Flashback Measurements in Hydrogen Enriched Low Swirl Flames Using High Speed OH-PLIF

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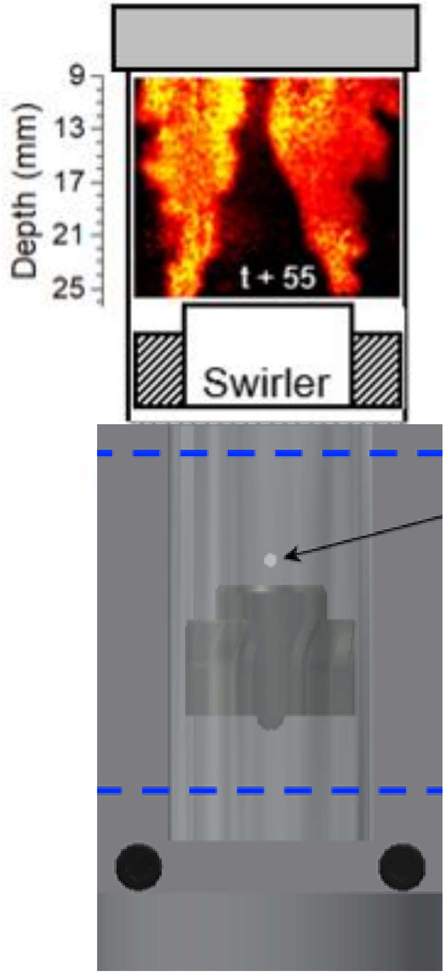

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Presentation Outline

Motivational Factors and Background

- Issues with hydrogen gas turbine systems
- Potential of low swirl flames with hydrogen-enriched systems

Experimental Apparatuses

- High-repetition rate ns-pulse laser system
- An optically accessible laboratory-scaled, swirl-stabilized burner

Results and Discussions

- Characterization of low swirl-stabilized flame
- Flashback characterization in low swirl burner
- Effects of fuel composition and varying swirler geometries
- Jet-in-Cross-Flow experiments.

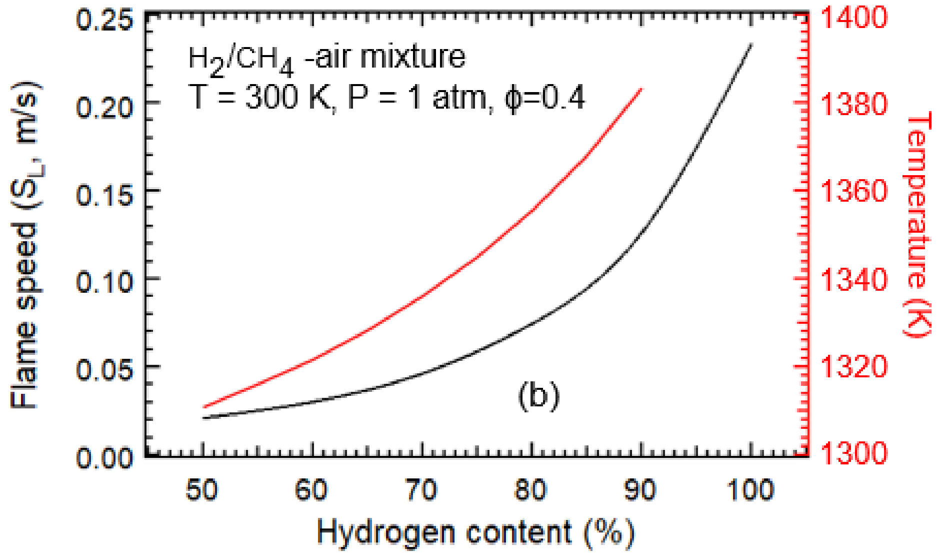
Summary and Ongoing Work

- Jet-in-cross-flow experiments, computational fluid dynamics (CFD) modeling.

Introduction

Hydrogen – a clean and sustainable energy source

- Significantly different combustion characteristics compared to natural gas – higher flame speed and adiabatic temperature
- Supports net zero carbon policy, however, NO_x emissions pose a problem with non-premixed systems
- Ultra-lean premixed hydrogen combustion has a great NO_x reduction potential
- Higher flame speed increases the risk of flashback and equipment damage



Source: GE Gas Power

Introduction

- **Swirl-stabilized flames are well-known methods to stabilize premixed flames**
  - Low swirl burners (LSBs) have gained increasing attention
  - Increases flame intensity reduces the flame length
  - LSBs have non-swirling core surrounded by a swirling shroud and produce freely propagating lifted flames
- **OH-PLIF diagnostic technique – a well-known laser diagnostic tool to gain insight into flashback phenomena**

- Study reported two peak values of turbulence intensities showing presence of inner and outer shear layer and credited its role for the flame flashback [1]

Objective of the current study:

Characterize the flashback process observed in a swirl-stabilized, atmospheric-pressure burner with hydrogen-enriched flames.

- Develop correlations
- Validate CFD models

[1] Cheng, C&F (1995)
[2] Huang et al., Prog. Energy & Comb. Sci. (2009)
[3] Johnson et al., PROCI (2005)

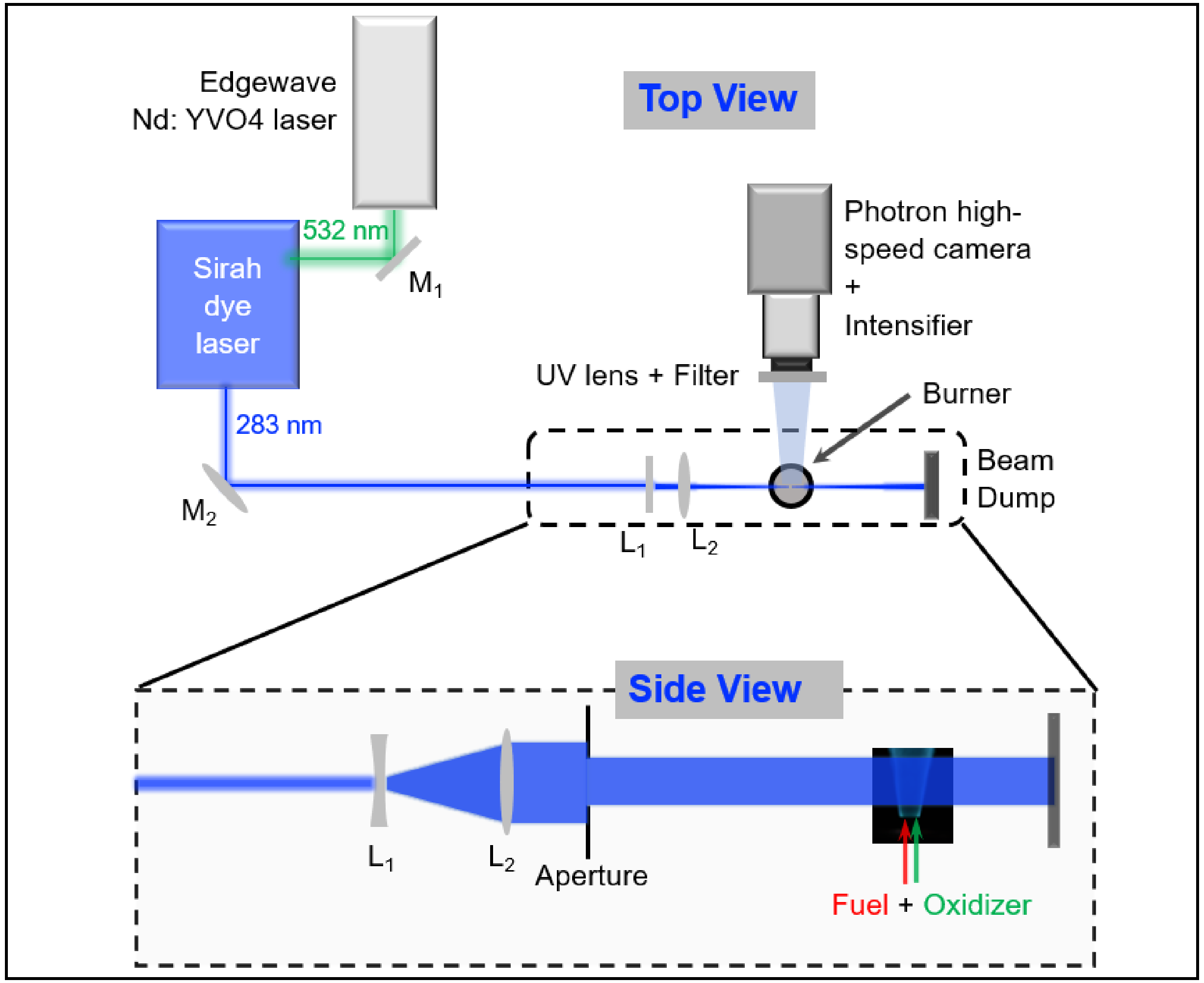
Experimental Apparatuses – Laser and Imaging System

