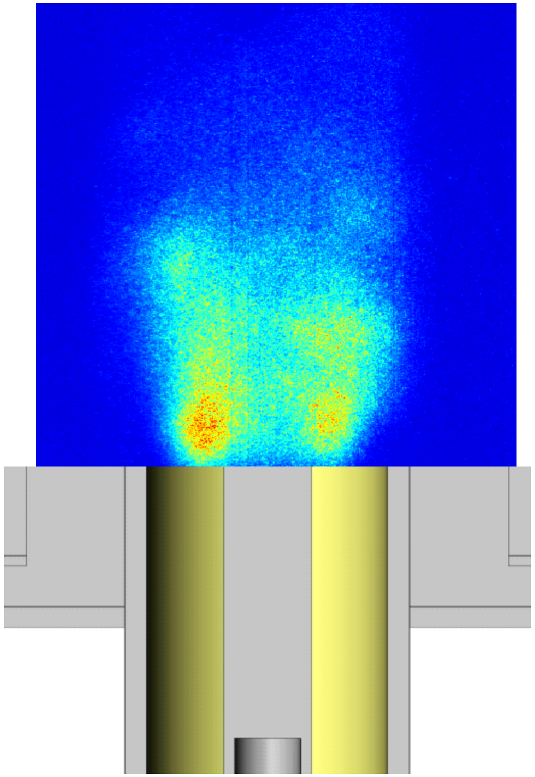
Effect of Hydrogen Volume Fraction and Equivalence Ratio on Dominant Frequency and RMS Pressure Level at a Fixed Air Flow Rate Qair=6.2 l/s



