Effects of Combustion–Induced Vortex Breakdown on Flashback Limits of a Syngas–Fueled Swirl Combustor

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Overview

- Introduction: Flashback and Syngas
- Motivation and Objective
- Technical Approach
- Results
- Summary and Conclusions

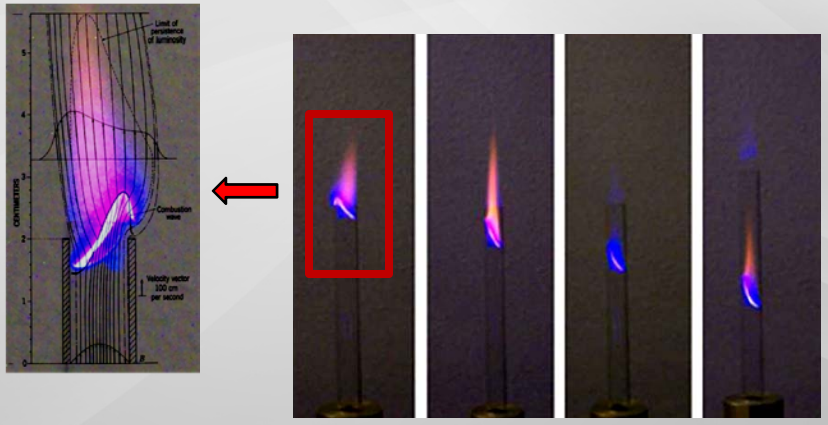
ACKNOWLEDGMENTS
This research was done with the support of the U.S. Department of Energy, under awards DE-FG26-04NT42133 and DE-FG26-08NT0001719 (Project Managers Robie Lewis and Norm Popkie). However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the Department of Energy.

Flashback and Syngas

INTRODUCTION

Flashback and Syngas

- **<u>Flashback:</u>** flame propagates upstream against the gas stream into the burner tube



- **<u>Causes:</u>** hardware damage, unsafe operating conditions, increased pollutant emissions

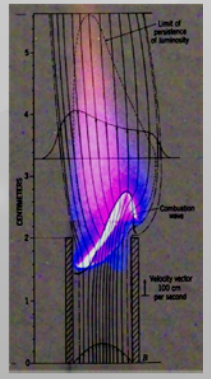
Flashback and Syngas

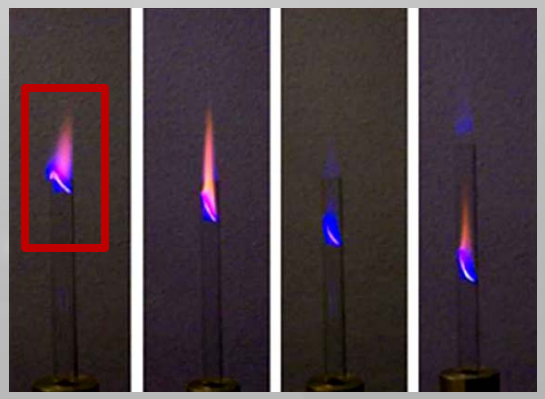
- Flashback occurs due to:
  - **Boundary layer flame propagation**
  - Turbulent flame propagation
  - Combustion instabilities
  - **Combustion Induced Vortex Breakdown (CIVB)**
    - **Prevailing mechanism for swirl stabilized flames**

Background-Flashback

- <u>Boundary Layer Flame Propagation:</u>
- The flame propagates upstream when its normal burning velocity exceeds the local flow velocity.
- This type of flashback generally occurs close to the wall where a no slip boundary condition exists.
- Lewis and Von Elbe defined a term 'Critical velocity gradient(g_f)' to explain flashback phenomena for a flame stabilized over a circular burner.

$$g_F = c\frac{S_L^2}{\alpha}$$





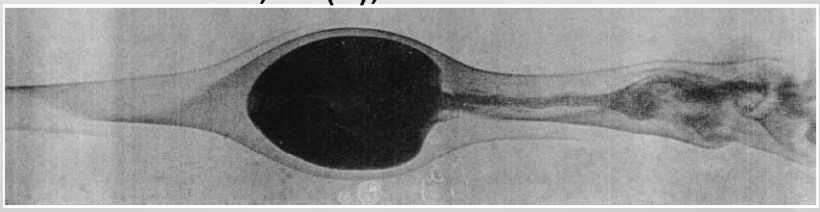
Background-Flashback

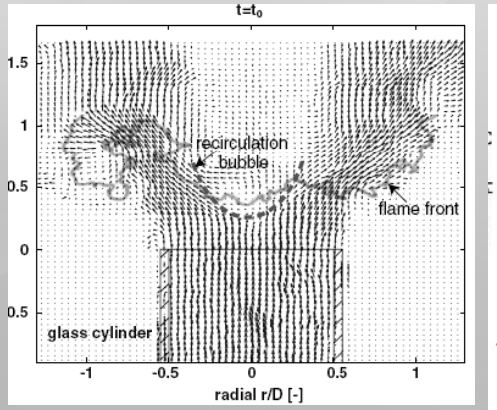
- **CIVB flashback** occurs due to complex interactions of
  - Flow-field
  - Heat release processes:
    - fuel composition
    - unburned mixture conditions
    - local stoichiometry
- The swirl generator strongly influences the CIVB flashback behavior
- Past CIVB flashback investigations primarily focused on mixing tube type configurations (No Centerbody)
- Most previous investigations limited to Methane combustion

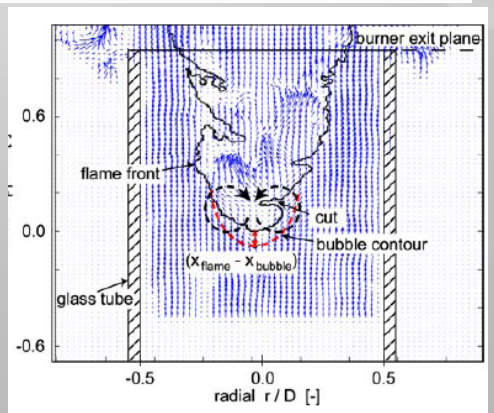
Background-Flashback

- **<u>Vortex Breakdown</u>**: *"Change in structure of a vortex initiated by a variation in the characteristics ratio of tangential to axial velocity components."*

Faler, J. and Leibovich, 1978, "An Experimental Map of the Internal Structure of a Vortex Breakdown," **Journal of Fluid Mechanics**, 86(2), PP. 313-335.







Konle, M., Kiesewetter, F., and Sattelmayer, T., 2008, " Simultaneous High Repetition Rate PIV-LIF-Measurements of CIVB Driven Flashback," **Exp. Fluids**, 44, pp. 529-538.

Background-Syngas

- Syngas:
  - Two major constituents are H_2 and CO
  - Significant quantities of N_2, CO_2, CH_4, and higher hydrocarbons may be present in the fuel mixture
  - H_2 in syngas significantly increases the potential for flashback

Flashback

MOTIVATION AND OBJECTIVE

Motivation

- Lieuwen et al. (2008) – *"The dependence of breakdown conditions depends on swirl number."*
  - No breakdown for $S < 0.5$
  - Vortex breakdown for $S > 1$
  - Hysteresis regime exists between these states (either state can exist)

- Kroner et al. (2007) – tested natural gas and hydrogen, found strong dependence on hydrogen content
  - Kinetic effects also play a key role

Objective

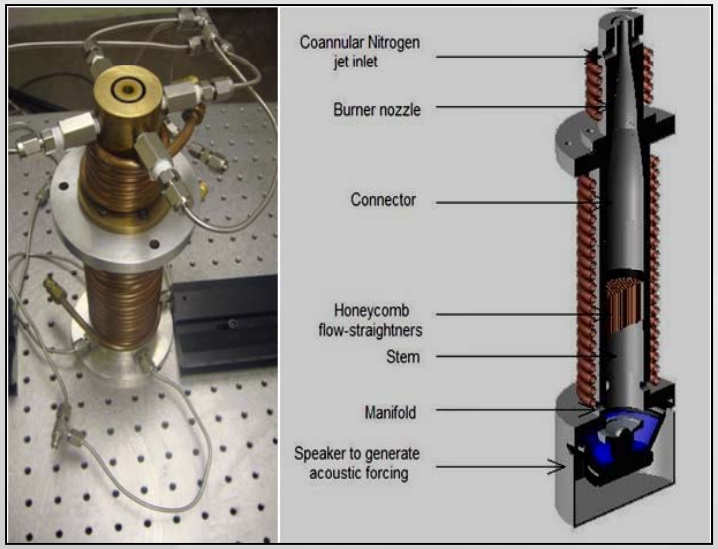
- To study the effects of **syngas fuel compositions** and **diluents** on:
  - **Boundary layer flashback**
  - **CIVB flashback** of H_2-CO mixtures in swirl stabilized combustors
    - Swirl numbers within hysteresis region of $0.5 < S < 1$
      - 0.71 and 0.97

TECHNICAL APPROACH

Technical Approach- Boundary Layer Flashback

– Burner tube assembly (converging nozzle, glass tubes, glass tube adapters, adjustable supports, and c-clamps)

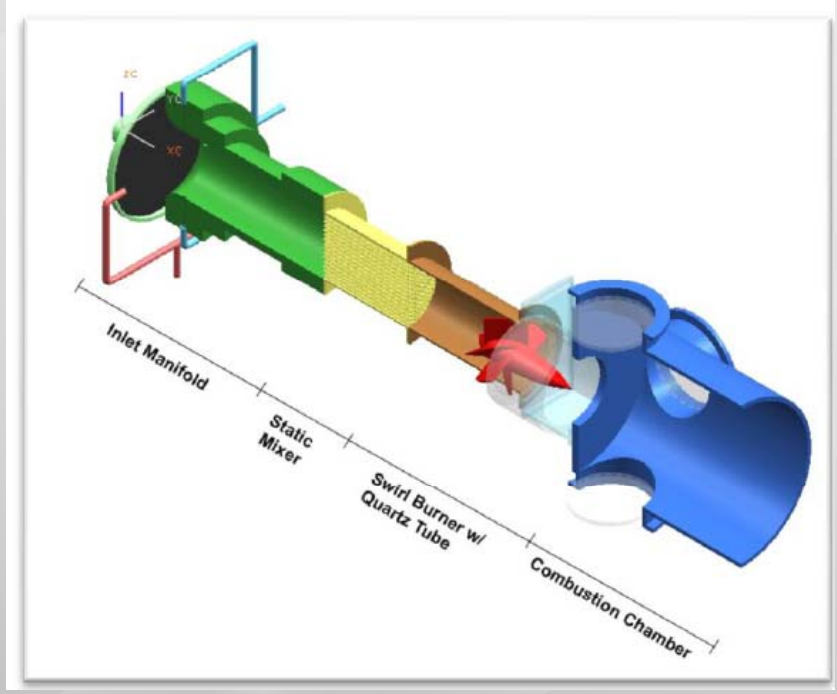
Technical Approach- Laminar Burning Velocity