Laser system

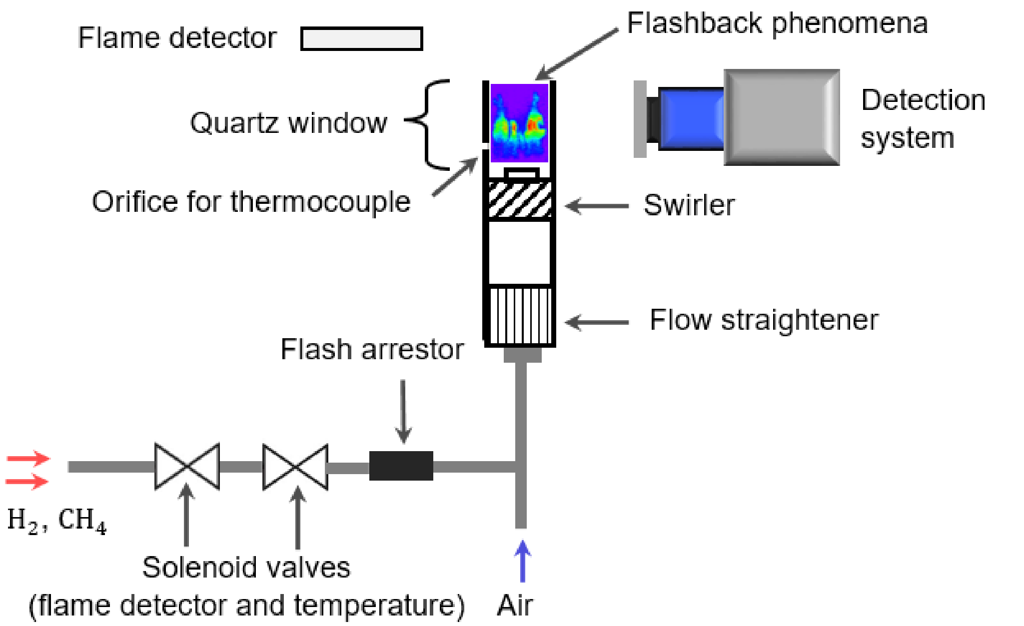
- Pump laser: A ns-duration Nd:YVO4 laser (INNOSLAB, Model: IS400-2-L), P ~ 75 W @ 20 kHz-repetition rate emitting a unique 3 mm × 8 mm rectangular beam
- Dye laser: Frequency-tunable dye laser (Sirah, Model: CREDO-DYE-N) filled with a solution of rhodamine-6G dye diluted in pure ethanol
- Excitation wavelength: 283.9 nm, E ~ 0.05 mJ/pulse

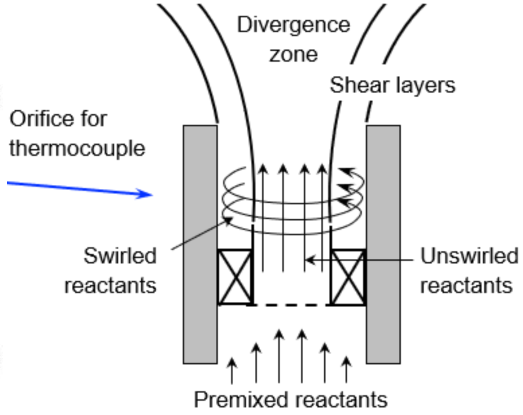
Imaging system

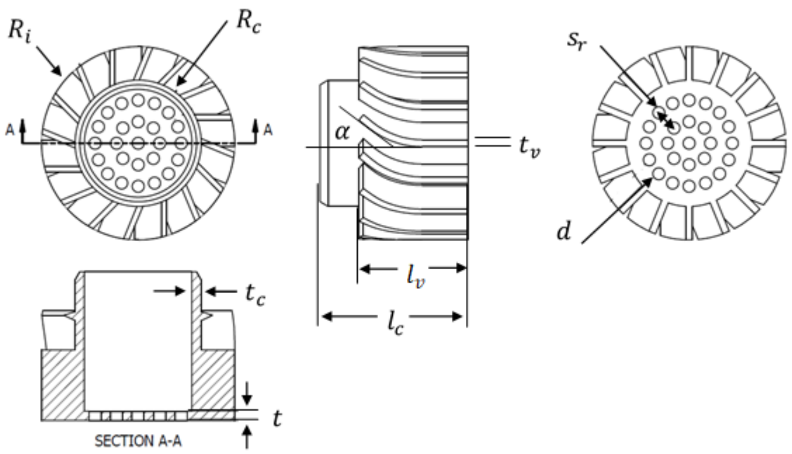
- Camera: A high-speed CMOS camera (Photron, Model: FASTCAM SA-Z)
- Intensifier: A high-speed intensifier (Invisible Vision, Model: UVi 1850-10 S25)
- UV lens (Cerco, Objectif UV, f/1.8)
- Filter



Experimental Apparatuses – Burner System







Burner configuration

- A 21.2-mm ID low swirl burner with optically accessible pre-mixer system
- Fuel (H_2 and CH_4) with 50%–90% H_2 by mole
- Thermocouple (inserted in pre-mixer unit) senses the rise in temperature and shuts off fuel

Swirler design

- Swirling vane angles (α) – 26º and 33º.
- Perforated plate hole diameters – 1.08, 1.12 and 1.16 mm.
- Blockage ratio (BR) – 0.783, 0.767, and 0.75.
- Radius ratio – 0.65.

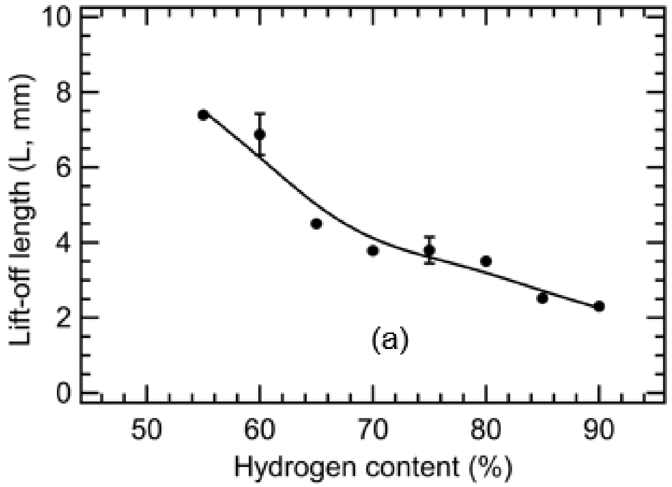
Results and Discussion: Stable Flames

Characterization of Low Swirl Burner Flame – Variation of Fuel Compositions

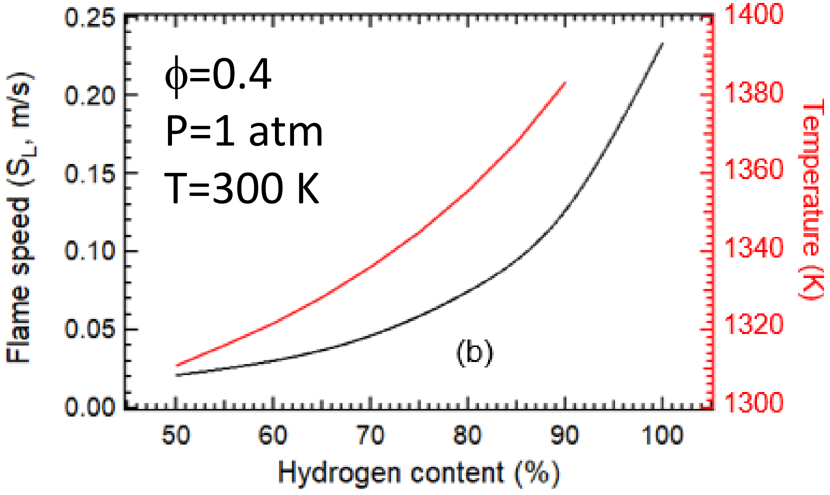
Effects of Pre-mixer Velocities (V)

- Velocity varied: 5.5 ≤ V ≤ 10 m/s
- Lift-off length (L) tends to increase linearly with Velocity
- The local gas velocity is increased compared to flame speed and becomes less flashback prone