Scaling of RMS Pressure Level



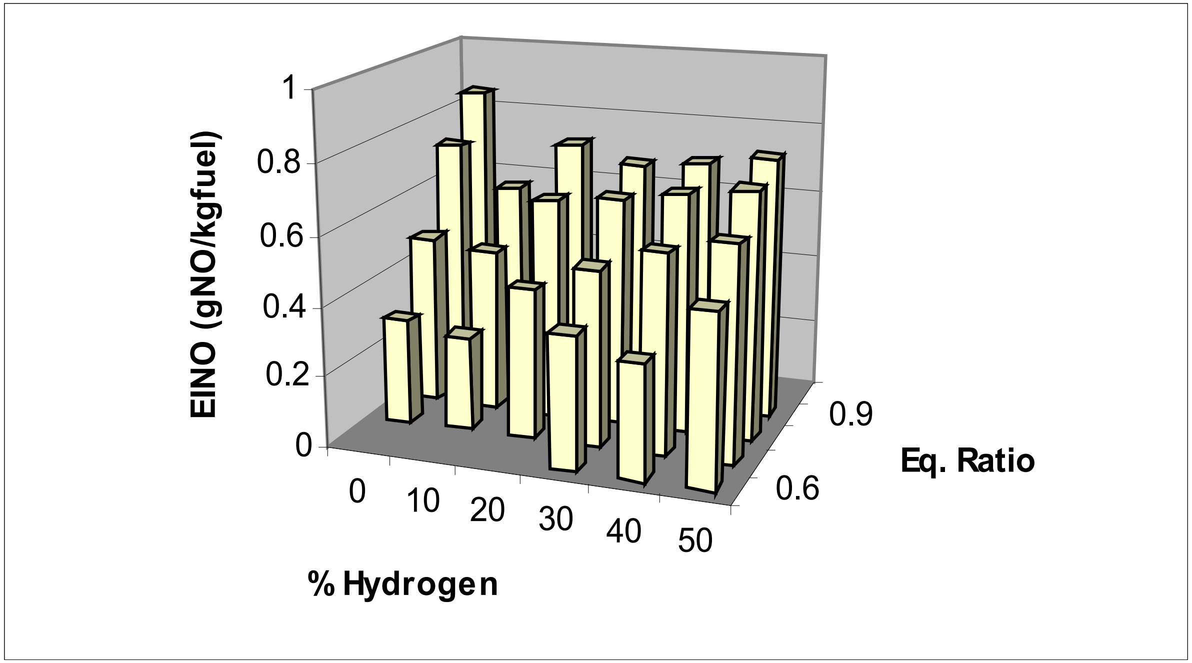
Pure Methane

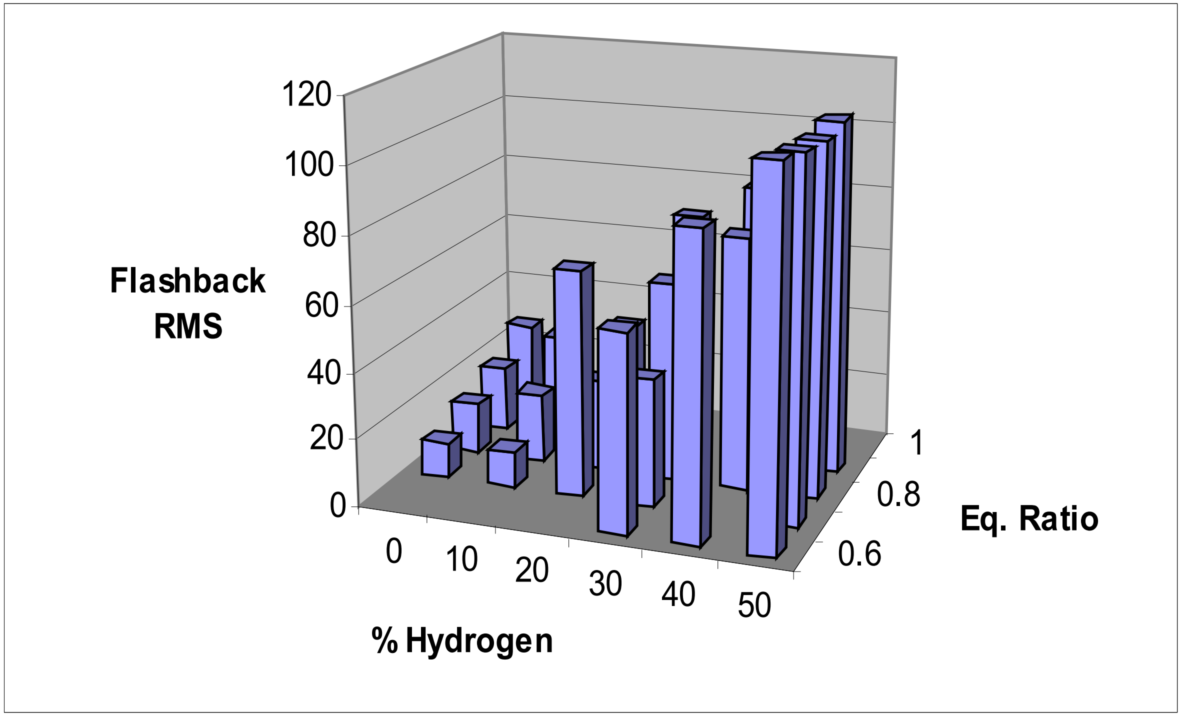


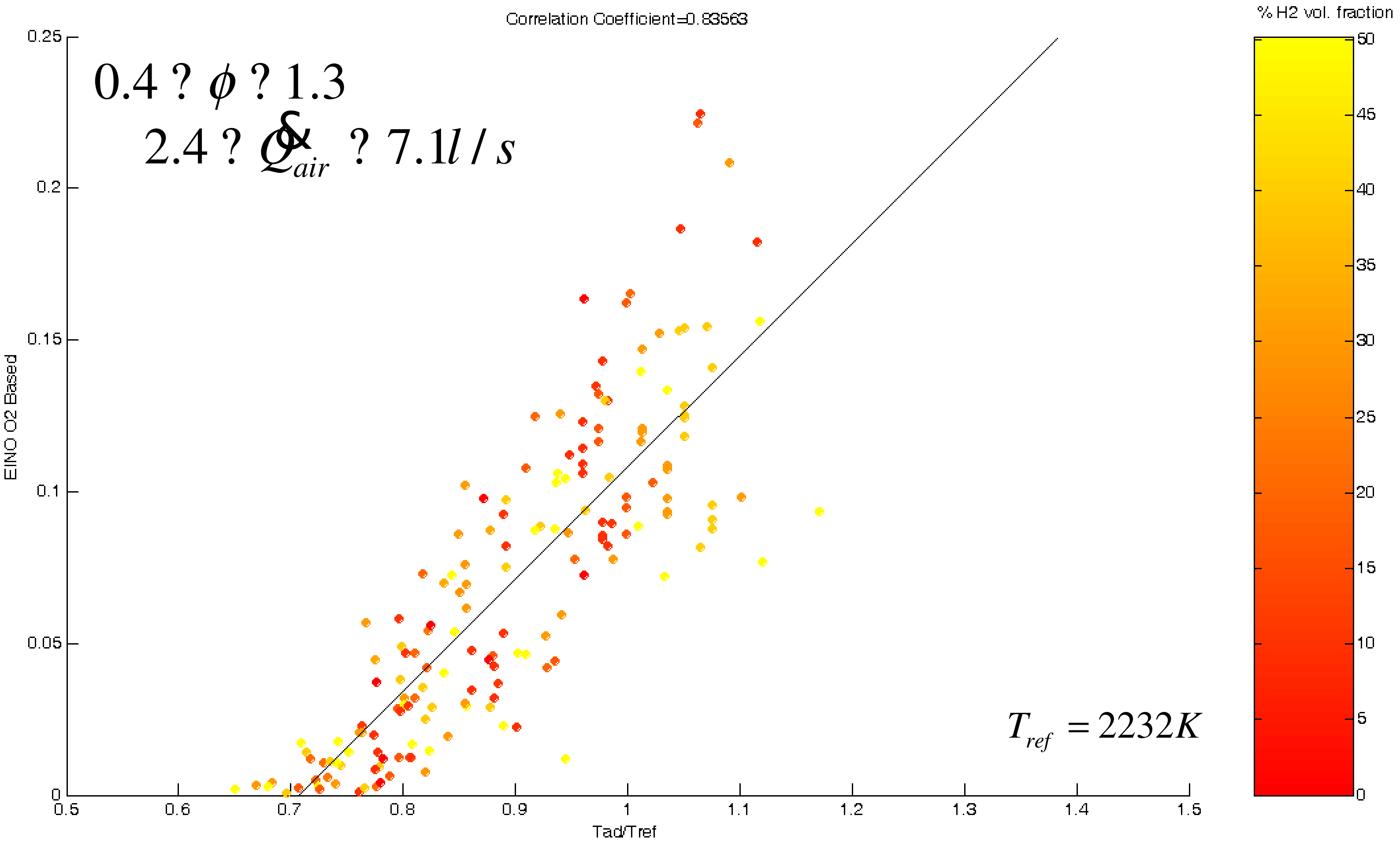
50% H2 by volume

OH* Chemiluminesence Images Demonstrating Effect of Fuel Composition on the Distance to the Flame Center of Mass at a Fixed Flow Rate and Equivalence Ratio (Qair=6.2 l/s, Φ=0.7)

Effect of Hydrogen Volume Fraction and Equivalence Ratio on Dominant Frequency and RMS Pressure Level at a Fixed Air Flow Rate Qair=6.2 l/s