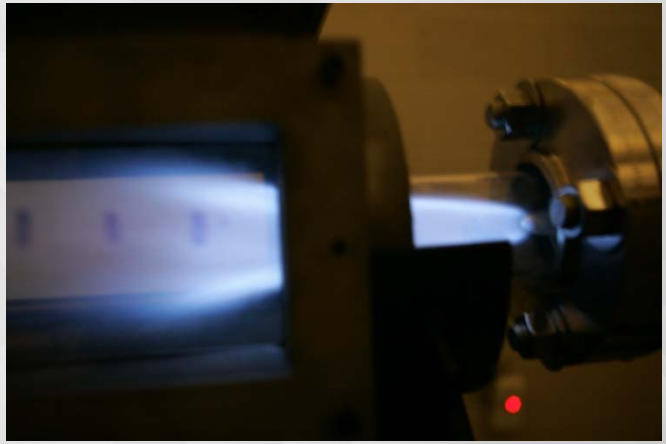
- Measurement of laminar burning velocities of various H_2 – CO mixtures and actual syngas compositions were determined using different burners and imaging techniques*

*Dam, B., Ardha, V., and Choudhuri, A., 2010, "Laminar Flame Velocity of Syngas Fuels," **Journal of Energy Resources Technology** (Accepted).

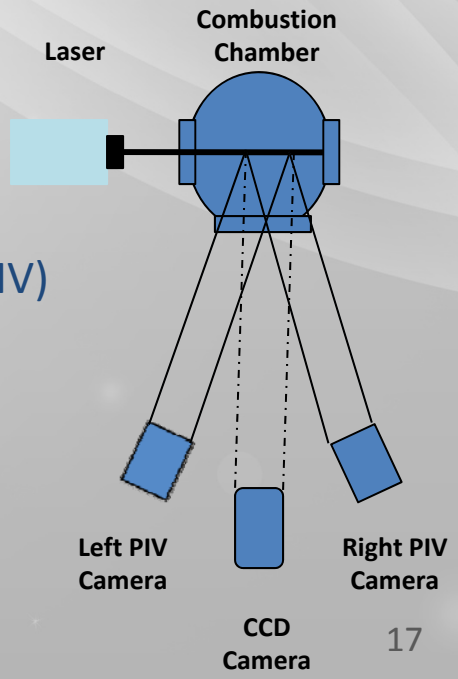
Technical Approach-CIVB



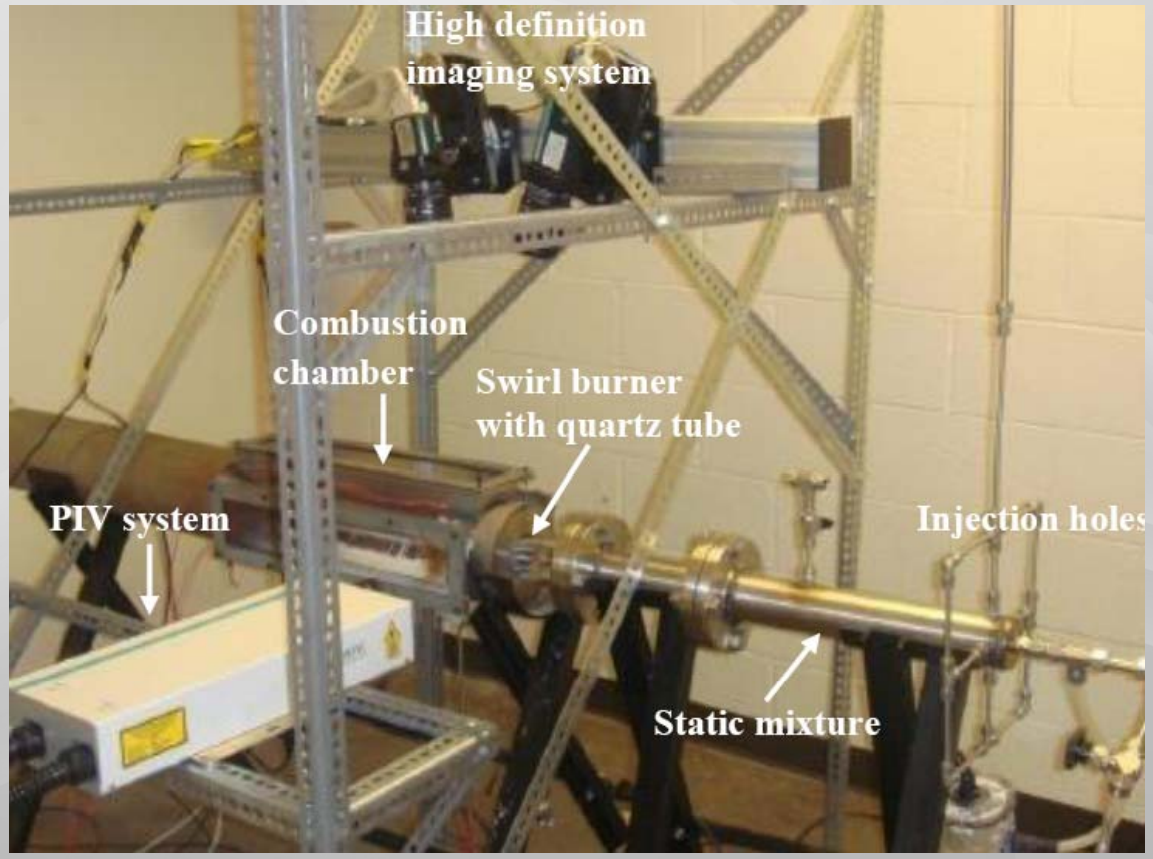
Technical Approach-CIVB



i. 2KHz Stereo Particle Image Velocimetry (PIV)
ii. 200 Hz Synchronized PIV/PLIF Imaging
iii. 10K fps High Speed Camera



Technical Approach-CIVB



Test Matrix – Boundary Layer Flashback

Burner Diameter = 6 mm			
Fuel Composition	**Critical Flashback Gradient**	**Laminar Flame Speed**	**Burner Scaling Factor**
10%H_2 - 95% CO	✓	✓	-
15%H_2 - 85% CO	✓	✓	-
25%H_2 – 75%CO	✓	✓	✓

***Repeated for burner diameters of 7 and 10.6 mm**

Test Matrix – CIVB Flashback*

Swirl Number = 0.71 (6- Vane)			
Fuel Composition	**Combustor Stability Map**	**High-Speed PIV**	**Parametric Model**
CH_4	✓	✓	-
10%H_2 - 90% CO	✓	✓	✓
15%H_2 - 85% CO	✓	✓	-
20%H_2 – 80%CO	✓	✓	✓
4 actual syngas compositions	✓	✓	-

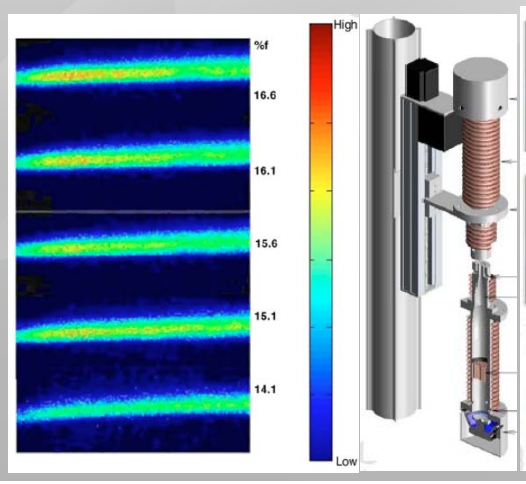
***Repeated for a Swirl Number of 0.97**
12 Vane Swirler

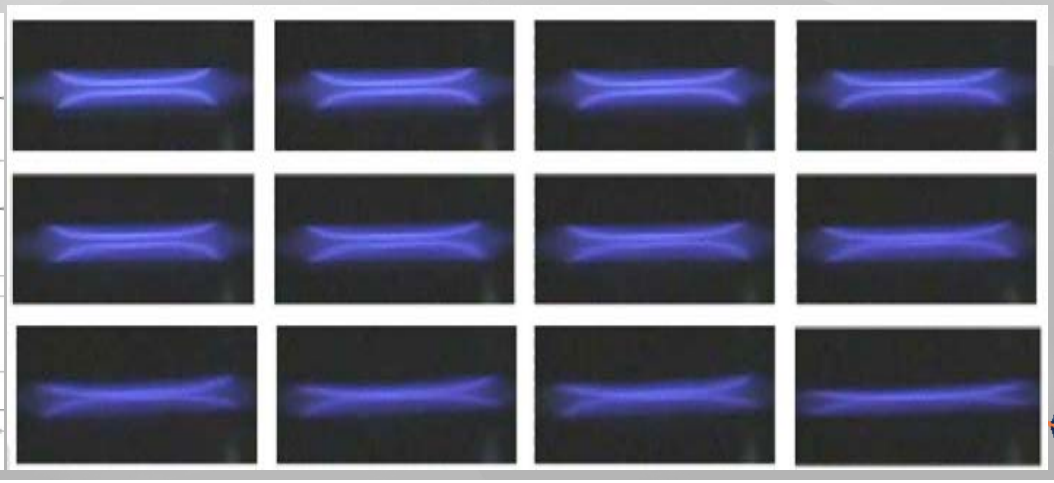
RESULTS

Results – Laminar Burning Velocity

- Laminar Burning Velocity:
  - Dam, B., Ardha, V., and Choudhuri, A., 2010, "Laminar Flame Velocity of Syngas Fuels," **Journal of Energy Resources Technology** (Accepted).