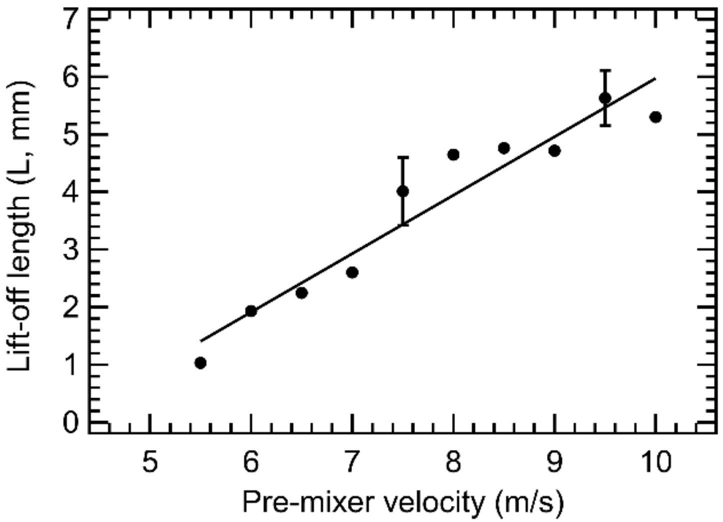
V= 7.5 m/s and ϕ = 0.4



Cantera Calculations



$70\%H_2/30\%CH_4$, ϕ = 0.4

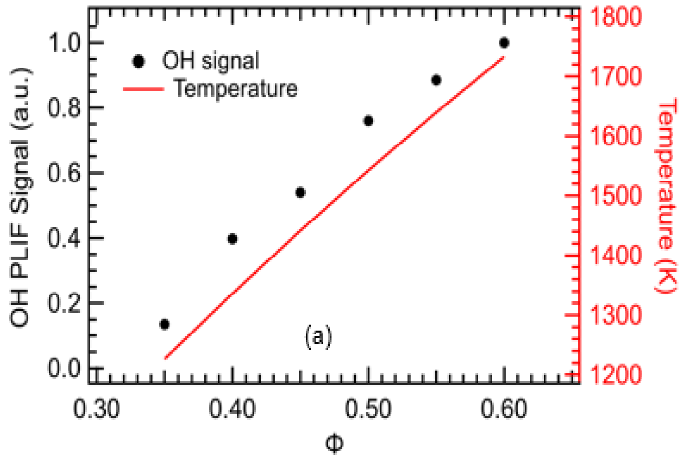


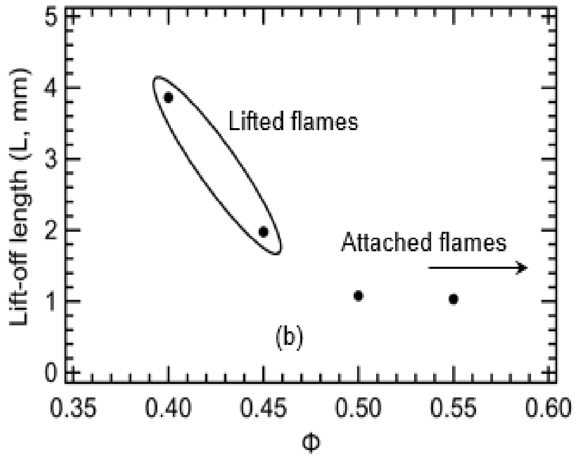
Effects of Hydrogen Content (X_{H2})

- Increasing X_{H2} tends to decrease lift-off length and increase the chances of flashback – due to a increase in flame speed
- Expected rise of flame temperature as hydrogen flame is hotter than methane flame at same ϕ

Effects of Equivalence Ratio (ϕ) on Stable Flames

- Increasing ϕ decreases *L*, i.e., it brings the flame closer to the burner surface, increasing the risk of flashback
- Increasing ϕ increases flame speed
- Lifted-to-attached flame transition can be observed
- OH-PLIF signal increases with increasing ϕ

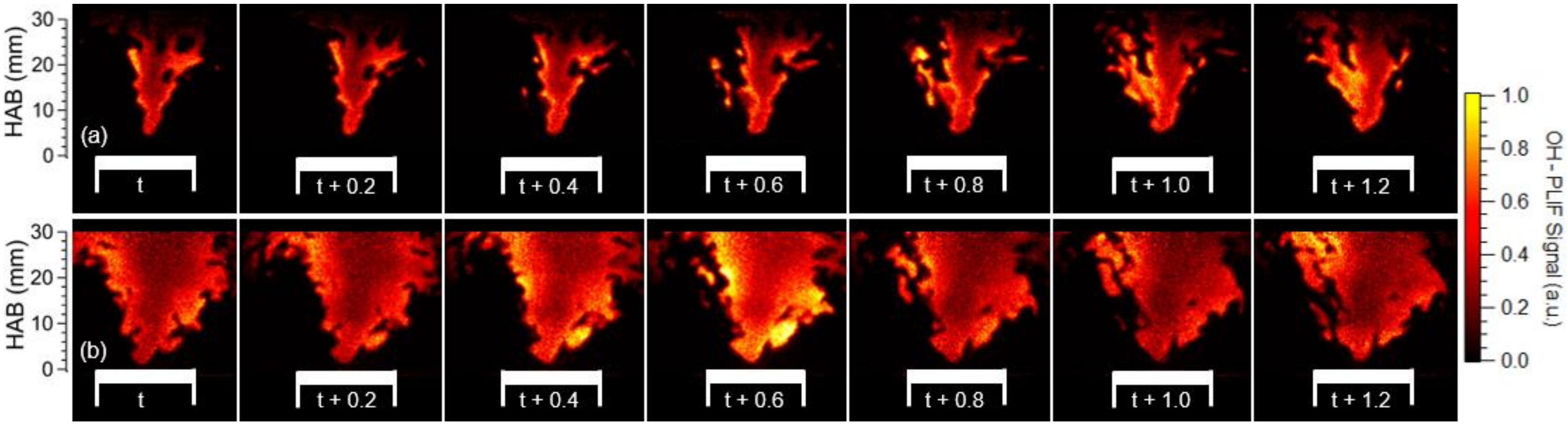




70%H_2/30%CH_4-air flame, V = 7.5 m/s

ϕ= 0.4

ϕ= 0.55

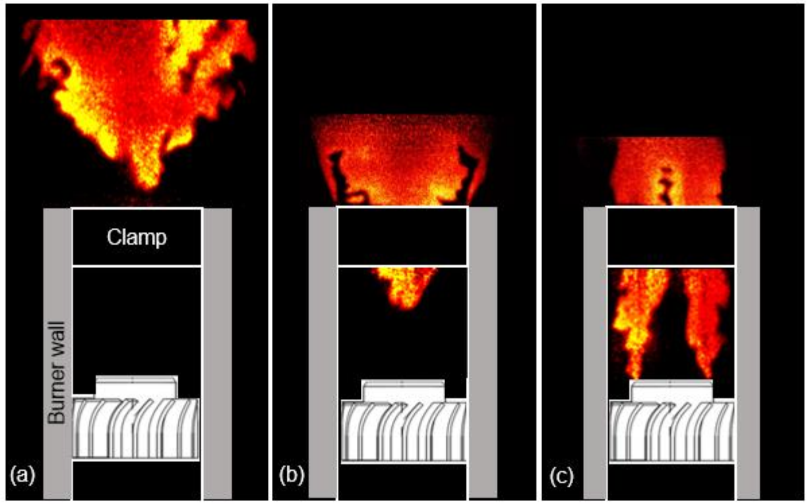


Investigation of Flame Flashback Events

Flashback Characterization in Low Swirl Burner

Experimental test conditions: $5 \leq V \leq 10$ m/s and $50\% \leq X_{H_2} \leq 90\%$

- At low ϕ or H_2, the flame is lifted and has V shape.
- Increasing ϕ or H_2 pulls the flame closer to the tube exit; however, the general shape remains unchanged.
- Significant change in flame shape occurs at ϕ = 0.65 or H_2 = 75%.
- High-speed OH-PLIF images show intermittent burning in the outer shear layer.