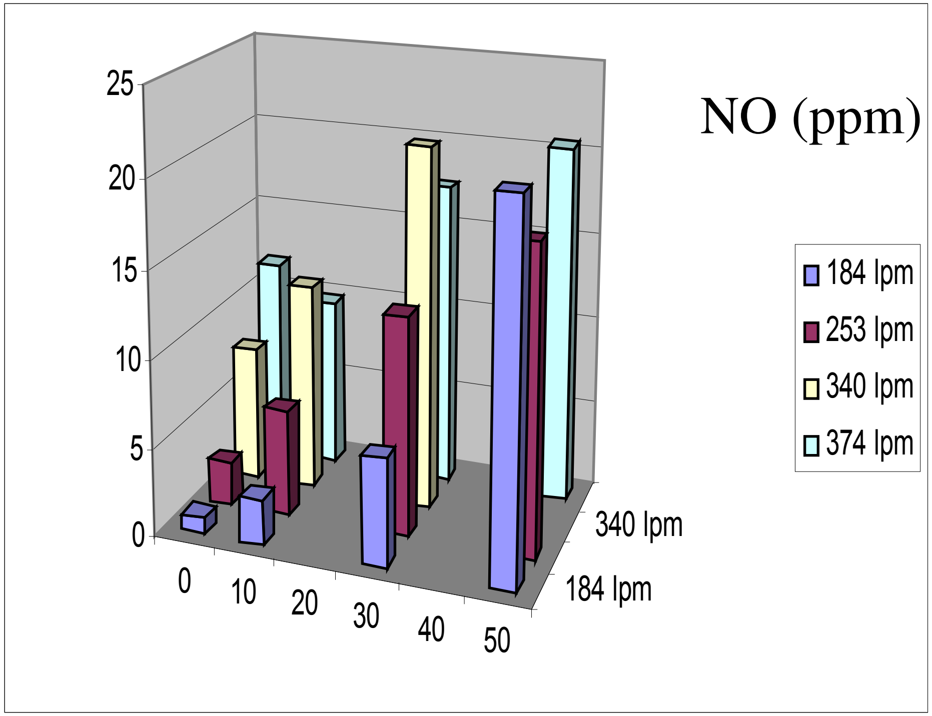


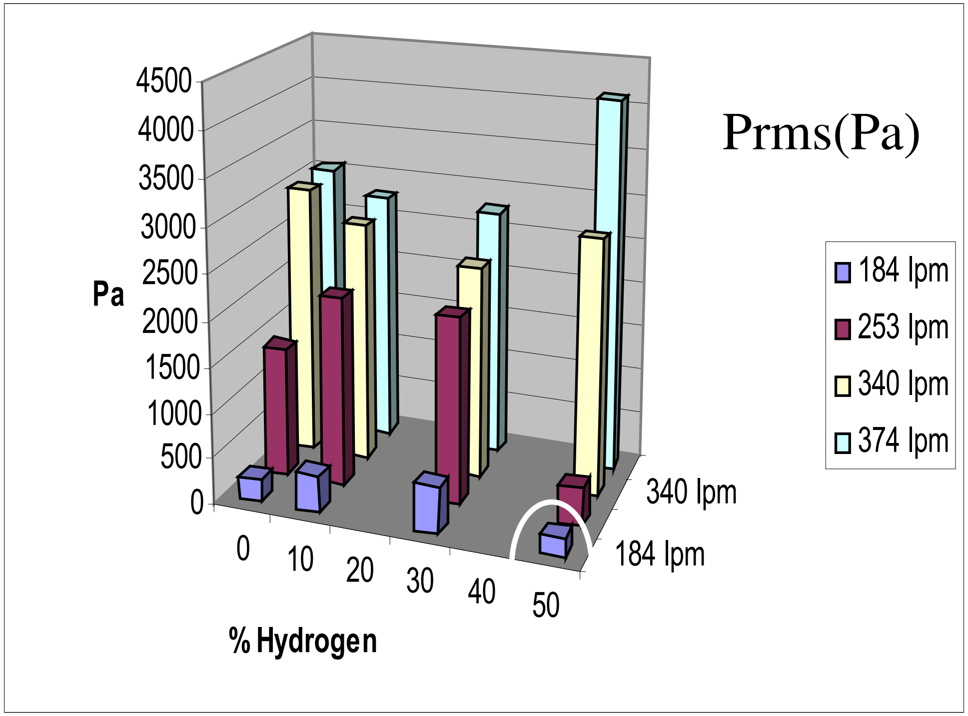
$0.4 ? \phi ? 1.3$

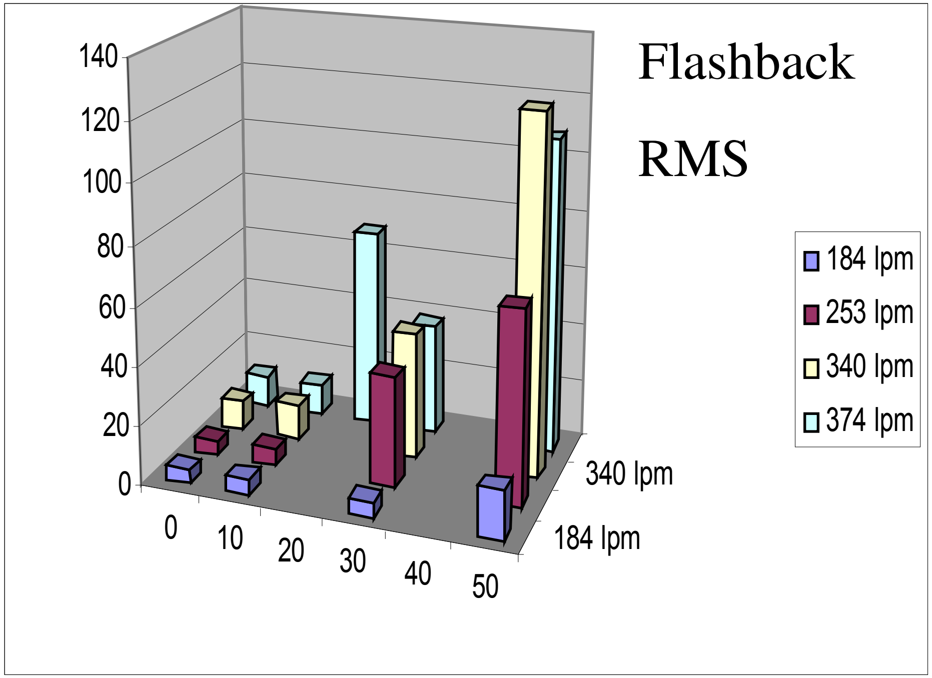
