NATIONAL ENERGY TECHNOLOGY LABORATORY

Influence of Exhaust Gas Recirculation on Combustion Instabilities in CH_4 and H_2/CH_4 Fuel Mixtures

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Presentation Overview

- **Background**
  - Carbon management
  - Thermoacoustic instabilities
- **Experimental Setup**
  - Swirl stabilized, atmospheric burner
- **Results and Conclusions**
  - Changes in dynamic instabilities with varying EGR
- **Summary and Future Steps**

Carbon Dioxide Management

- **Pre-Combustion**
  - Coal-derived Syngas
- **Non-Traditional Combustion**
  - Oxy-Combustion
    - Products limited to CO2 and H2O
    - Oxygen source
  - Chemical looping
    - No separate oxygen source required
    - Products limited to CO2 and H2O
- **Post-Combustion**
  - Amine solvent scrubbing
  - Efficiency Penalty around 8% with nearly 85% of CO_2 captured[1]
    - May improve with EGR

[1]*Botero, et al. (2009), Energy Procedia, 1, 3835.*

The Cost of Carbon Capture

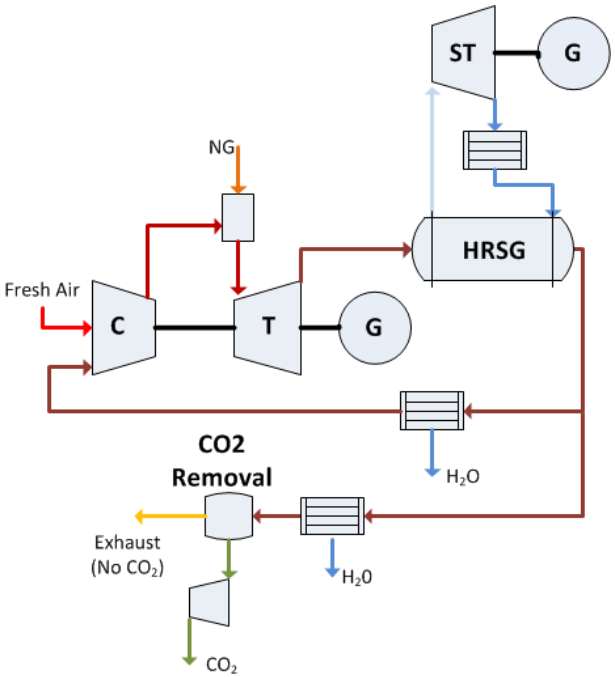
- **CCS is expected to have significant capital cost and add to COE.**
  - Large capital cost due to the need to oversize clean-up system to deal with full volume of exhaust flow although low concentration of CO2..
- **Recycling % of exhaust with EGR permits smaller capture system[1]**
- **Proven technology could offer near-term pathway for incremental implementation.**

Estimated costs for NGCC plant with and without amine-based carbon capture[2]		
	No CCS	With amine CCS
Capital cost	$ 554/kW	$ 1172/kW
LCOE[3]	68 mills/kWh	97 mills/kWh

[1] *Finkenrath et al (2007). Proc. ASME Turbo Expo 2007, Paper GT2007-27764*
[2] *NETL Report DOE/NETL-2007/1281*
[3] *LCOE: 20-year levelized cost-of-electricity*

Exhaust Gas Recirculation and Impact on Combustion

- **Experiments by GE show feasibility up to 35% EGR with few modifications to existing designs[1]**
  - EGR reduces NOx at a fixed flame temperature
- **Effect of significant dilution on combustion process unknown**
  - Air stream diluted primarily by CO_2 and N_2
    - H_2O condensed out
    - Reduced Flame Speeds
  - May impact blowoff/anchoring, combustion dynamics, emissions
  - Similarity to potential issues related to "fuel flexibility"
- **Objective of current study**
  - Investigate the influence of EGR on dynamic combustion instabilities in methane and methane/hydrogen blended fuels.



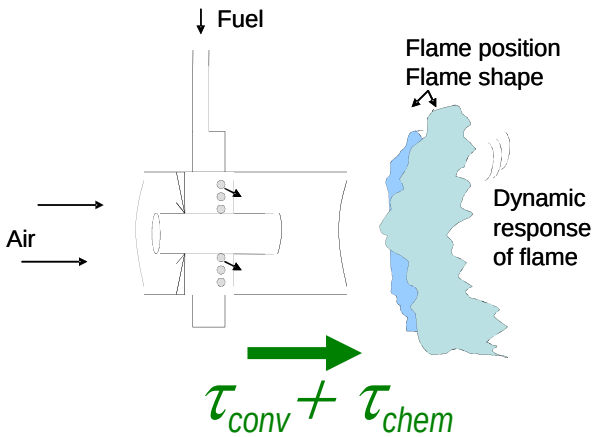
[1]ElKady, et al., Proc. ASME Turbo Expo 2008, GT2008-51152

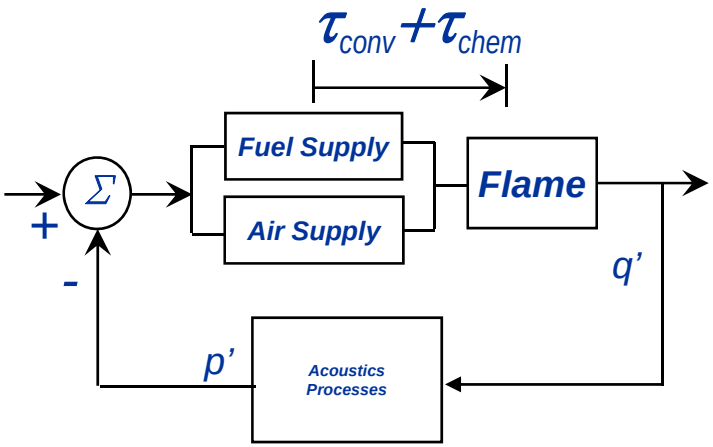
Thermoacoustic Combustion Instabilities

- **Closed-loop coupling relies on proper phase (time delay) between system acoustics and unsteady heat release.**
  - Time delay must be function of acoustic period (T)
  - Acoustic disturbance must convect to flame "center of mass" (heat release).
  - Governed by convective and chemical time scales which can vary depending on fuel composition[1].

$$\tau_{conv} + \tau_{chem} = f(T)$$

- Changes in fuel composition impact flame speed (τ_{chem}) and flame "center of mass" (τ_{conv}) .