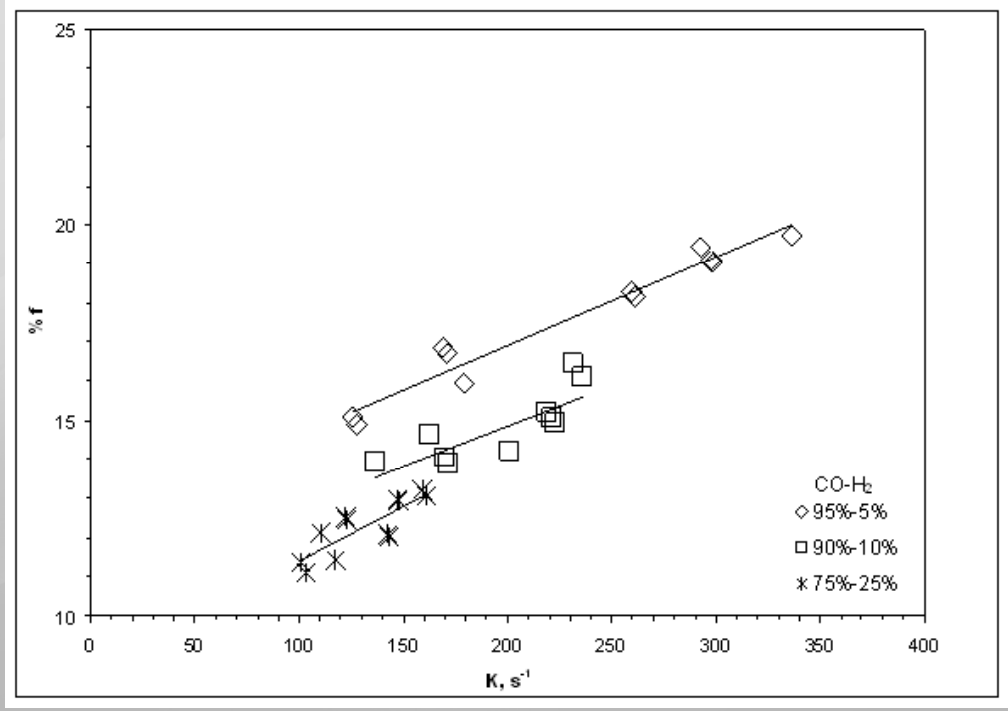
- Flame Extinction Limits:
  - Choudhuri, A., Subramanyam, M., and Gollahalli, S., 2008, "Flame Extinction Limits of H_2-CO Fuel Blends," **Journal of Engineering for Gas Turbines and Power**, Vol. 130.





Extinction Limit of Lean Mixtures

- Flame extinction limits of different H_2-CO blend compositions at different stretch conditions



Choudhuri, A., Subramanyam, M., and Gollahalli, S., 2008, "Flame Extinction Limits of H_2-CO Fuel Blends," **Journal of Engineering for Gas Turbines and Power**, Vol. 130.

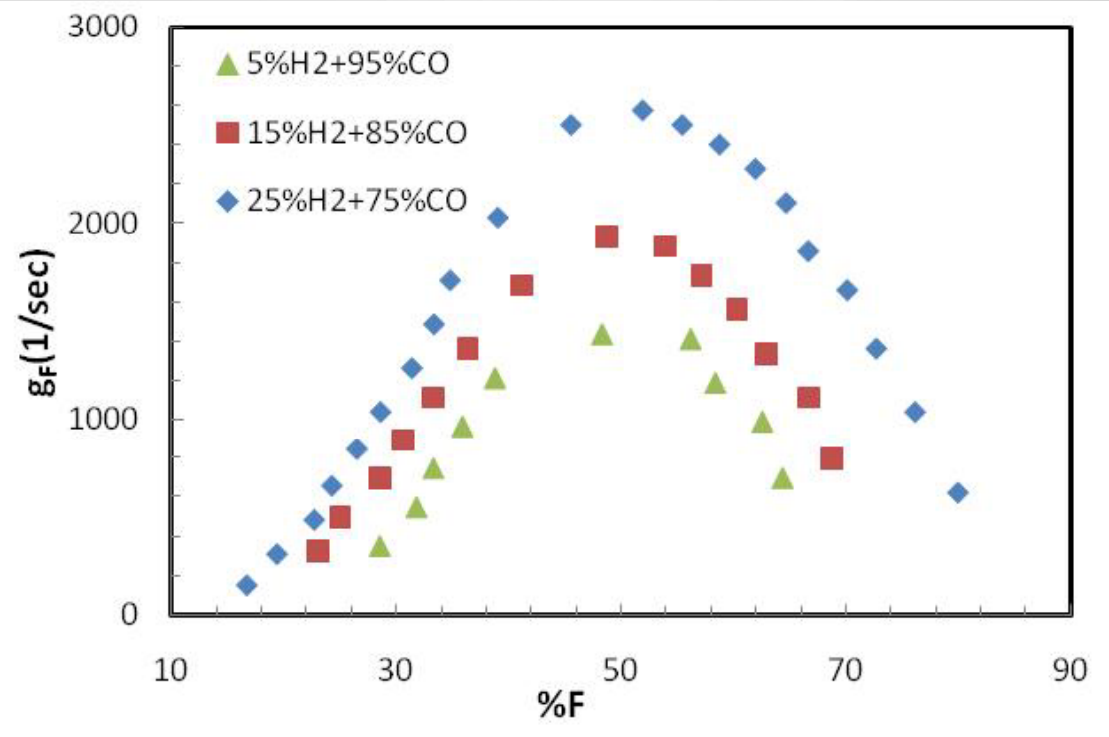
Laminar Burning Velocity of Lean Mixtures

Flat Flame Burner

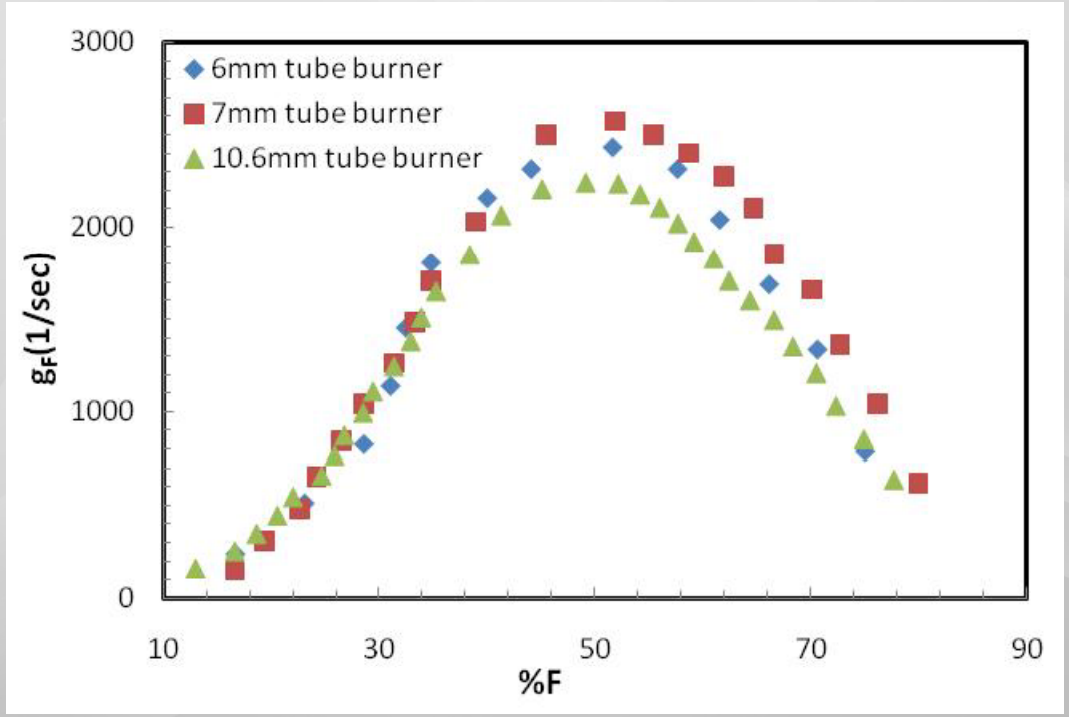
Composition	ϕ	Flame Speed(cm/sec)
5% H2+95%CO	0.45	10.4
	0.48	11.1
15%%H2+85%CO	0.39	9.2
	0.45	10.66
	0.48	12.13
20%H2+80%CO	0.39	13
	0.45	13.88
	0.48	16.66

Dam, B., Ardha, V., and Choudhuri, A., 2010, "Laminar Flame Velocity of Syngas Fuels," **Journal of Energy Resources Technology** (Accepted).

Results – Boundary Layer Flashback



Results – Boundary Layer Flashback



25% H2 – 75% CO

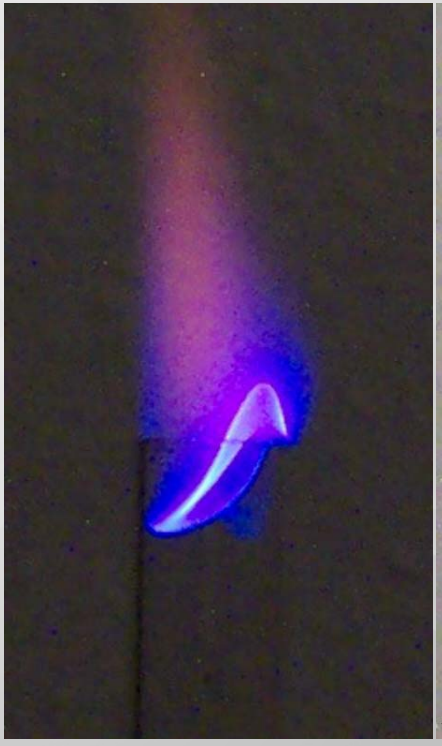
Results – Boundary Layer Flashback

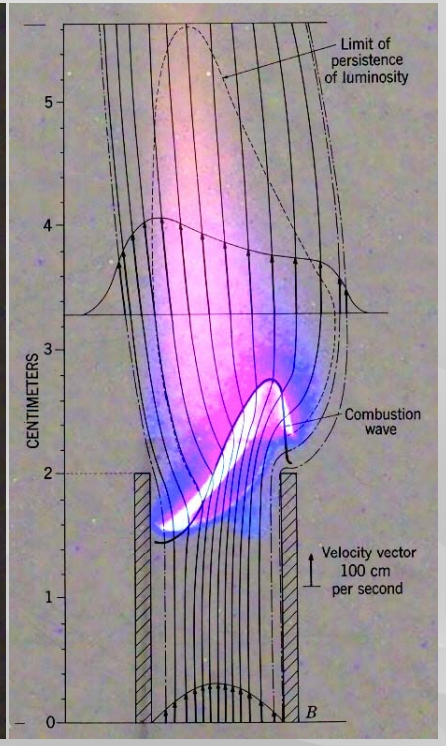
$$g_F = \left.\frac{\partial u_u}{\partial r}\right|_R \approx \frac{u_u}{r} = \frac{s_L}{d_p}$$