$2.4 ? \dot{Q}_{air} ? 7.1 l / s$

$T_{ref} = 2232K$

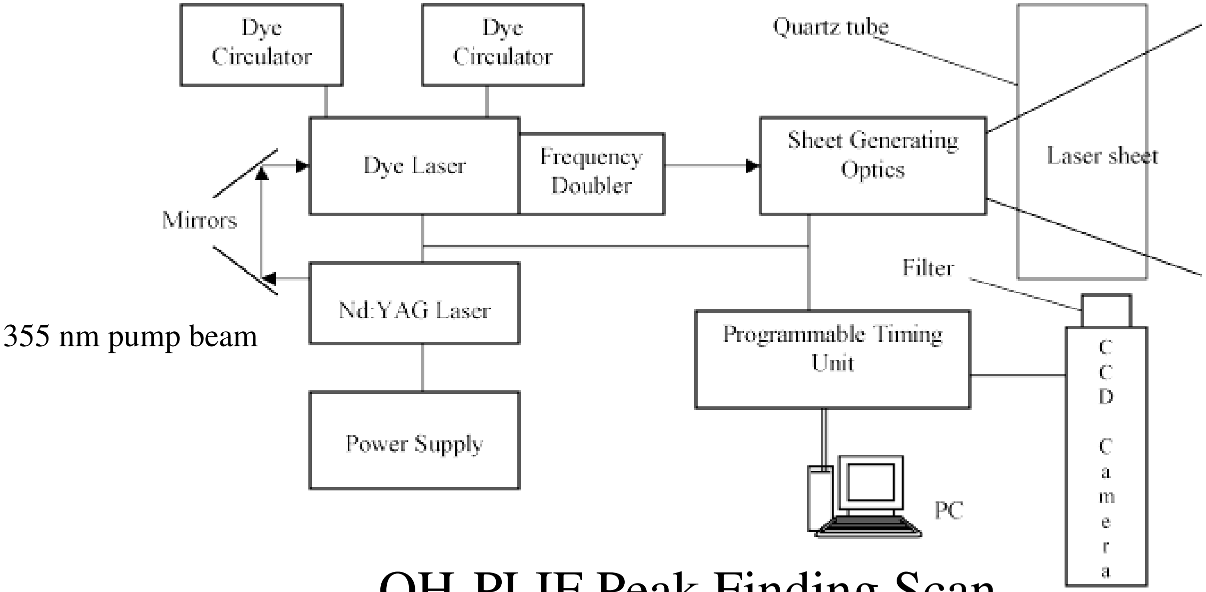
Relationship Between Adiabatic Flame Temperature and Emissions Index