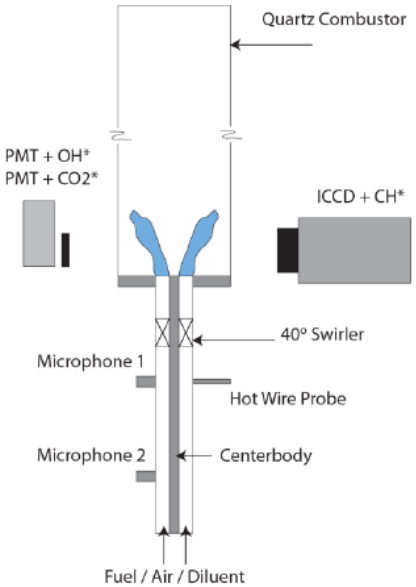


1. Lieuwen et al., Proc. ASME Turbo Expo 2006, GT2006-90770

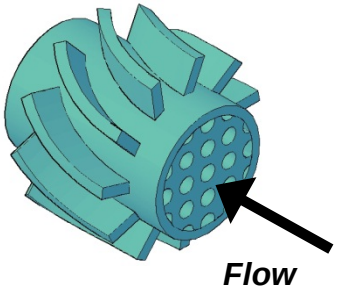
Experimental Set-up

- **Lab scale measurements of flame dynamics under EGR conditions**
  - Atmospheric, Swirl stabilized
    - High Swirl S = 0.88
    - Low Swirl S ~ 0.55
  - Perfectly pre-mixed and choked inlet (no ϕ')
  - Simulated EGR: N_2 and CO_2 dilution

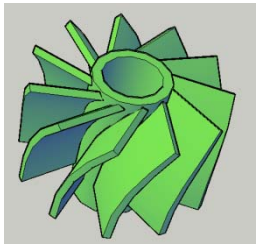
- **Diagnostics**
  - Hot wire probe measures acoustic velocity perturbations.
  - PMTs (OH*, CO2*) measures heat release perturbations
  - ICCD captures time-averaged images of flame



Low Swirl



High Swirl



Fuel Composition

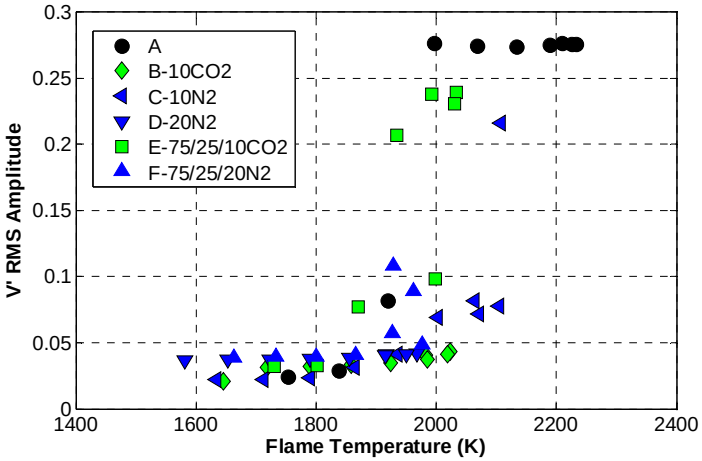
- **Test Cases**
  - 100% CH_4 and 75/25 CH_4/H_2 blend
  - Operating conditions selected to maintain flame temperature (Cantera-GRI Mech 3.0).
  - Dilution limited by blow-off

	A	B	C	D	E	F
Phi	0.65-1.10	080-1.10	0.75-1.10	0.85-1.10	0.80-1.10	0.75-1.10
Total Flow (LPM)	100-150	100-150	100-125	100-150	100-150	100-140
Diluent Comp.						
CO2 (% Total)	0	10	0	0	10	0
N2 (% Total)	0	0	10	20	0	20
Fuel Composition						
CH4 (% Fuel)	100	100	100	100	75	75
H2 (% Fuel)	0	0	0	0	25	25
T adiabat. (K)	1754-2232	1790-2024	1790-2107	1790-1967	1802-2033	1663-1977

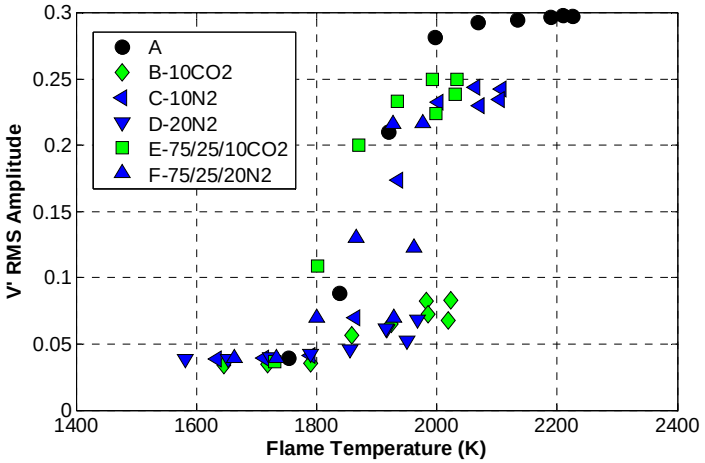
Influence of EGR Composition on Dynamic Response

High Swirl Case

- **Dynamic response of the flame as a function of flame temperature**
  - Same basic response across flow rates
  - Distinct change in the dynamic response once some threshold temperature is reached
- **Observed change in dynamic response at constant flame temperature with addition of CO2 or N2.**
  - 100% CH4 vs 10% CO2 and 10-20% N2
  - Flames diluted with 20% N2 (Fuel D) had a response similar to that of the 10% CO2 diluted (Fuel B) case.
  - Substitution of 25% H2 produced a more significant impact for CO2 dilution than N2.
    - C vs E
    - D vs F



Velocity perturbation RMS versus adiabatic flame temperature for Q = 125 lpm.