$$d_p = a d_q \qquad d_q = 2\sqrt{b}\,\frac{\alpha}{S_L}$$

$$c = \frac{1}{2a\sqrt{b}}$$

$$g_F = c\,\frac{S_L^2}{\alpha}$$

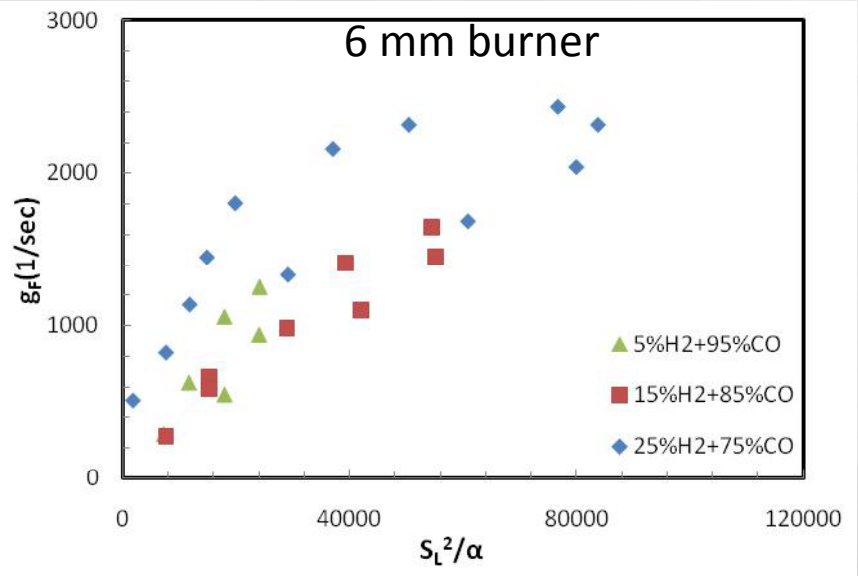




Past Investigation: Natural Gas

$$g_F = 14.125\left[\frac{S_L}{d_q}\right]^{1.00}$$

Results – Boundary Layer Flashback



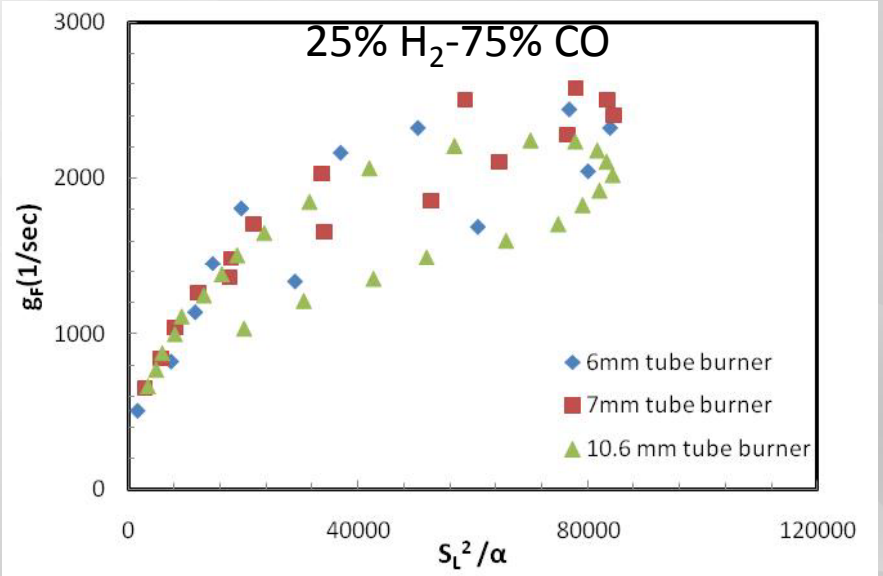
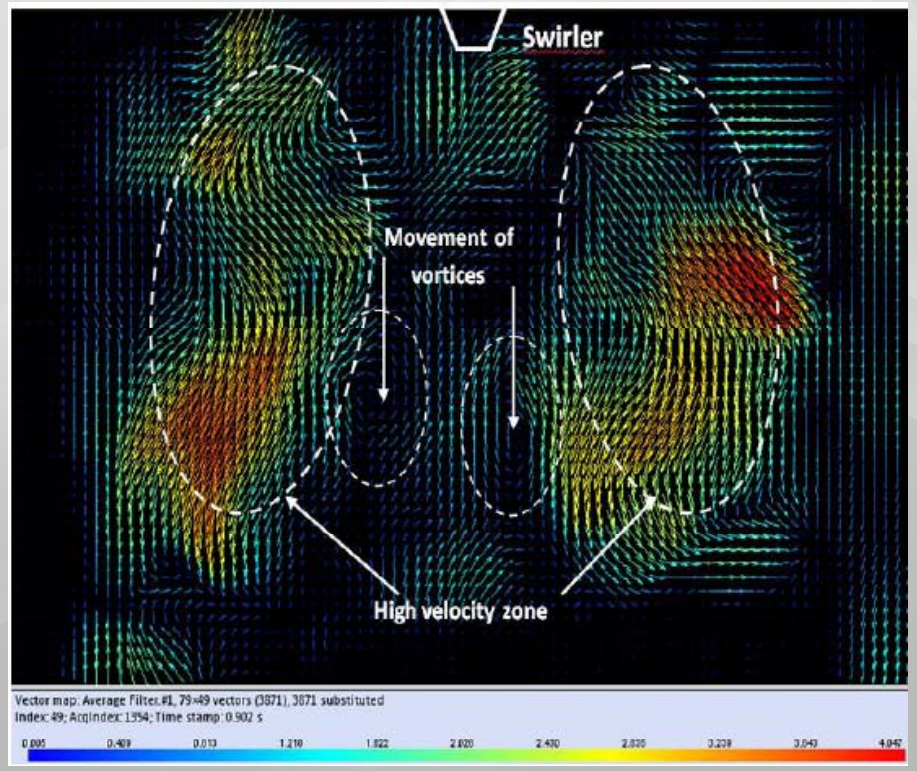


Table showing results from 6 mm burner

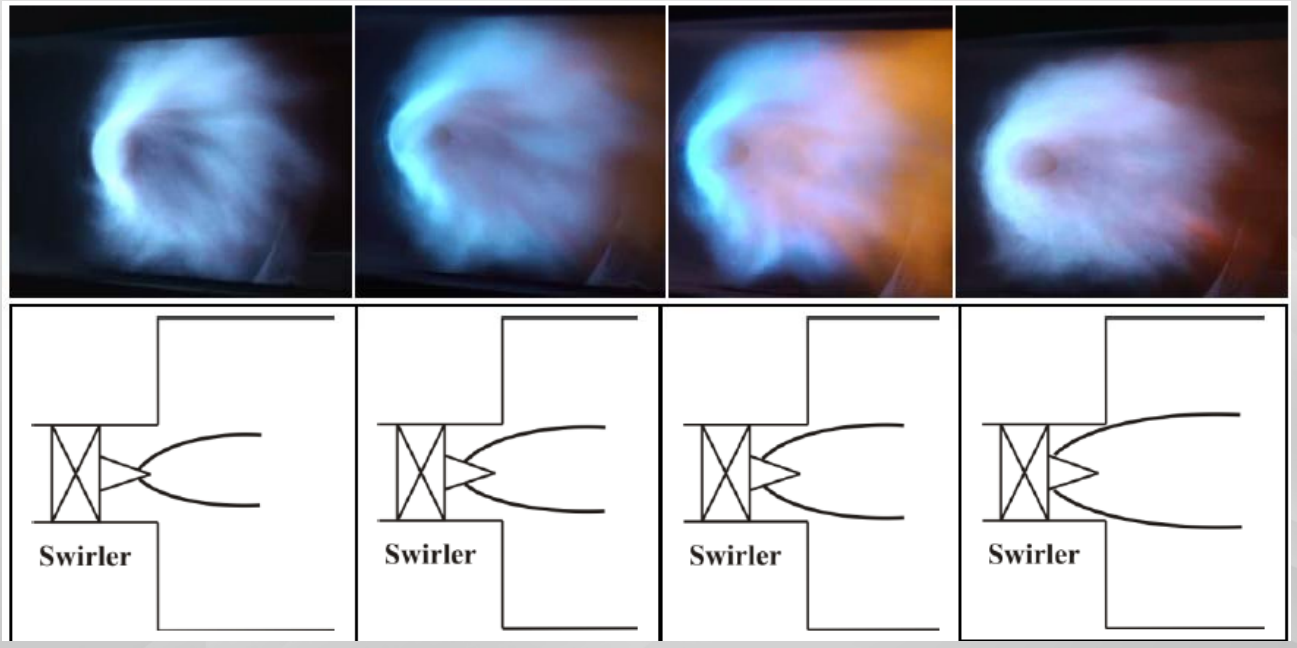
Composition	Scaling Factor (c)	R^2 Value
5% H_2+95% CO	.04	.7
15% H_2+85%CO	.025	.9
25%H_2+75%CO	.049	.8