Effect of Flow Rate



Dye Circulator

Dye Circulator

Quartz tube

Dye Laser

Frequency Doubler

Sheet Generating Optics

Laser sheet

Mirrors

Filter

Nd:YAG Laser

355 nm pump beam

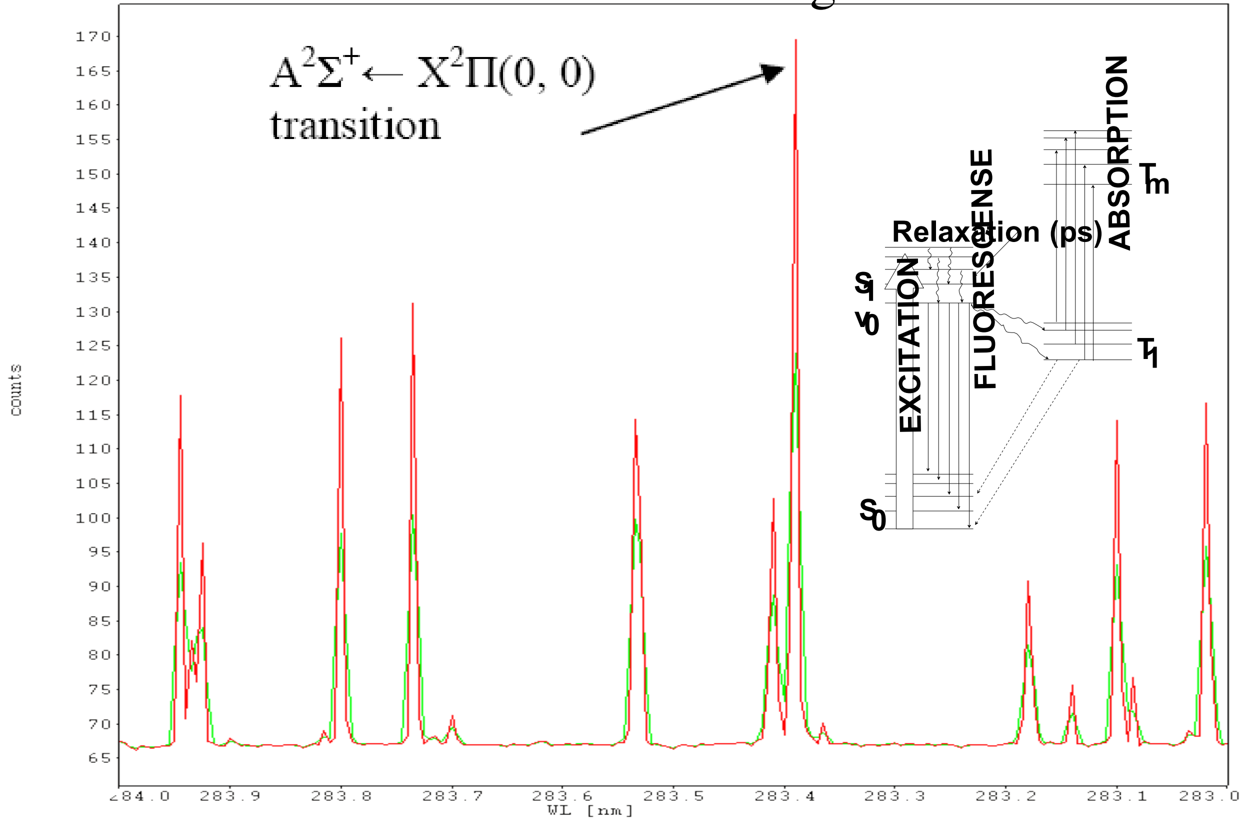
Programmable Timing Unit

CCD Camera

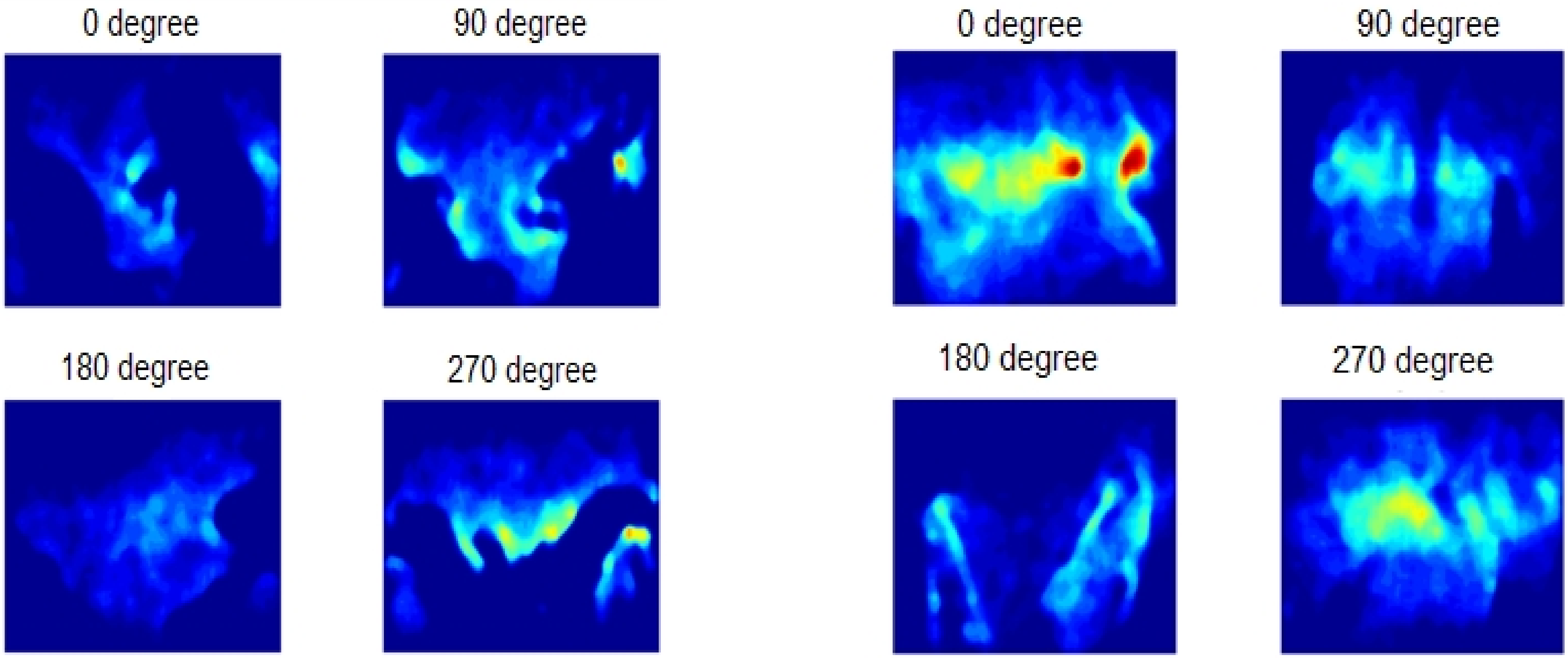