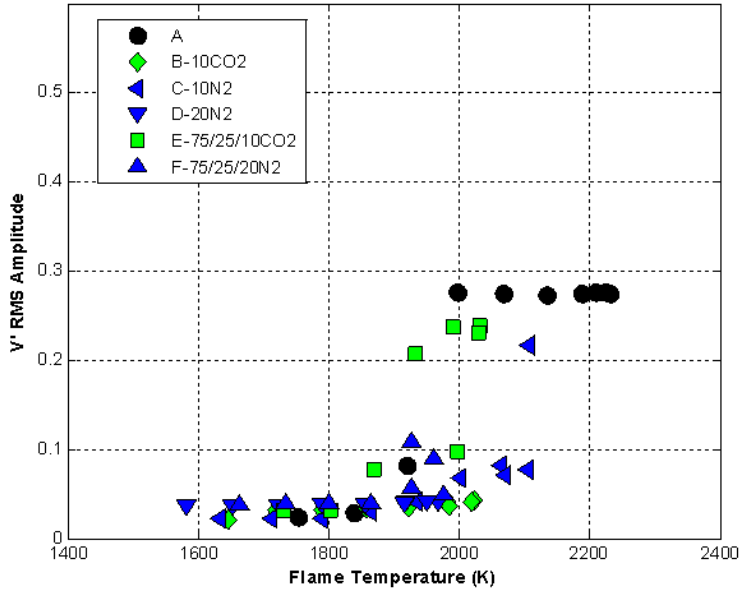
Velocity perturbation RMS versus adiabatic flame temperature for Q = 150 lpm.

Influence of EGR Composition on Dynamic Response

Low Swirl Case vs High Swirl Case

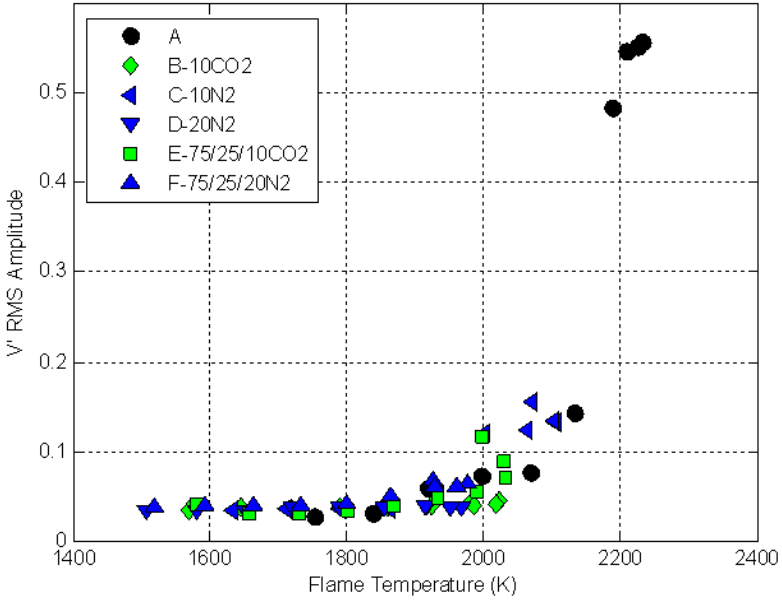
- **Similar response to flame temperature as high swirl case**
  - Peak response almost double
  - Trend independent of flow rate.
  - Less dependent on diluent?

High Swirl Injector



Velocity perturbation RMS versus adiabatic flame temperature for Q = 125 lpm (HSI)

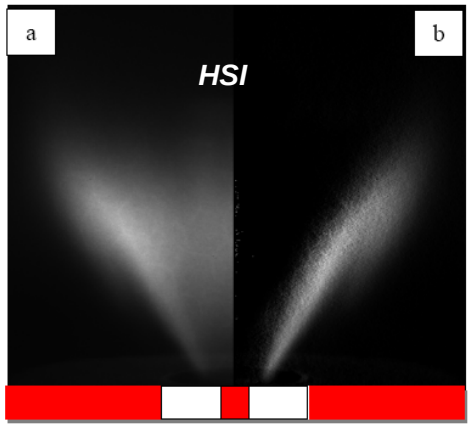
Low Swirl Injector



Velocity perturbation RMS versus adiabatic flame temperature for Q = 125 lpm (LSI)

Flame Center of Mass

- **Center of mass defined as the phase averaged center of the CH* intensity (recorded by ICCD)**
  - Abel Inversion of time-averaged (10) image.
  - High Swirl: distance from the center-body tip to COM and an angle representing the flame orientation relative to the center axis
  - Low Swirl: axial distance from COM to dump plane.



a) Time-averaged image of unstable flame at Q = 150 lpm, ϕ = 0.95, V'rms = 0.3; b) Abel inverted image of the flame surface

Unstable flame oscillates around steady flame location.