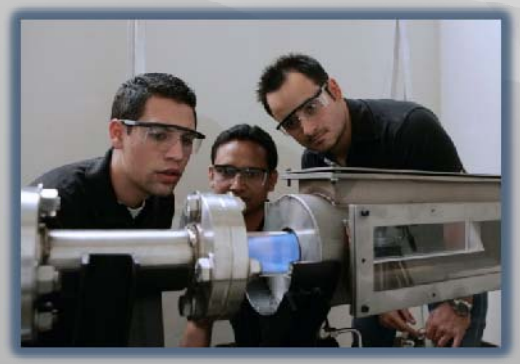
Results

Non-Reacting Flow-Field



Results – Flashback



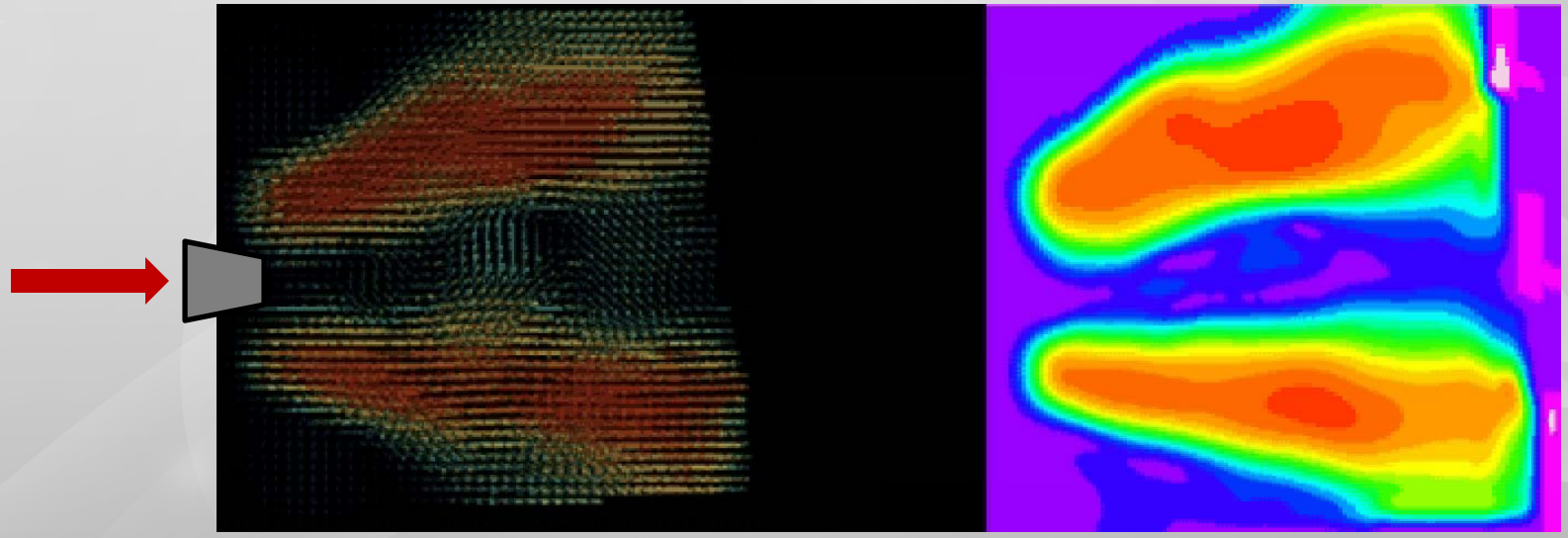


Results – Flashback

Sample PIV flow-visualization videos using Methane

Vector

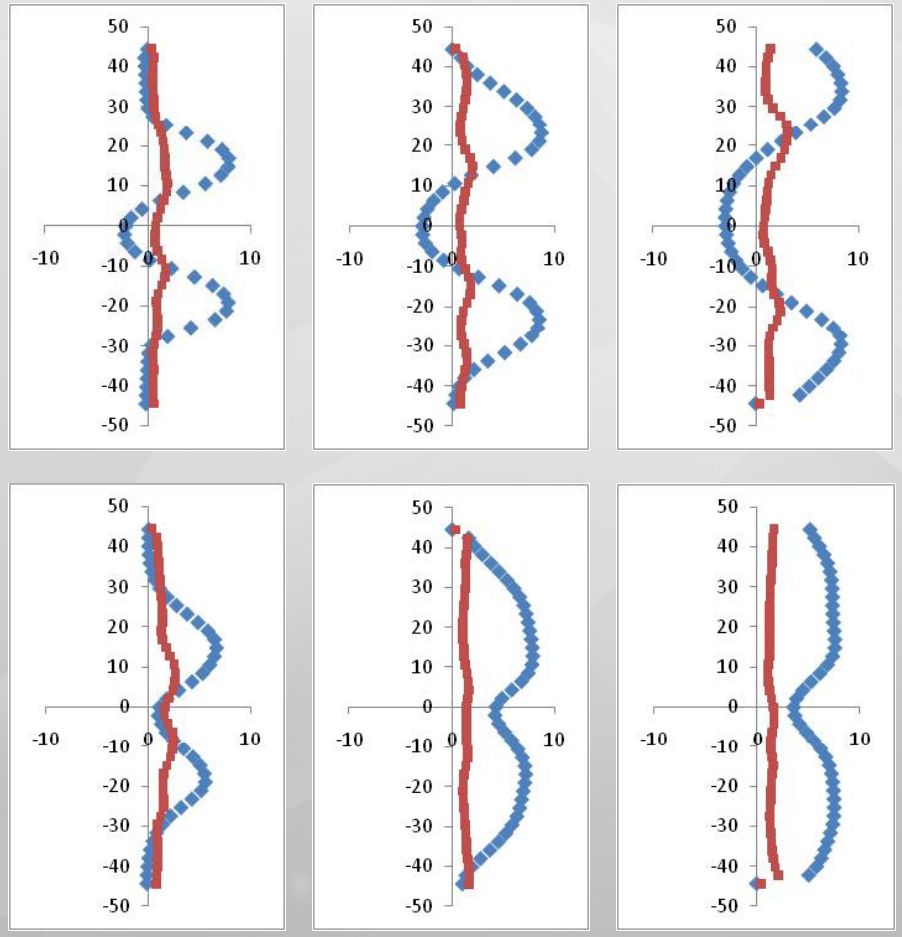
Scalar



Results- Axial Velocity and S_T

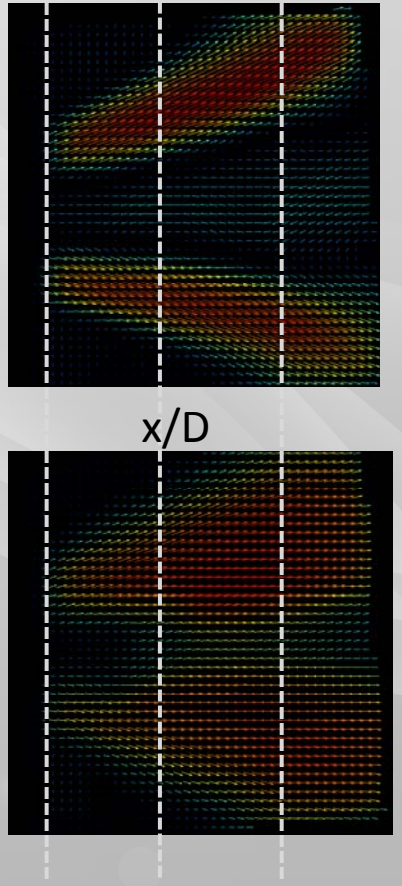
Stable

Flashback



x/D = 0.1 x/D = 0.4 x/D = 0.7

Methane



x/D

0.1 0.4 0.7

Results- Axial Velocity and S_T

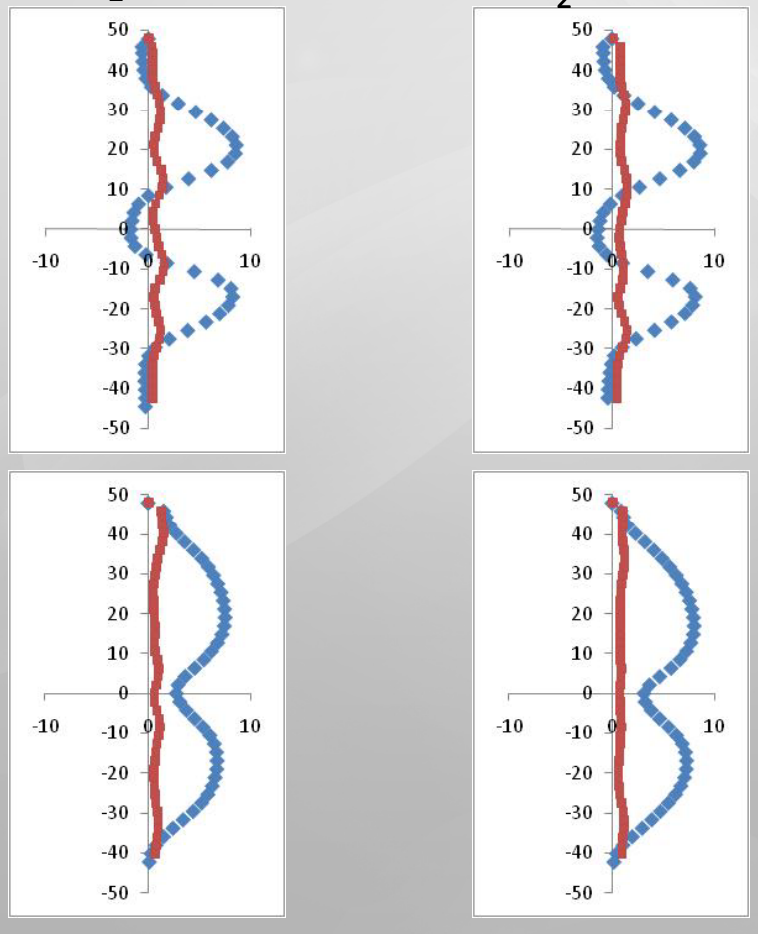
Fuel Composition

10%H_2 – 90% CO

20%H_2 – 80% CO

Stable

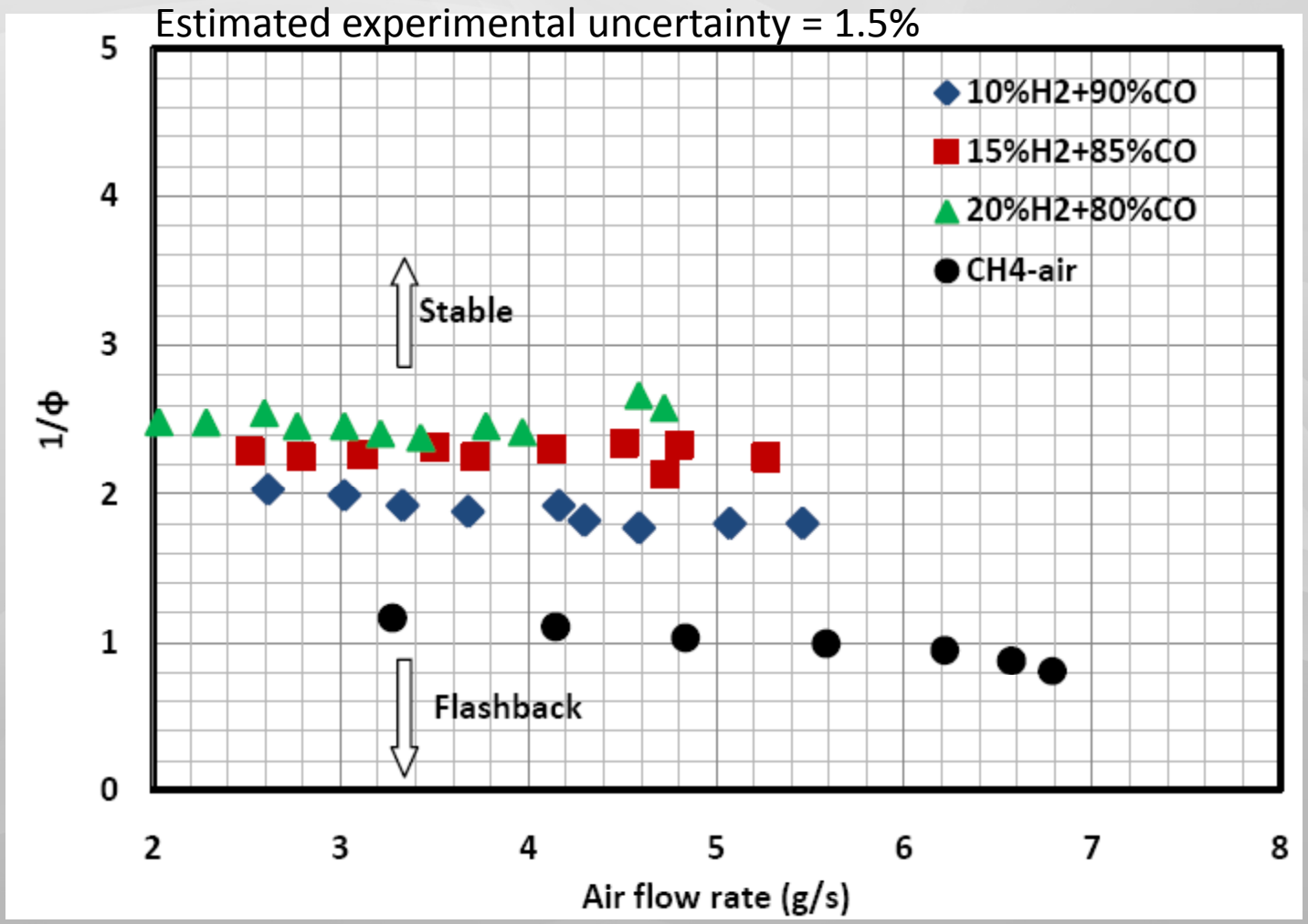
Flashback



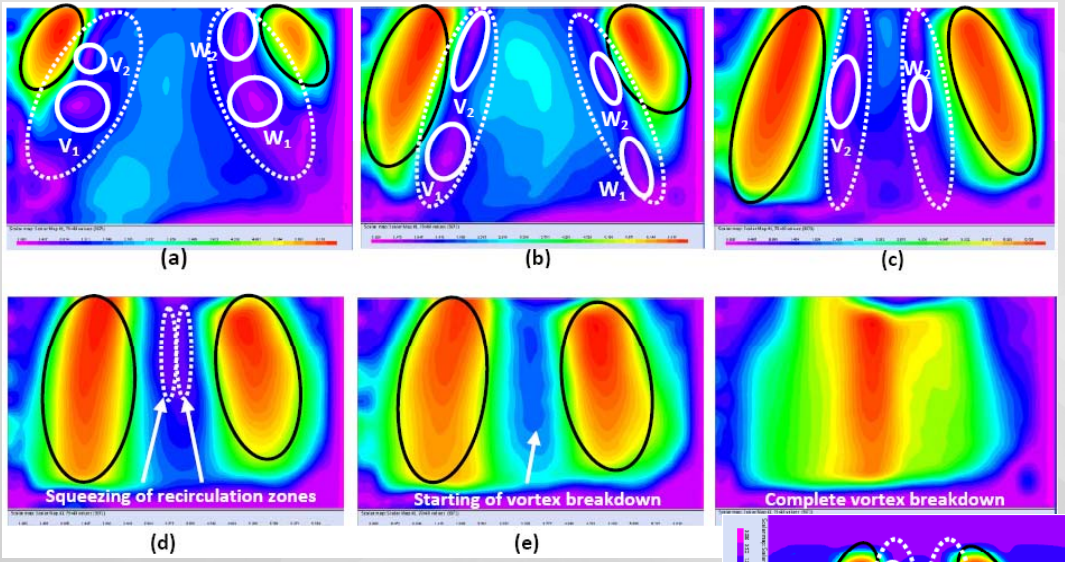
Although, U>>S_T flashback occurs

x/D = 0.4

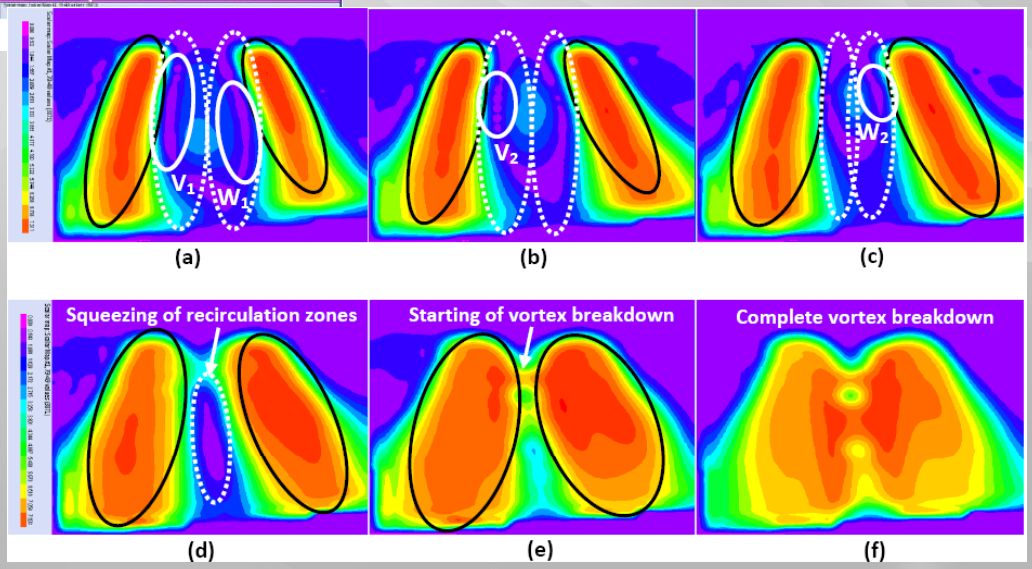
Results- Fuel Composition



Results- Flashback

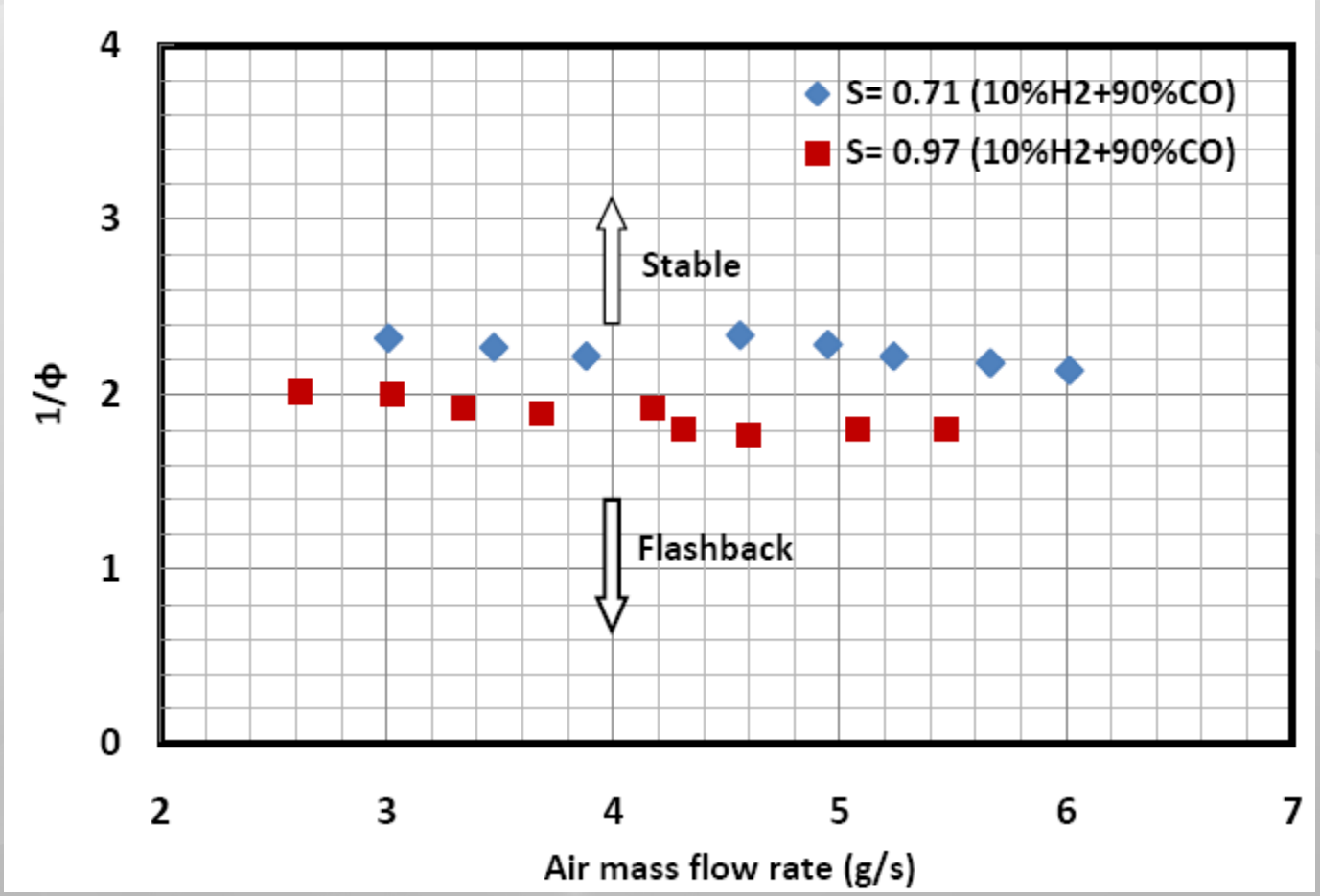