Power Supply

PC

OH-PLIF Peak Finding Scan



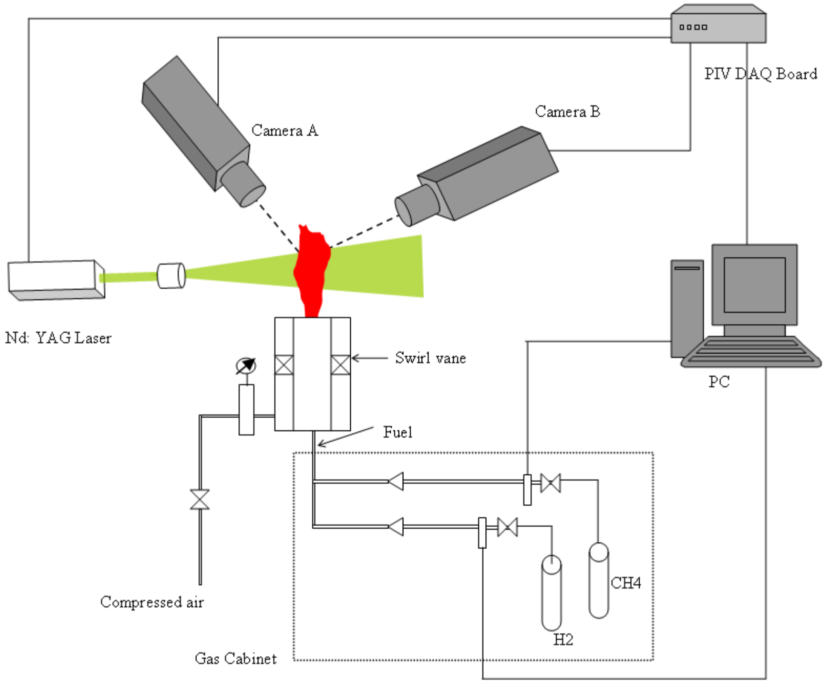
$A^2\Sigma^+ \leftarrow X^2\Pi(0, 0)$ transition



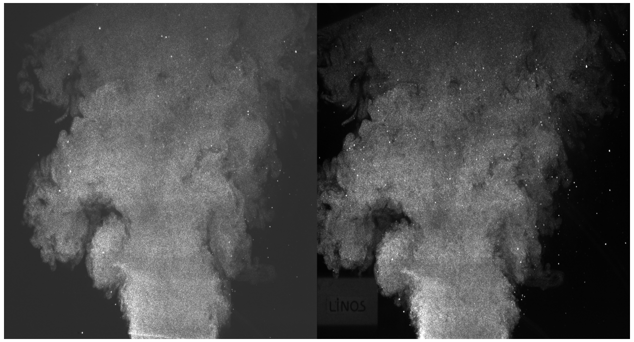
Pure Methane

50% H_2 by volume

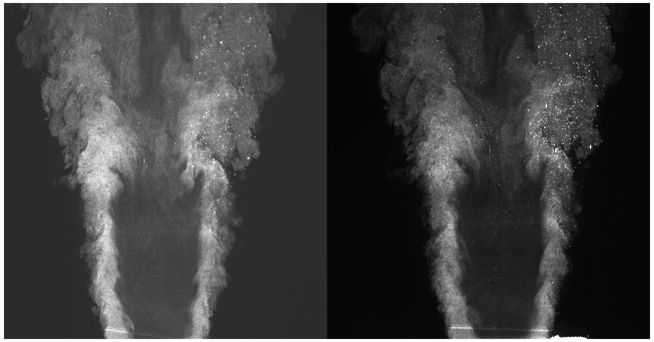
Phase Locked OH-PLIF Images
(Q_{air}=6.2 l/s, ϕ=0.8)