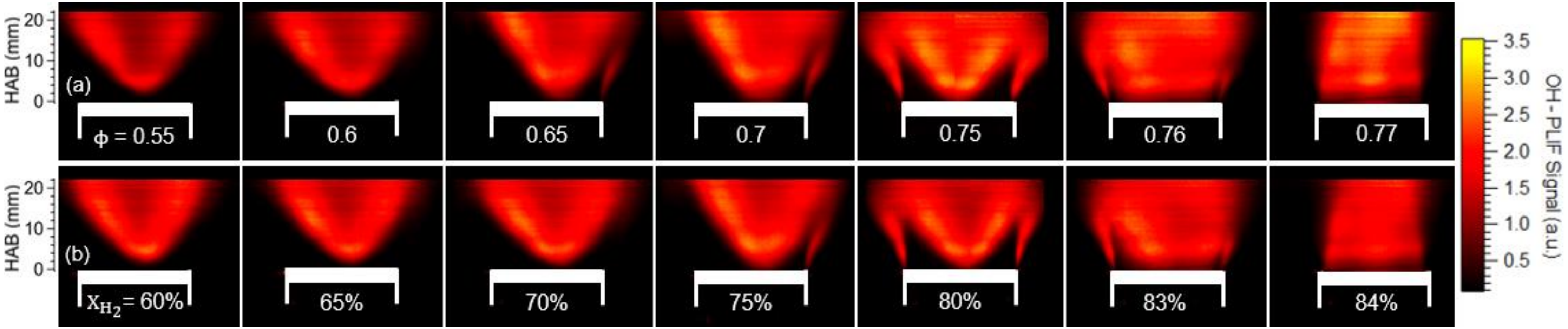


increasing ϕ →

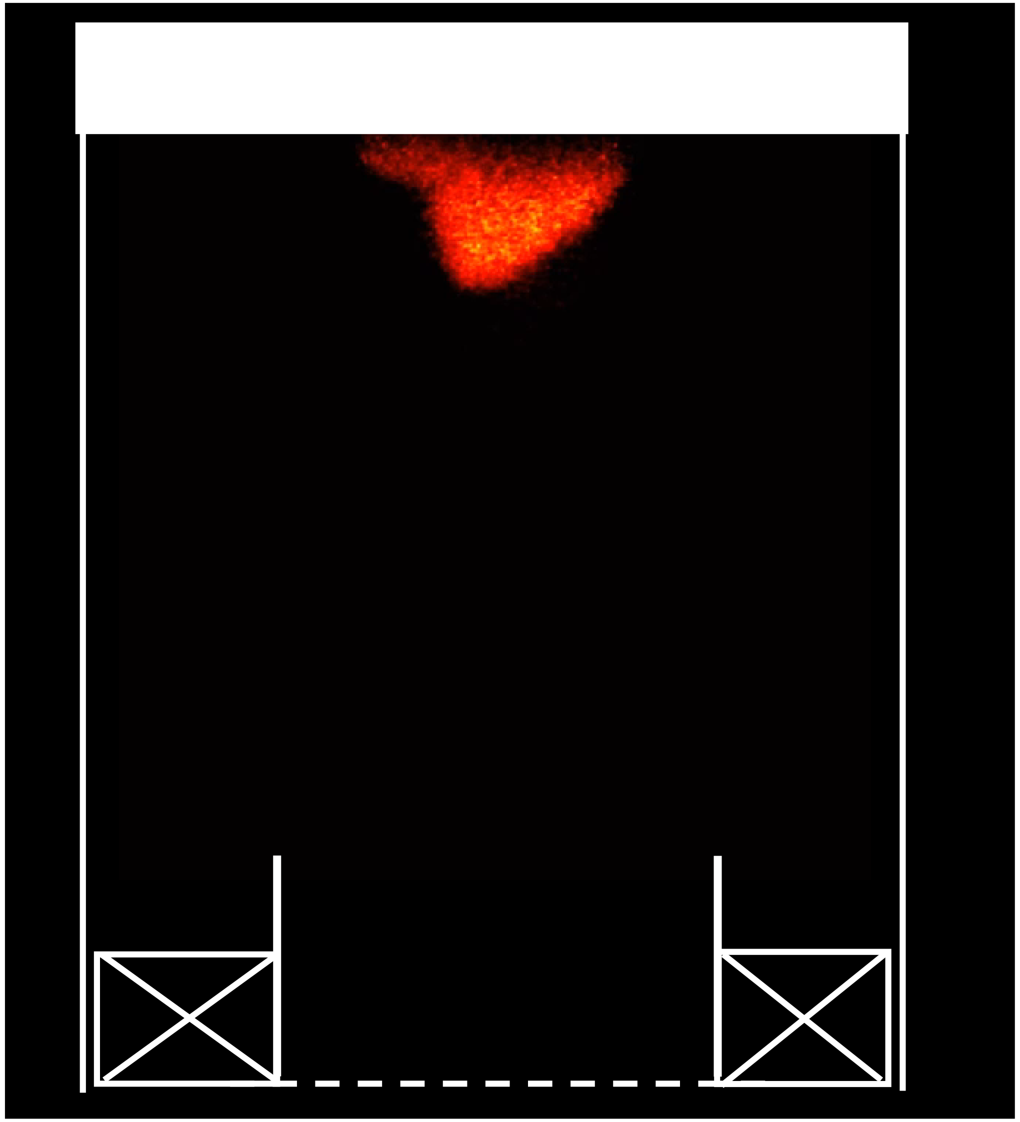
Changes in flame shape and stabilization pattern as a function of ϕ or H_2 at V = 10 m/s

X_{H_2}=70%

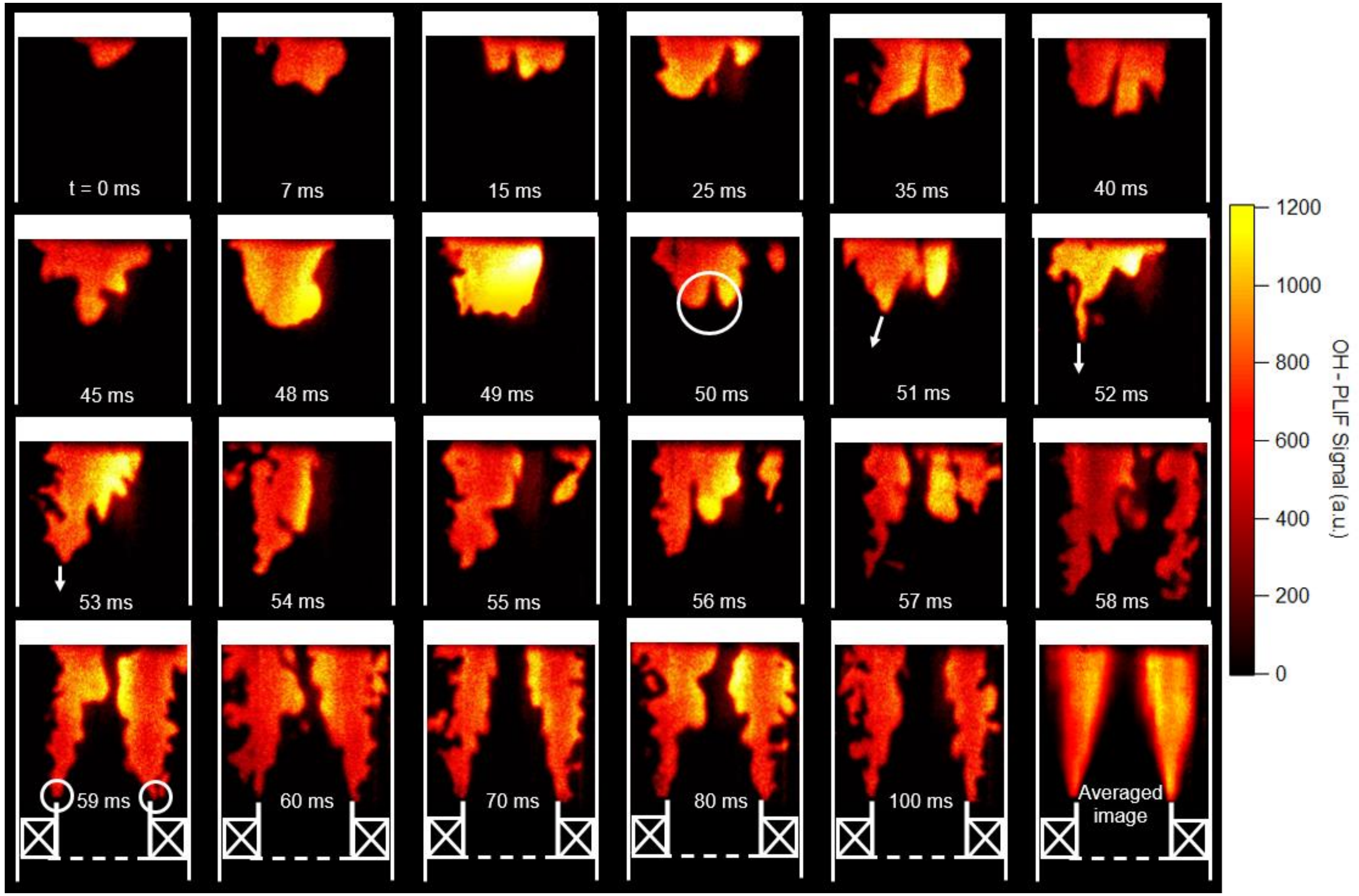
ϕ= 0.60



Investigation of Flame Flashback Events



$70\%H_2/30\%CH_4$-air flame, V = 7.5 m/s



1 kHz frame rate (100 msec video)

Investigation of Flame Flashback Events

Flashback initiation

- Burning of outer shear layer pulls the flame upstream into the nozzle.