10%H_2 – 90%CO



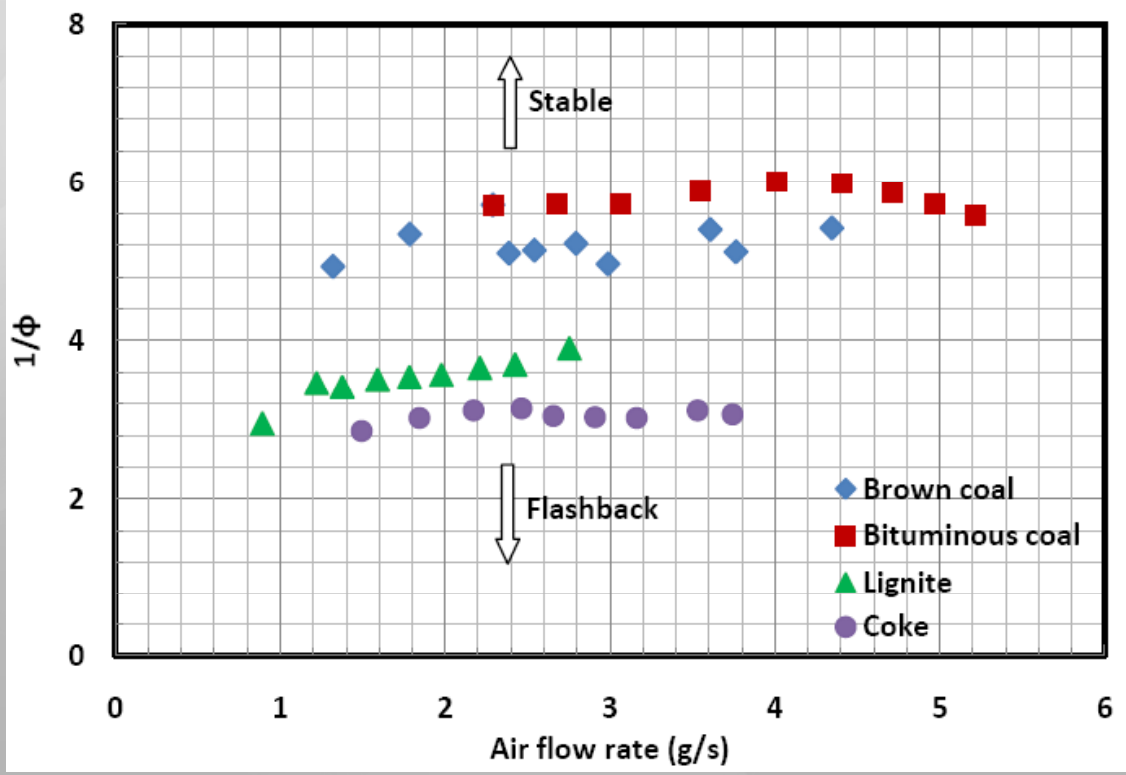
20%H_2 – 80%CO

Results- Swirl Number



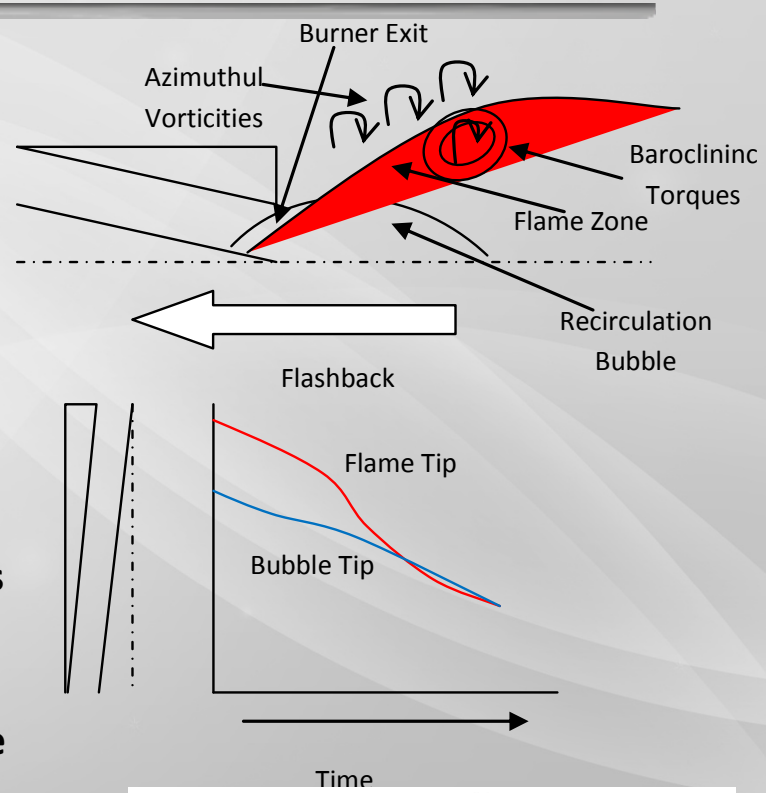
Results- Actual Syngas

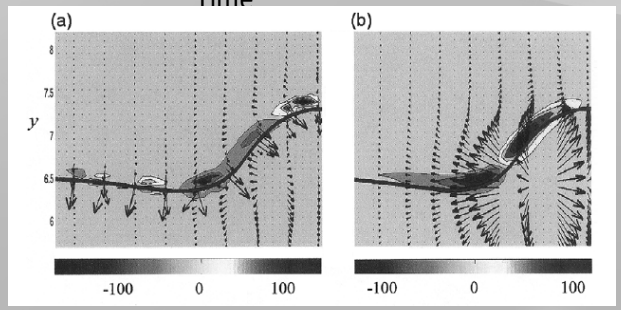
Gasification	Types of coal	CO (%)	H_2 (%)	CH_4 (%)	N_2 (%)	CO_2 (%)	Calorific Value (MJ/m^3)
Coal	Brown Coal	16	25	5	40	14	6.28
	Bituminous	17.2	24.8	4.1	42.7	11	6.13
	Lignite	22	12	1	55	10	4.13
	Coke	29	15	3	50	3	6.08
Wood		2.1	21	1.83	43	12	7.07



CIVB- Flashback

1. **Flame stabilizes slightly upstream of the recirculation zone**
2. **As the flame approaches the CIVB limit combined effects of baroclinic torque within the reaction zone and azimuthul vorticities pushes the recirculation tip slightly upstream.**
3. **The flame position also moves upstream and stabilizes in a new location**