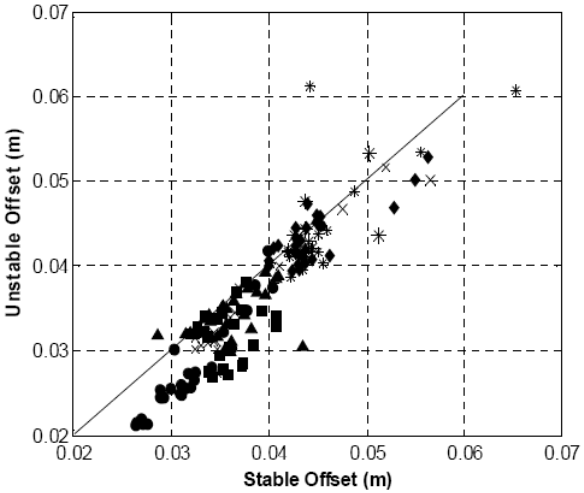
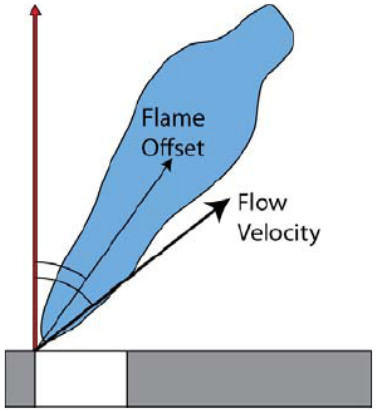
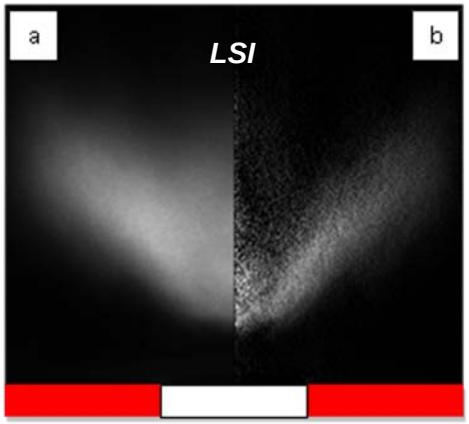


Figure 5. Phase-averaged unstable flame offset versus stable flame offset measured from CH* chemiluminescent images.





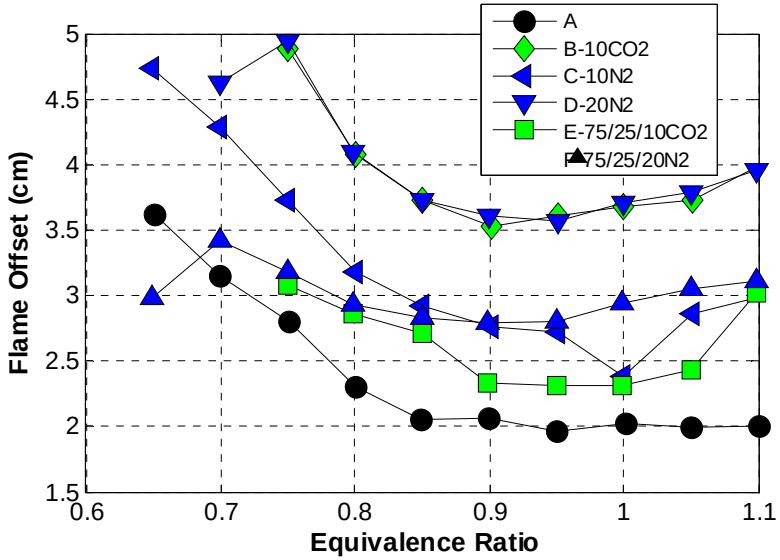
a) Time-averaged image of unstable flame at Q = 100 lpm, ϕ = 0.80, V'rms = 0.02; b) Abel inverted image of the flame surface

Effect of EGR on Flame Offset

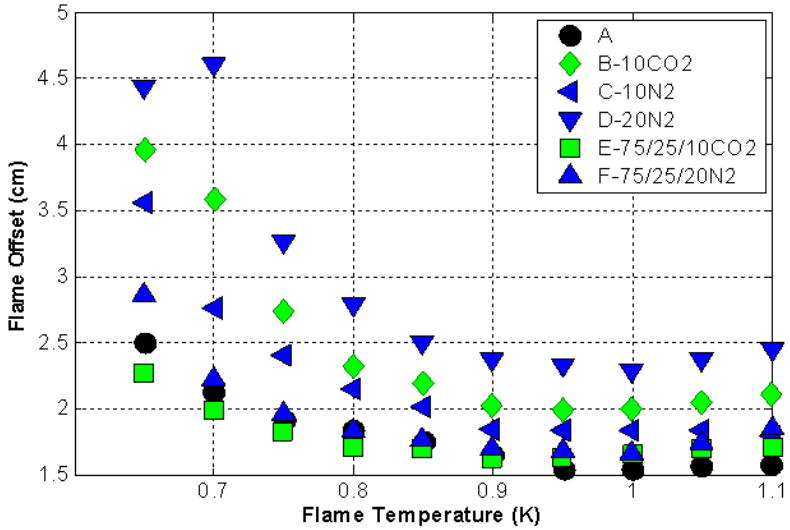
- **Addition of diluent increased flame length**
  - Addition of 10% CO_2 equivalent to 20% N_2 not 10% N_2 for HIGH SWIRL
  - Liu et al.[1] suggest effects due to:
    - Variation of transport and thermal properties
    - Possible direct chemical effect of CO_2
    - Enhanced radiation transfer by CO_2