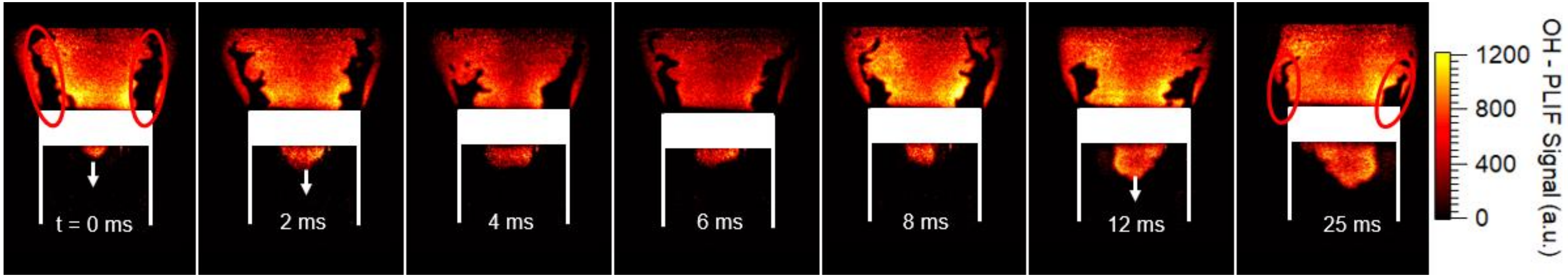
Flashback propagation inside the nozzle

- Inner shear layer above the center channel wall (between swirled and unswirled flows) facilitates upstream flame propagation inside the nozzle.

Post-flashback flame holding

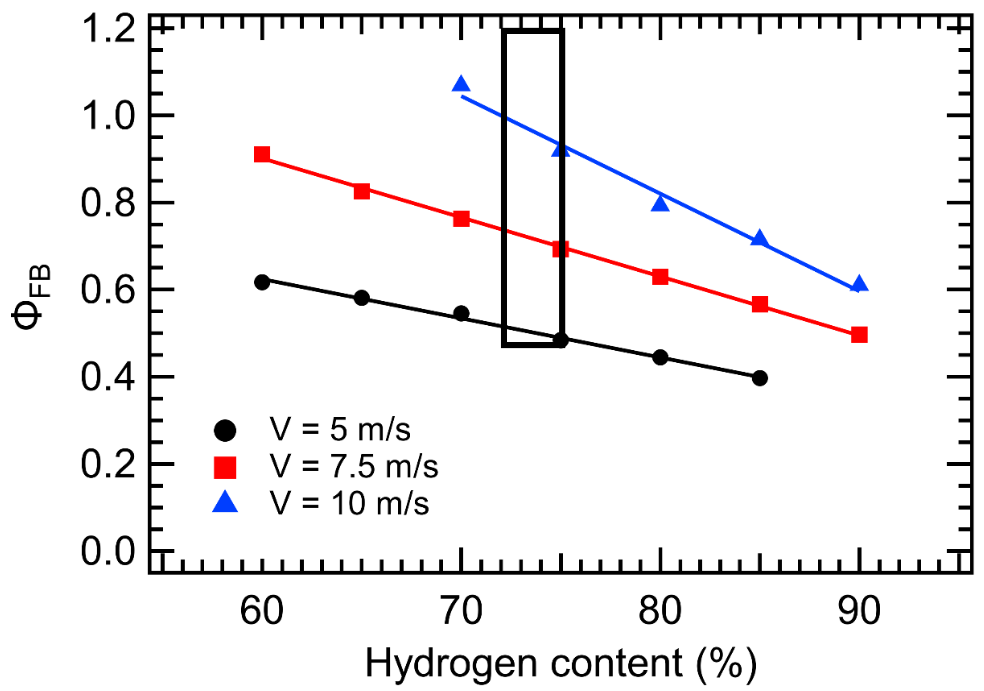
- Once a part of flame is attached to the rim of the swirler, it ignites the incoming fresh mixture (likely along the inner shear layer) forming a conical flame
- The flame structures anchor inside the mixing tube between the swirling and non-swirling regions.

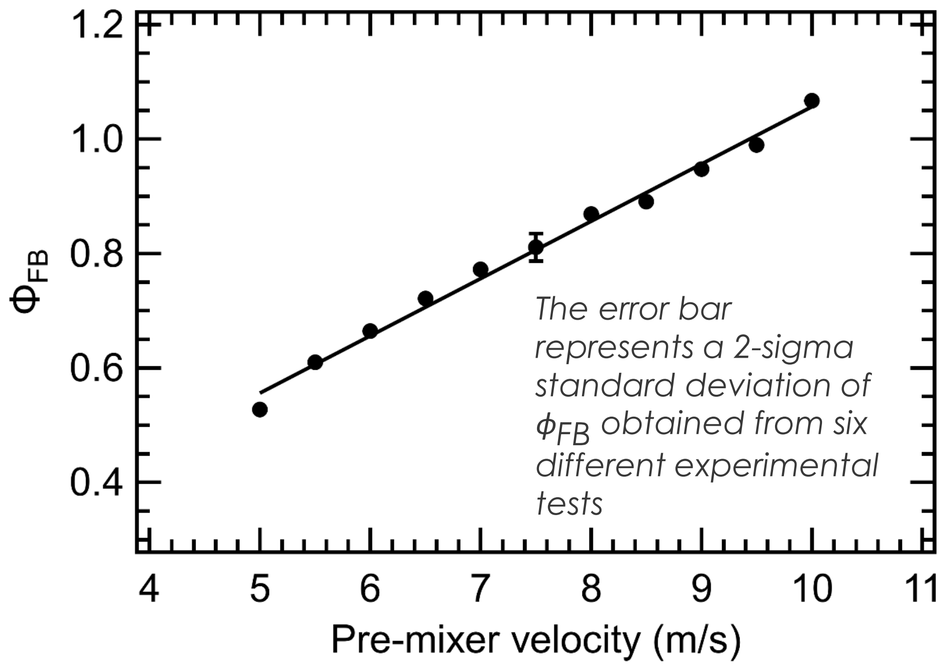
70%H_2/30%CH_4-air flame, V = 10 m/s



Effects of Fuel Composition

- As X_{H2} increases, the burner system is more prone to flashback
- ϕ_{FB} decreases linearly with an increase in X_{H2} in the reactant mixture

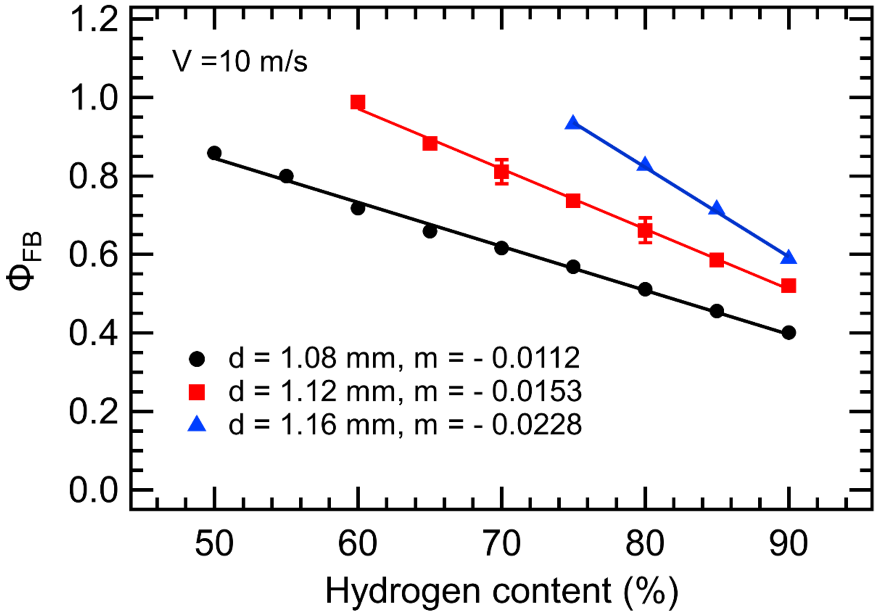


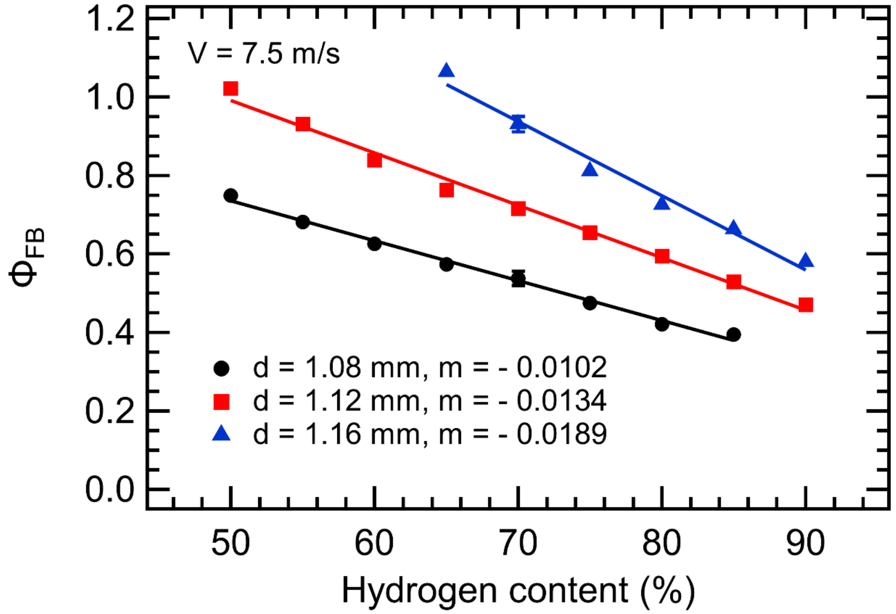


- As V increases, the flashback resistance of the burner system increases
- ϕ_{FB} increases linearly with an increase in pre-mixer velocity

Effects of Varying Swirler Geometries

- Dependence of ϕ_{FB} on X_{H_2} for three different perforated plated hole diameters (d) keeping $'\alpha'$ fixed at 33°.
- An increase in '*d*' decreases the blockage ratio which increases the flow via the center-body and the burner system becomes less flashback prone.