4. **Further increase in the equivalence ratio increases the negative axial velocity generation through flame vortex interactions and pushes the recirculation tip further upstream. However, the difference between the recirculation tip and flame stabilization points decreases.**
5. **Once the equivalence ratio exceeds a critical value, flame becomes unstable and flashback occurs.**





Pan et al. (2002)

Results – Parametric Model

$$Pe_{flow} \propto Pe_{flame}^2$$

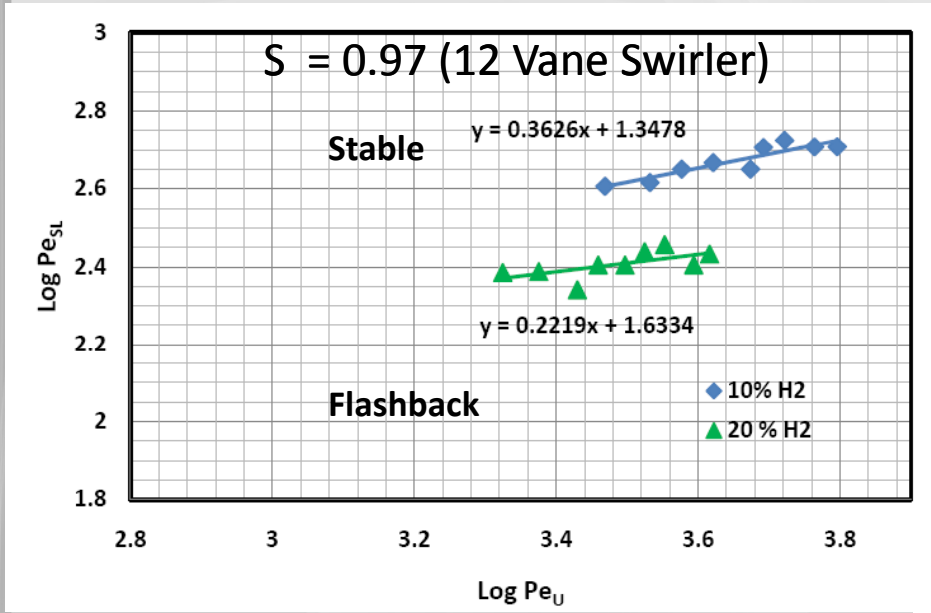
$$\frac{UD}{\alpha} = C\frac{S_L^2 D^2}{\alpha^2}$$

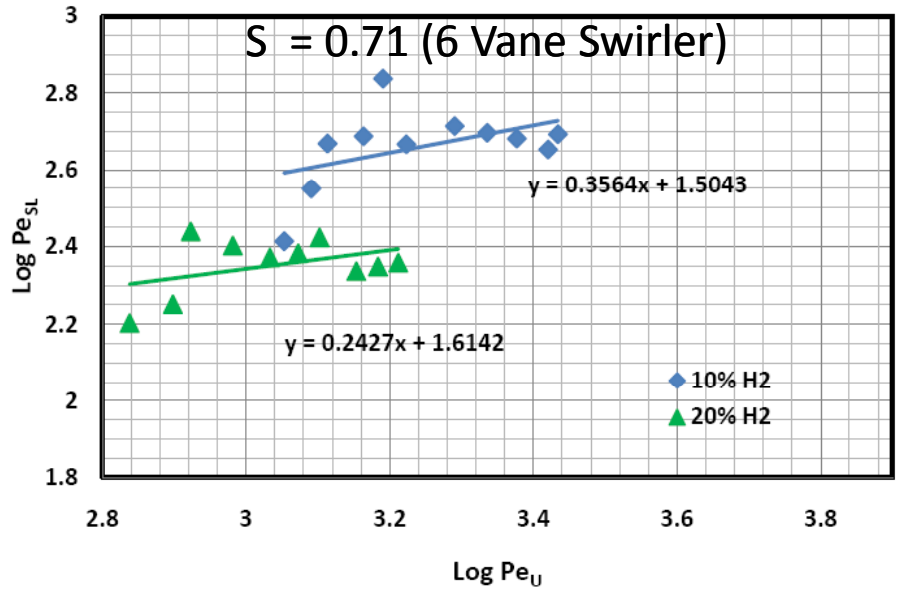
$$Pe_{flow}(\text{or } Pe_U) = \frac{UD}{\alpha}$$

$$Pe_{flame}(\text{or } Pe_{SL}) = \frac{S_L D}{\alpha}$$

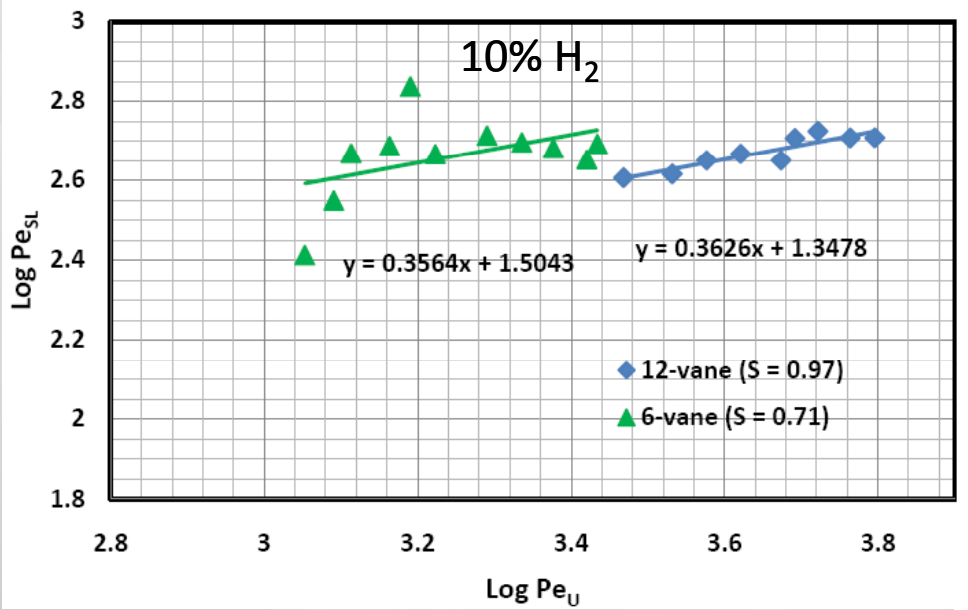
U	Bulk Velocity
D	Diameter of Mixing Tube
S_L	Flame Propagation Velocity
α	Thermal Diffusivity