High Swirl Injector

Q = 125 lpm



Low Swirl Injector



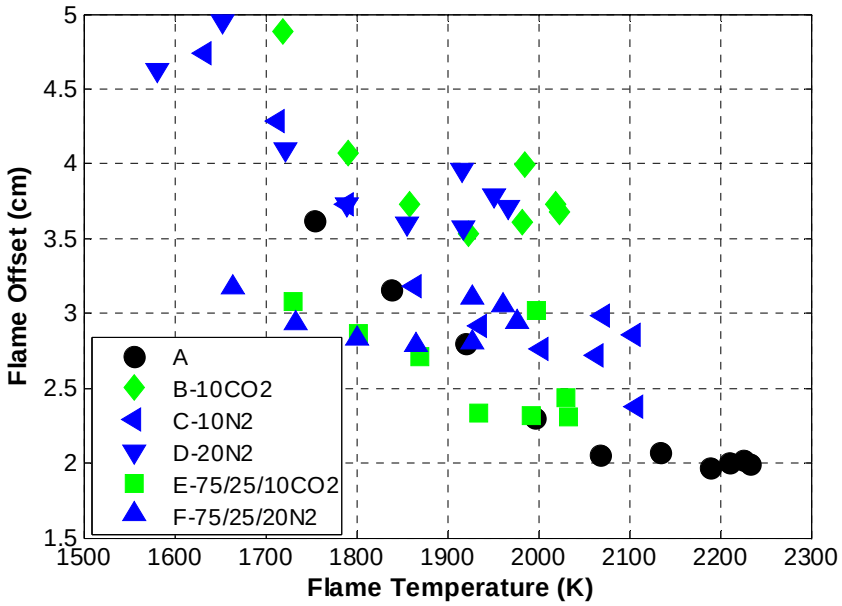
1. Liu et al., Combustion and Flame V133, 495–497, 2003

Effect of EGR on Flame Offset

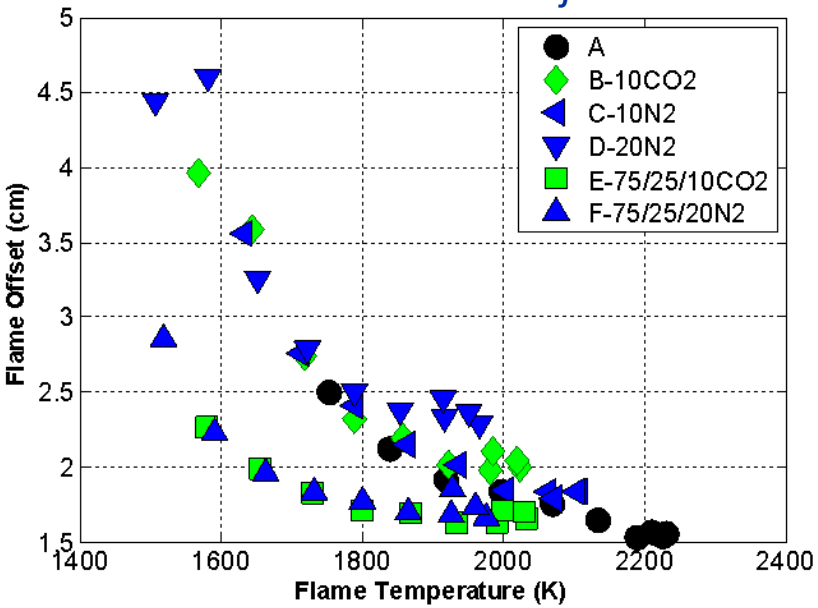
- **Similar outcome at constant flame temperature**
  - 10% CO_2 dilution equivalent to 20% N_2 dilution
  - LSI: similar response regardless of dilution
  - Addition of H_2 reduced flame offset below baseline