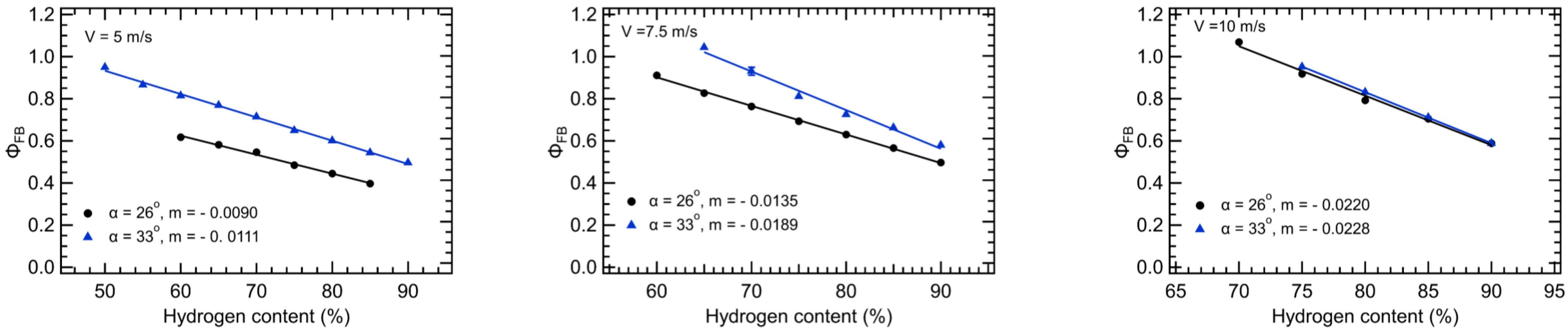




- Another interesting observation is on the slope of the flashback lines which shows a greater negative slope with increasing '*d*'
- The error bar represents a 2-sigma standard deviation of ϕ_{FB} obtained from five different experimental tests

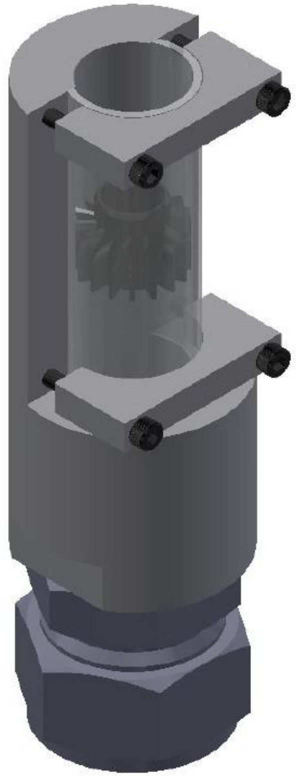
Effects of Varying Geometry

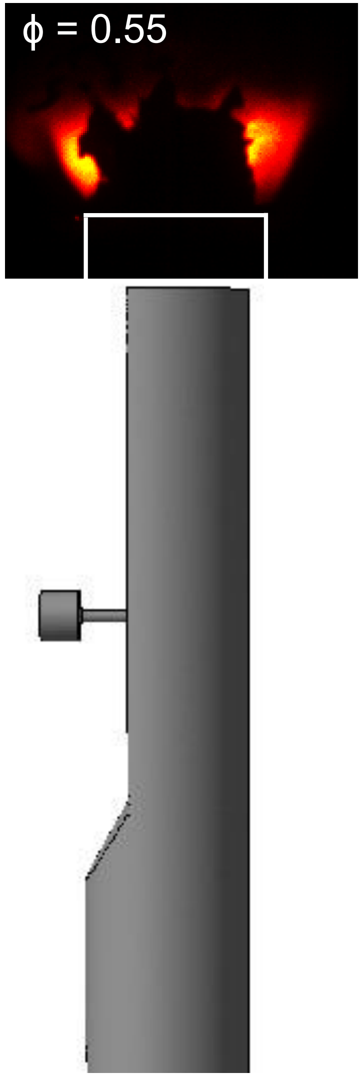
- Dependence of ϕ_{FB} on X_{H_2} for two different swirler vane angles keeping perforated plate hole diameter (d) fixed at **1.16 mm.**
- ϕ_{FB} increases with an increase in α especially at lower pre-mixer velocities of 5 and 7.5 m/s.
- Higher α may be increasing the core flow.
- ϕ_{FB} lines almost overlap for two αs at V = 10 m/s



Jet in Cross Flow Experiments

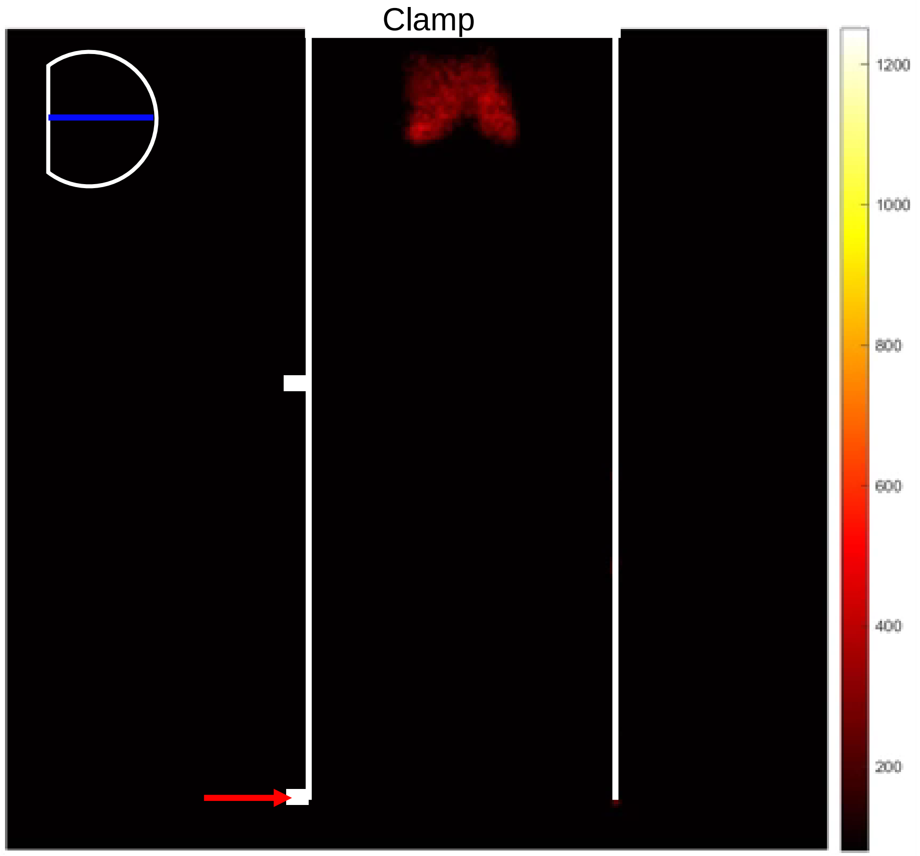
- Objective - Characterize flashback and flame-holding with a jet-in-cross-flow fuel injection strategy. Validate CFD codes.
- JICF used in conventional swirlers as well as micro-mixers for fuel injection.
- Swirler removed and flat plate installed on back side.
- 0.063” fuel jet located in flat plate.
- Lean flame attached to burner tube exit.
- Ramp up equivalence ratio while maintaining H_2/CH_4 ratio and air flow.