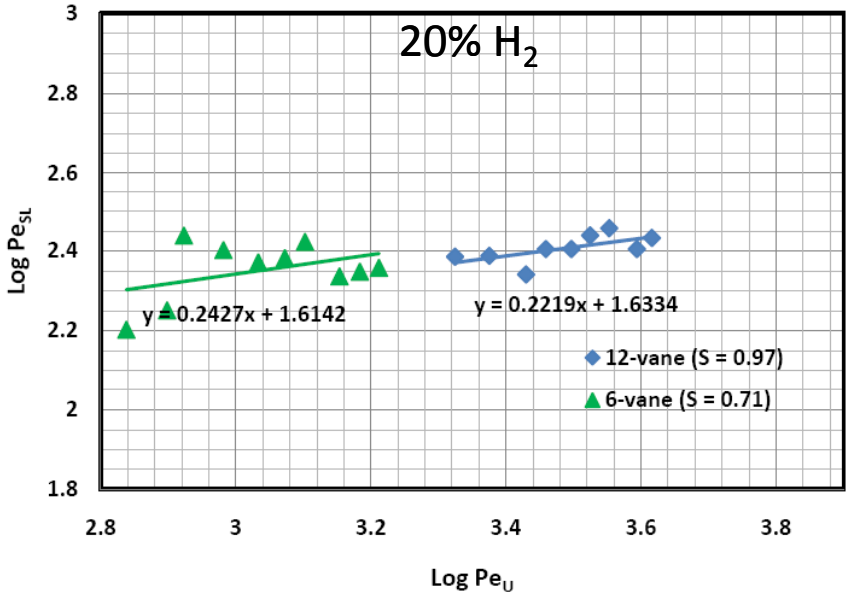
Results – Parametric Model





Results – Parametric Model





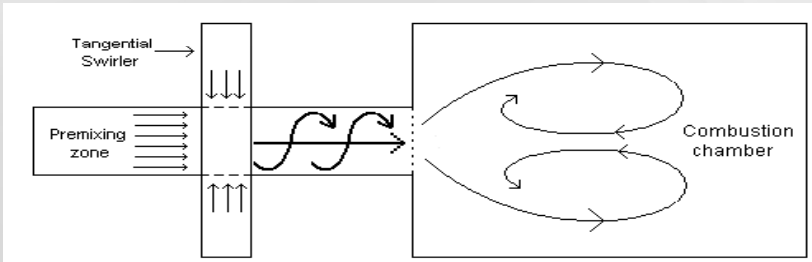
Results – Parametric Model

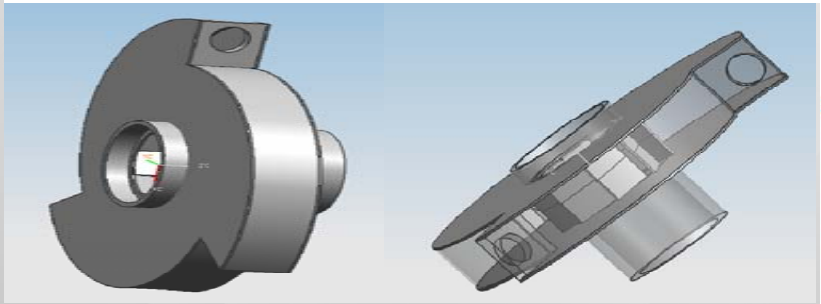
Swirl Number	Fuel Composition	C
0.71	10%H_2 – 90% CO	0.36
	20%H_2 – 80% CO	0.24
0.97	10%H_2 – 90% CO	0.36
	20%H_2 – 80% CO	0.22

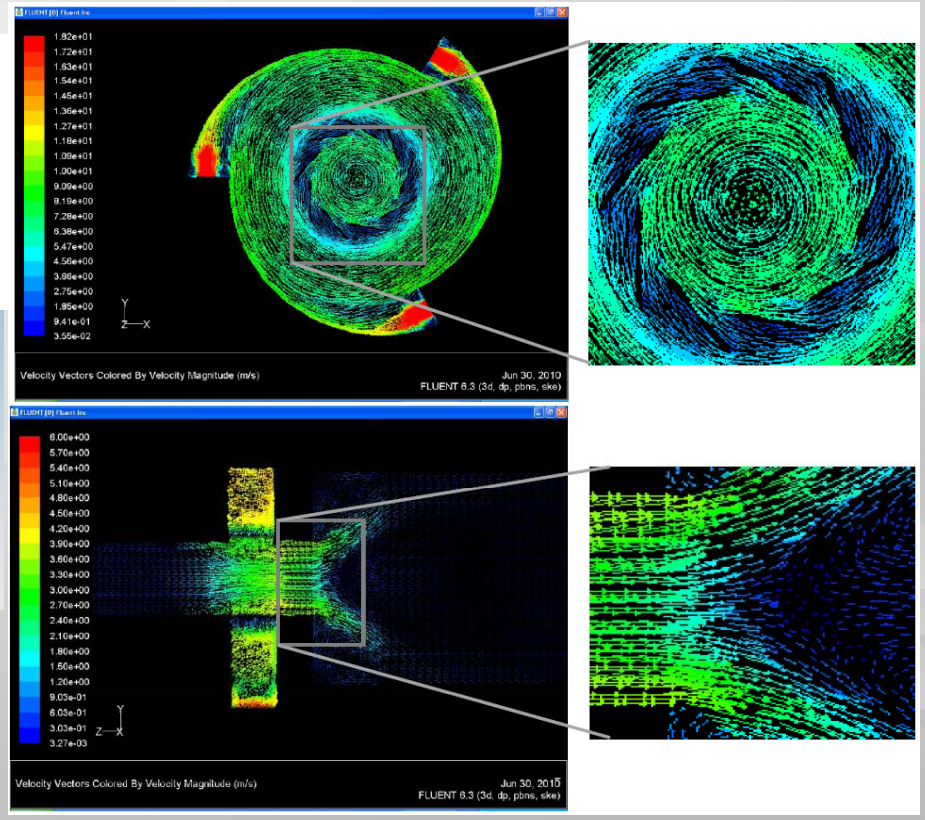
- C dominated more by fuel composition than swirl strength

Work In Progress

Tangential Entry Swirler Design



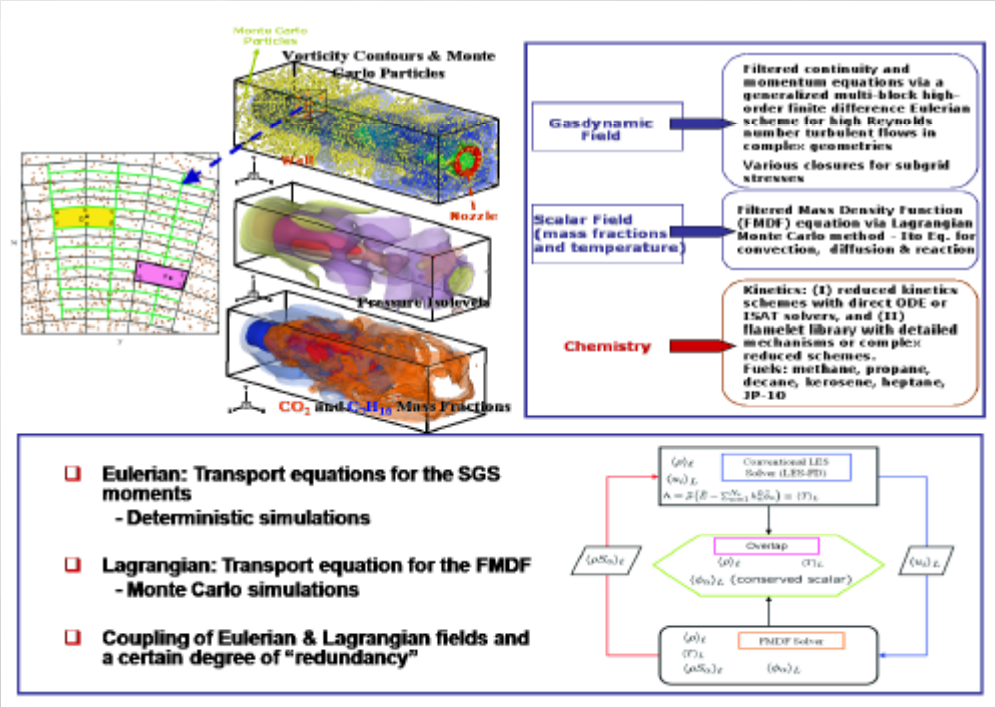




- Designed to create homogeneous flow distribution

Work in Progress

- LES modeling of CIVB Flashback
- Higher pressures
  - 5 atm
  - 12 atm



IN COLLABORATION WITH MICHIGAN STATE UNIVERSITY

SUMMARY AND CONCLUSIONS

Summary and Conclusions

- The boundary layer flashback behavior of H_2-CO flames changes nonlinearly with the increase in H_2 content in the mixture.
- The critical velocity gradient (g_F) values of 5%-95% and 15%-85% H_2-CO mixtures yield an average c value of 0.035.
- The g_F values of 25%-75% H_2-CO mixture show variations with the S_L^2/α ratio above 19,000 s^{-1}.
- At a lower S_L^2/α ratio, burner diameters have small effects on critical velocity gradient measurements; however, the effect is significant at higher S_L^2/α ratio.

Summary and Conclusions

- For a given mass flow-rate CIVB Flashback:
  - Occurred at lower ϕ when H_2 concentration in fuel mixtures was higher
  - ϕ increases for higher swirl number
  - ϕ decreases with the decrease in diluents (N_2, CO_2) concentration in fuel mixtures

- Parametric Model:
  - C dominated more by fuel composition than swirl strength