High Swirl Injector

Q = 125 lpm

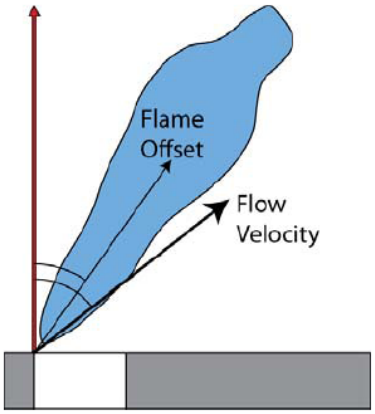


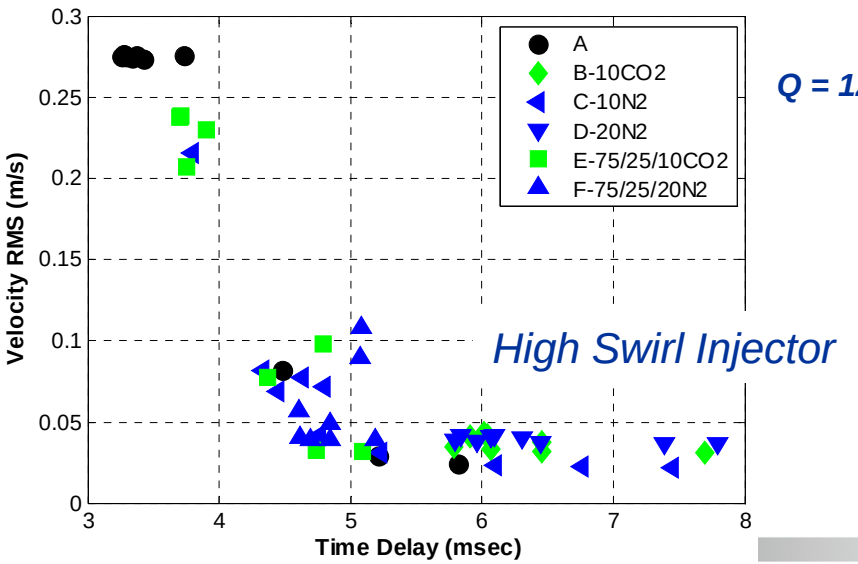
Low Swirl Injector



Effect of EGR on Time Delay

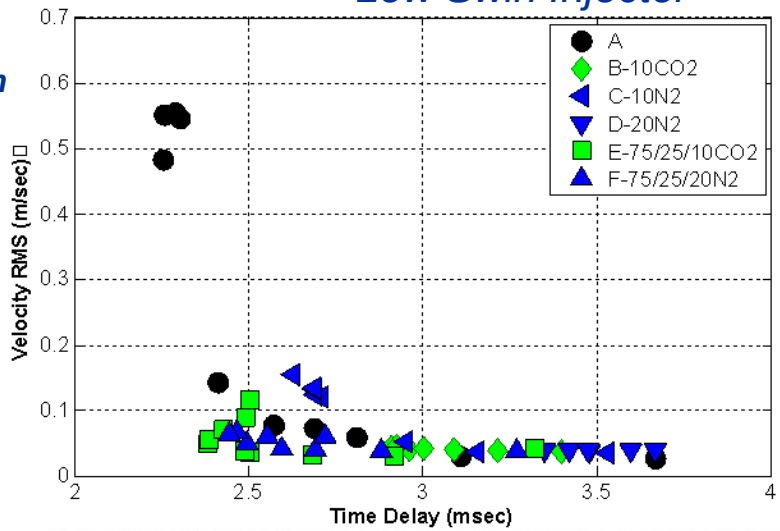
- **Delay associated with convection of disturbances along the flame surface**
  - Convective time delay approximated from flame angle(HSI), bulk velocity and flame offset (COM).
- **Regardless of fuel composition**
  - Unstable: $\tau < 5$ms (HSI), $\tau < 2.5$ms (LSI)
  - Marginal: 5 ms $< \tau <$ 5.5 ms (HSI), 2.5 ms $< \tau <$ 2.85 ms (LSI)
  - Stable: $\tau >$ 5.5 ms (HSI), $\tau >$ 2.85 ms (LSI)