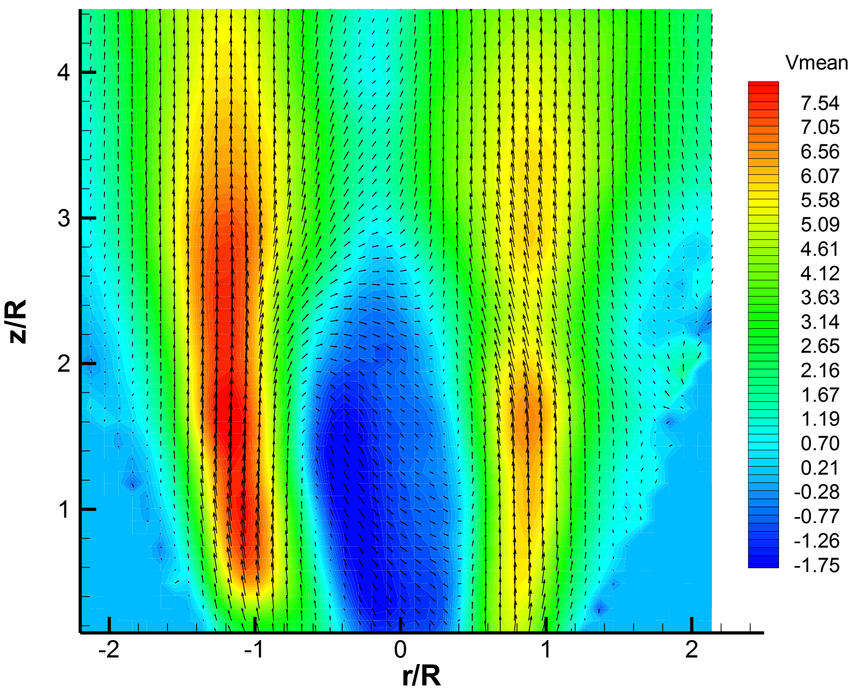
Experimental Setup for PIV



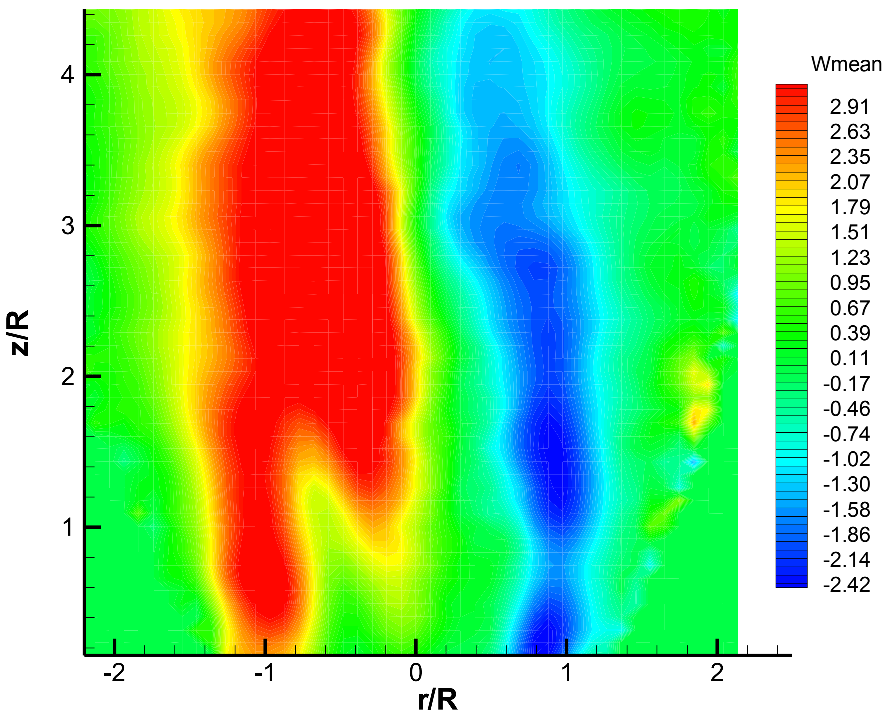
Cold Flow



Reacting Flow



In Plane Velocity Components



Swirl Velocity

$(Q_{air}=6.2\ \mathrm{l/s},\ \phi=0.7)$

CONCLUSIONS

- An experimental setup has been developed for studying synthesis gas combustion with a focus on hydrogen enrichment studies
- A mathematical model has been developed
- Hydrogen addition considerably extends lean flammability limits
- Very lean combustion enables near zero nitric oxide emissions
- Wobbe index (as often used with gaseous fuel mixtures) is not a good scaling parameter for hydrogen/methane mixtures
- Hydrogen rich mixtures pose a significant flame holding problem and can also induce a sudden change in the dominant thermo-acoustic mode
- Flashback is primarily triggered by thermo-acoustic instability
- Some passive strategies employed for flashback control (i.e. changes in injector & pre-mixer geometries) , however active control strategies may be employed as well
- Several blowout mechanisms have been examined

Questions?