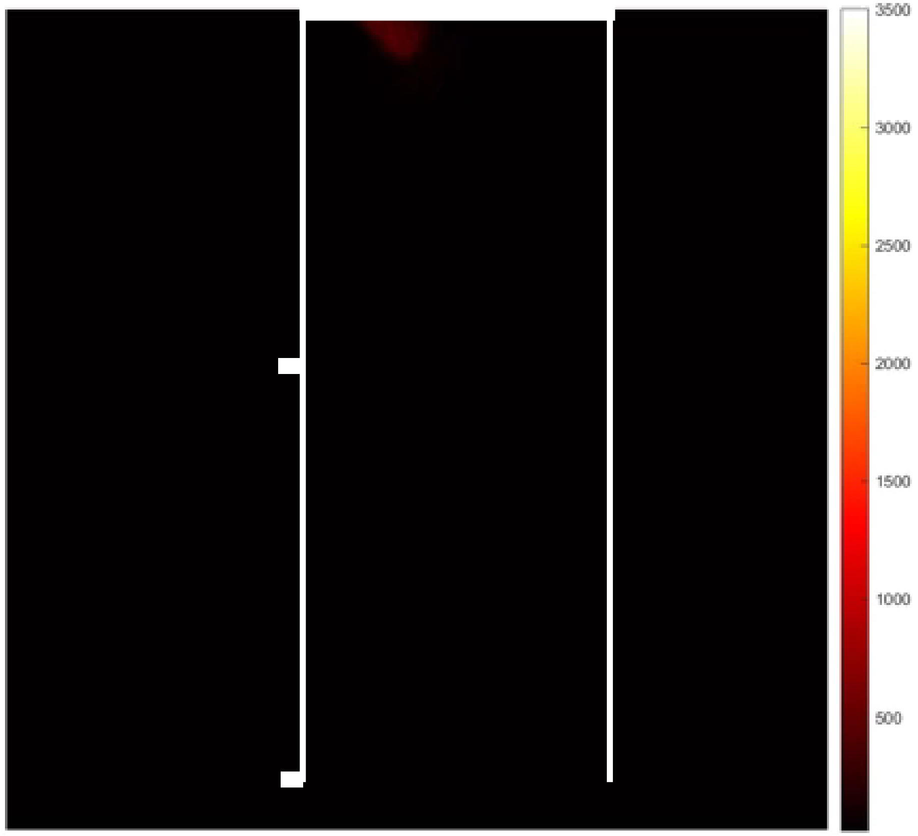


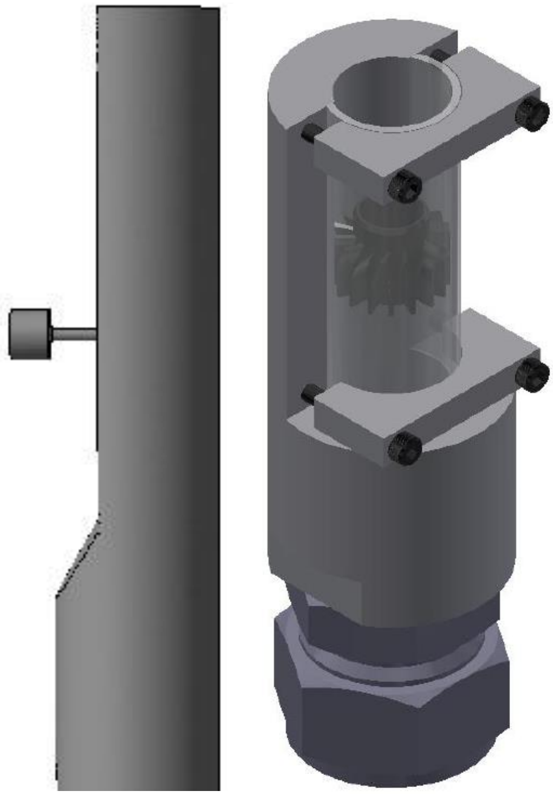
Jet in Cross Flow Experiments

1 kHz; OH-PLIF



1 kHz; OH* CL





70%H_2/30%CH_4-air flame; ϕ_{FB} =0.665; at V = 4 m/s

Jet in Cross Flow Experiments

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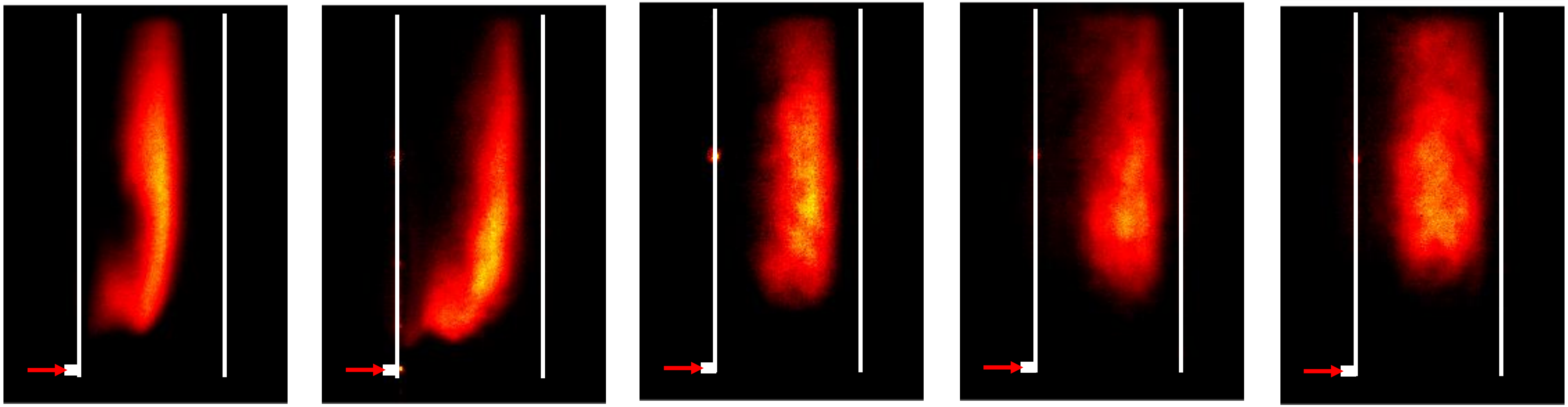
Time-Averaged OH PLIF Images After Flashback

$70\%H_2/30\%CH_4$-air flame at different pre-mixer velocities



V = 2 m/s, ϕ_{FB} = 0.4
Momentum flux ratio, r = 2.83

V = 3 m/s, ϕ_{FB} =0.5
r = 4.42

V = 3.5 m/s , ϕ_{FB} =0.68

V = 4 m/s, ϕ_{FB} =0.665
r = 7.83

V = 5 m/s , ϕ_{FB} = 0.73

Increasing Flowrates →

- As momentum flux ratio increases, the flame detaches from the fuel port completely and stabilizes in the form of a lifted flame.
- As r increases, the fuel jets penetrate further into the crossflow and the combustion zone shifts away from the fuel ports.

Jet in Cross Flow Modeling

- Fluent Large Eddy Simulation.
- 9M cells (0.2 mm).
- Skeletal methane-air mechanism (16 species, 45 reaction).
- No turbulence chemistry interaction.
- BCD for momentum, SOU for scalars, 2nd ddt implicit PB solver.
- Chemiluminescence sub-mechanism from Petersen.

```
!chemiluminescent reactions
!J. Hall, E. Petersen, Int. J. Chem. Kin. 38 (2006) 714-724.
!

H+O+M=OH*+M                        3.1E+14  0.0     10000.
OH*+H2O=>OH+H2O                    5.92e12  0.5     -861.
OH*+H2=>OH+H2                      2.95e12  0.5     -444.
OH*+O2=>OH+O2                      2.1e12   0.5     -482.
OH*+OH=>OH+OH                      1.5e12   0.5     0.0
OH*+H=>OH+H                        1.5e12   0.5     0.0
OH*+O=>OH+O                        1.5e12   0.5     0.0
OH*+N2=>OH+N2                      1.08e11  0.5     -1238.
OH*=>OH                            1.4e6    0.0     0.0
```

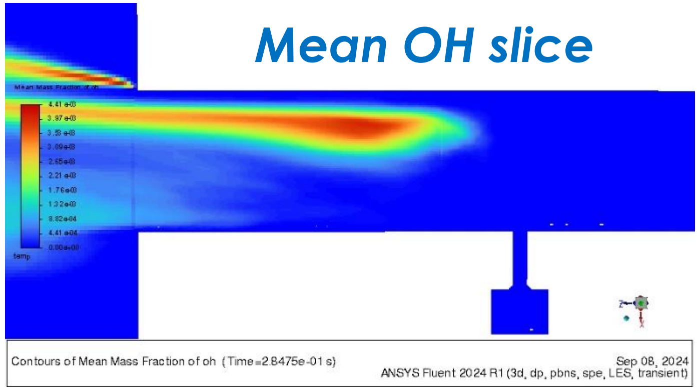
Jet in Cross Flow Experiments

Comparison to Fluent Simulations

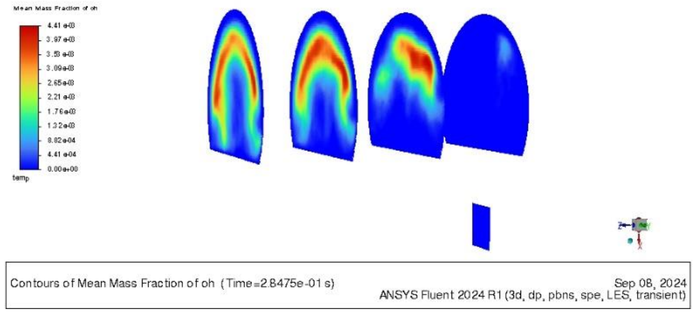
V = 5 m/s , H = 70%, ϕ_{FB} = 0.73

- **Simulations at highest flowrate shows fuel jet impingement on opposing wall and "horseshoe" shaped flame.**
- **Limits effectiveness of using planar techniques.**
- **Integrated line-of-sight chemiluminescence more useful.**