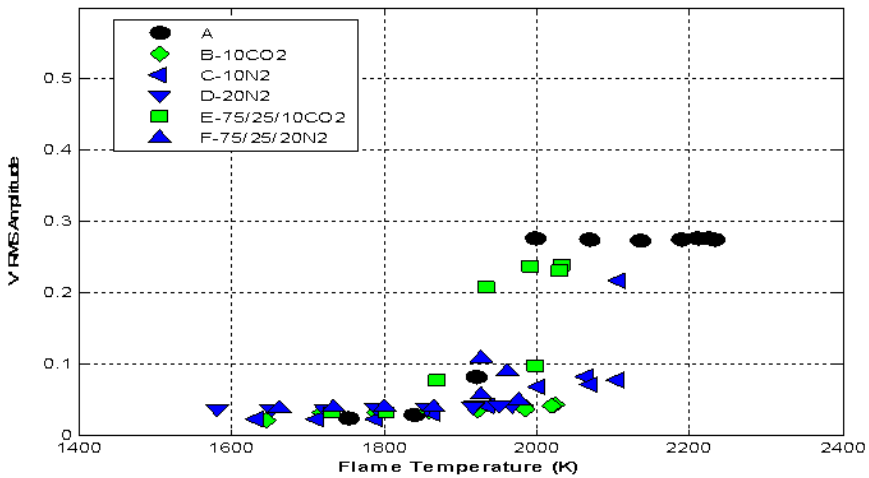


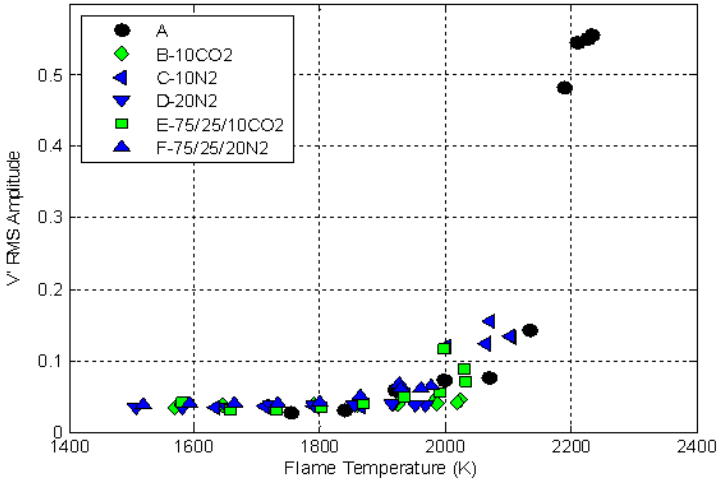
Q = 125 lpm

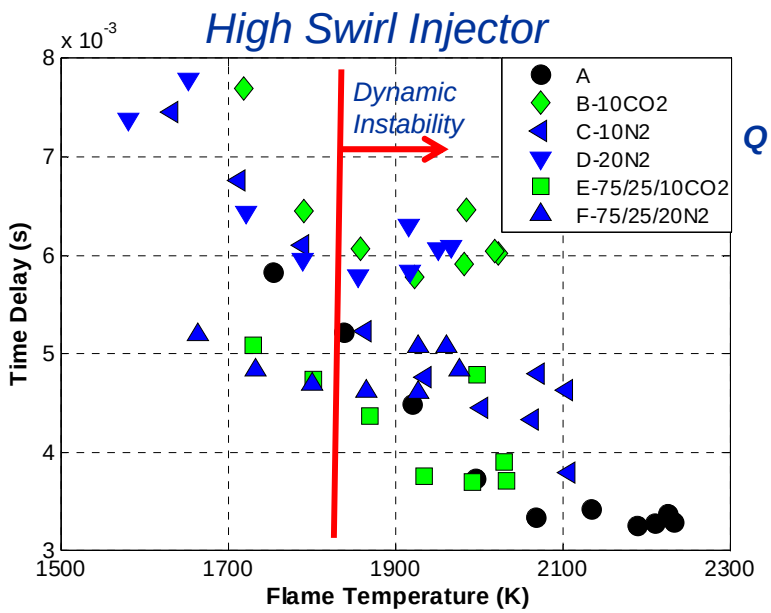
Low Swirl Injector



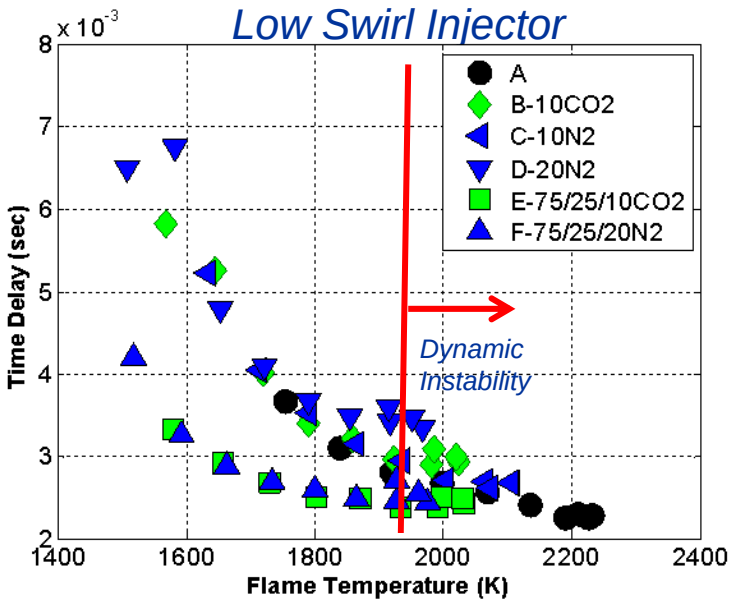
Time Delay and Flame Temperature



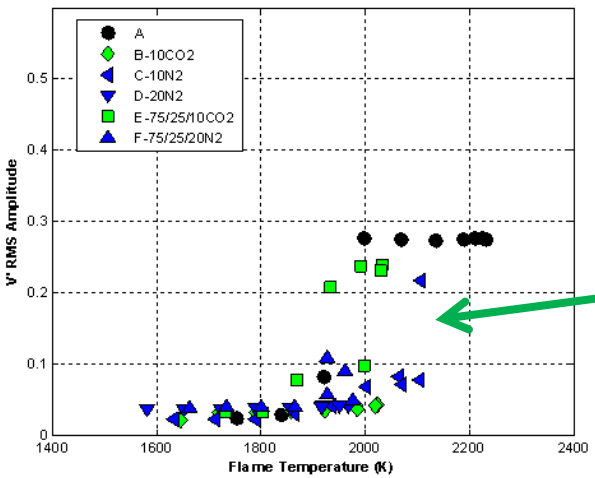




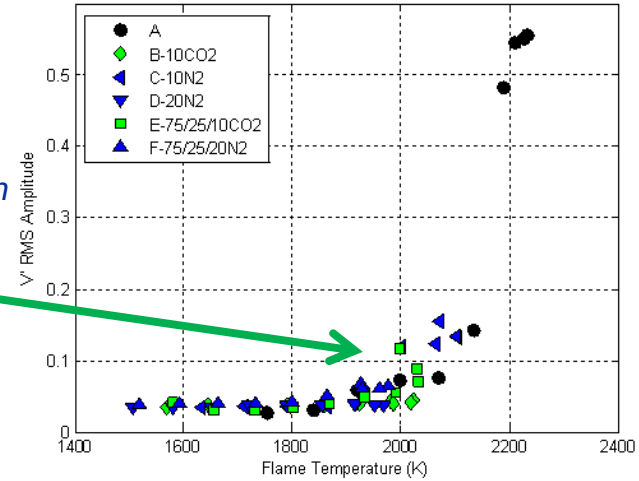
Q = 125 lpm

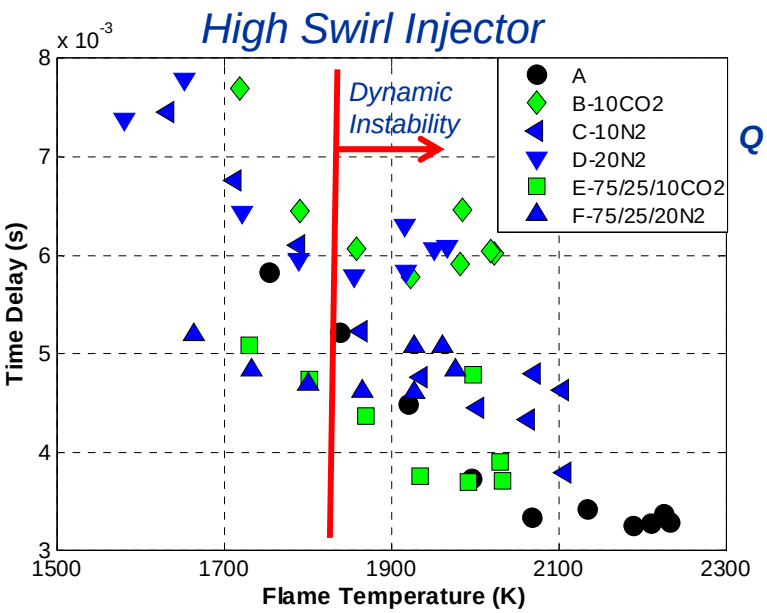


Time Delay and Flame Temperature

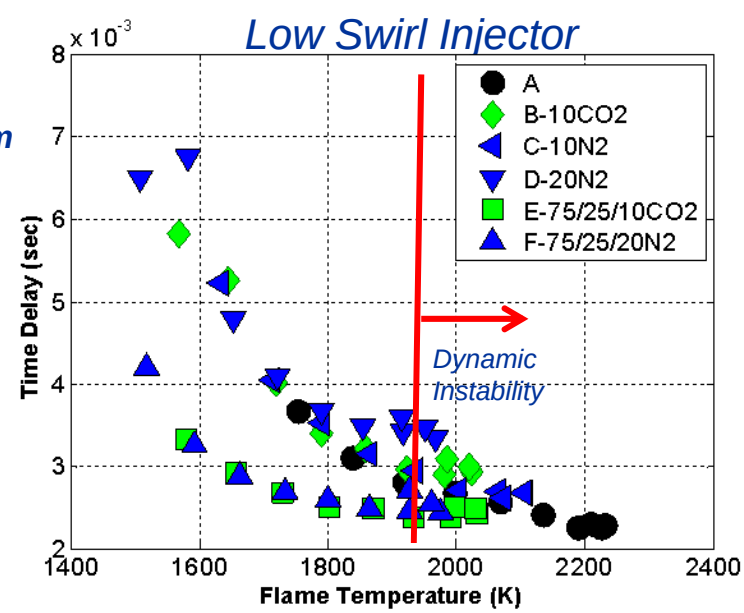


Diluent seemed to have less of an impact in Low Swirl Case



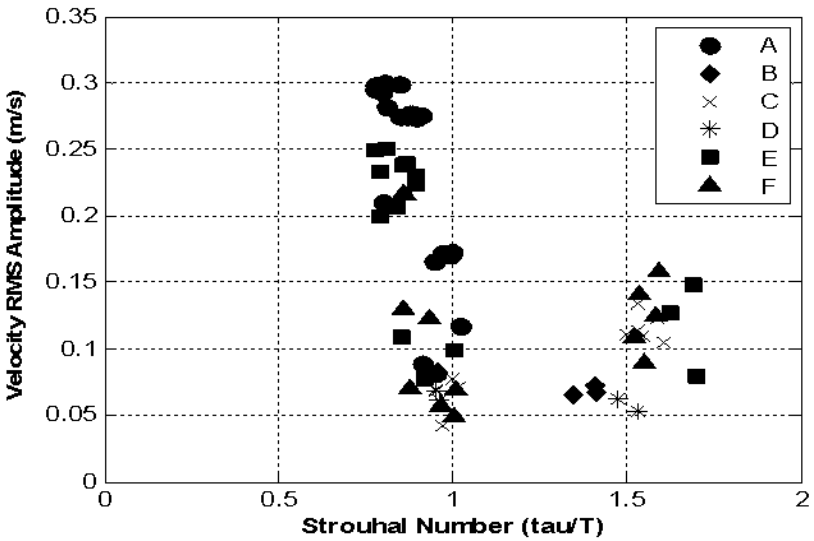


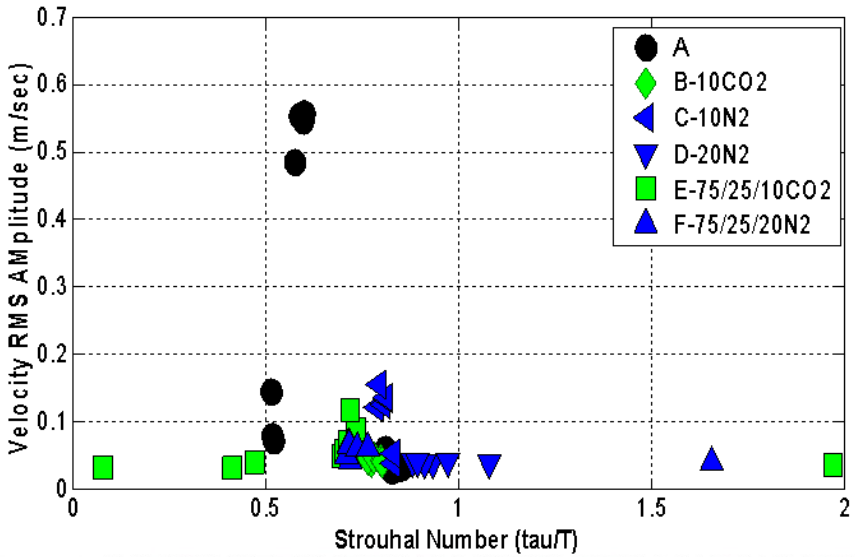
Q = 125 lpm



Instability as a Function of Non-Dimensional Frequency

- **Instability occurs in regions in which convective disturbance is in phase with heat release fluctuations**
  - Addition of diluent alters the time delay and flame length resulting in changes in the dynamic response
- **Strouhal number**
  - Non-dimensional frequency obtained by dividing convective time delay by acoustic period





Summary

- **EGR believed to be a viable option to concentrate CO_2 in the exhaust stream improving efficiency in post-combustion carbon capture schemes.**
- **High Swirl : Addition of EGR altered flame length and time delay disproportionately with 10% CO_2 addition behaved similar to 20% N_2 dilution.**
- **Low Swirl varying dilution have little impact on time delay.**
- **At a fixed flame temperature, EGR addition increased time delay and flame length changing the dynamic response (High Swirl).**
  - Consistent with Strouhal Number correlations shown in previous studies.

Next Steps

- **Gain a better understanding of the Low Swirl Injector response.**
  - Why does diluent seem to have a greater impact on high swirl case compared to low swirl
- **How high can the EGR rates go?**
  - 35, 40% or higher???
- **Consider variable EGR as a control method for altering the dynamic response.**

Thank You!

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