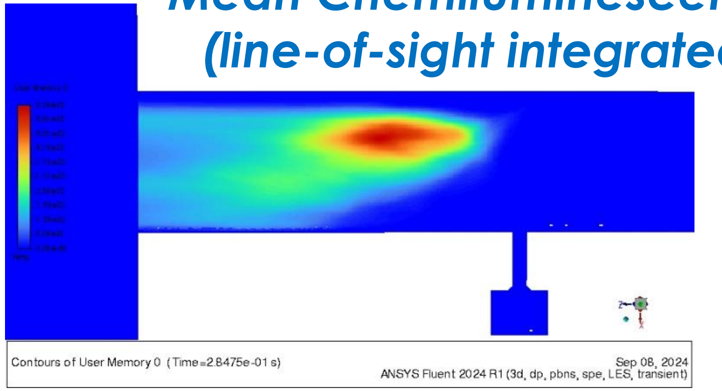
Mean OH slice



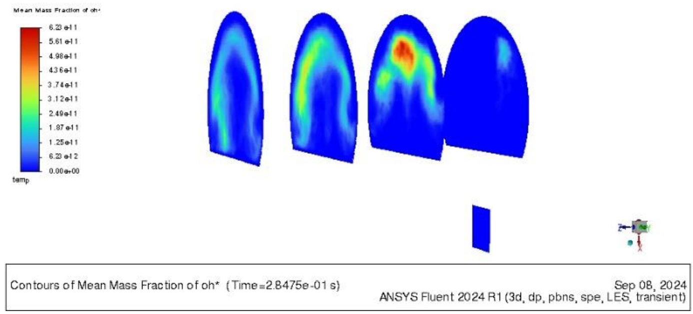
Mean OH slices



Mean Chemiluminescence (line-of-sight integrated)



Mean OH slices*

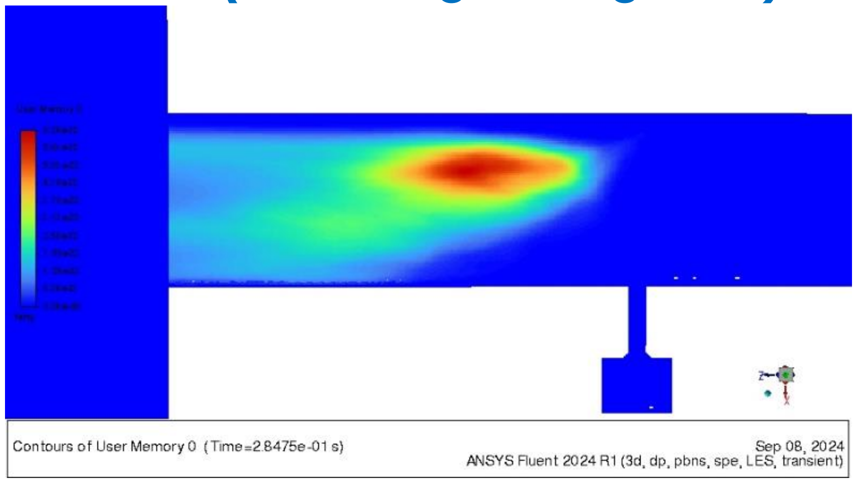


Jet in Cross Flow Experiments

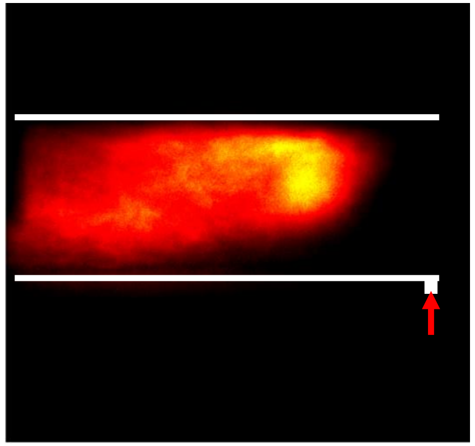
Comparison to Fluent Simulations

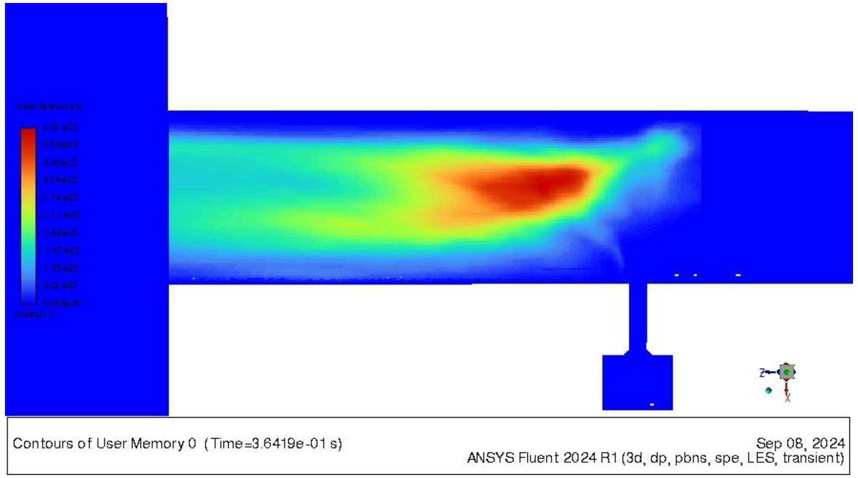
- **CFD results qualitatively similar.**
- **Testing sensitivity to air inflow boundary conditions.**
- **Testing PaSR combustion model.**

Mean Chemiluminescence (line-of-sight integrated)

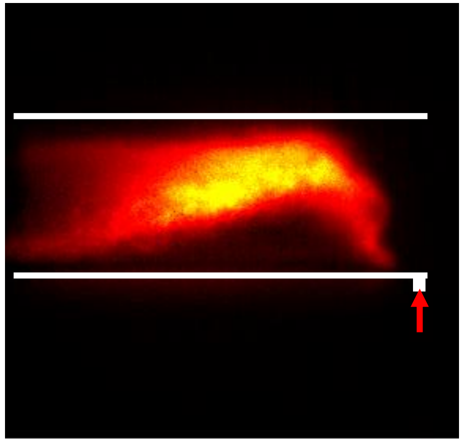


V = 5 m/s , H = 70%, ϕ_{FB} = 0.73



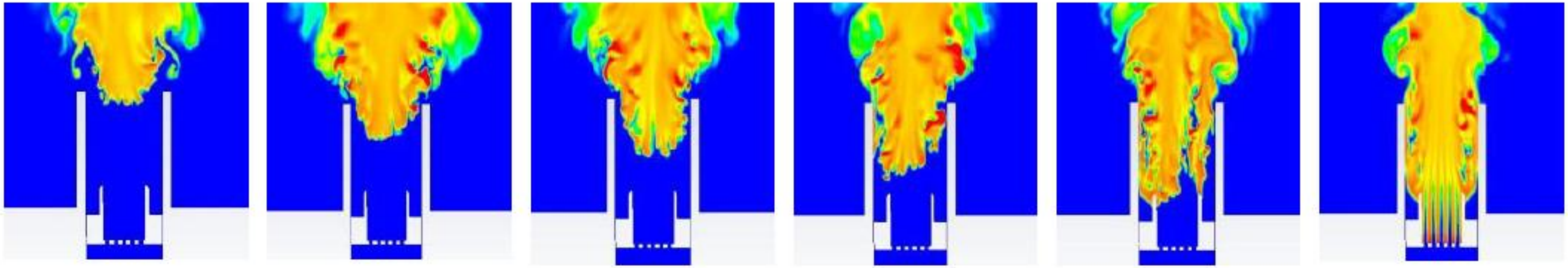


V = 3 m/s, H = 70%, ϕ_{FB} = 0.5



Summary and Ongoing Work

- OH-PLIF fluorescence provides an excellent marker of the lift-off length and can capture transient phenomenon.
- Flashback occurs at high ϕ or X_{H2} when burning occurs in the outer shear layer and the leading flame brush ingresses into the pre-mixer tube.
- Post-flashback flame is anchored on the rim of center-body between the swirling and non-swirling regions with conical flame front.
- Additional work includes CFD model validation at experimental conditions.
- JICF experiments and CFD modeling continuing.



Acknowledgments

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