Flame Flashback Investigations in Hydrogen-Enriched Low Swirl Flames Using High-Speed Hydroxyl (OH) Planar Laser-Induced Fluorescence

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Presentation Outline

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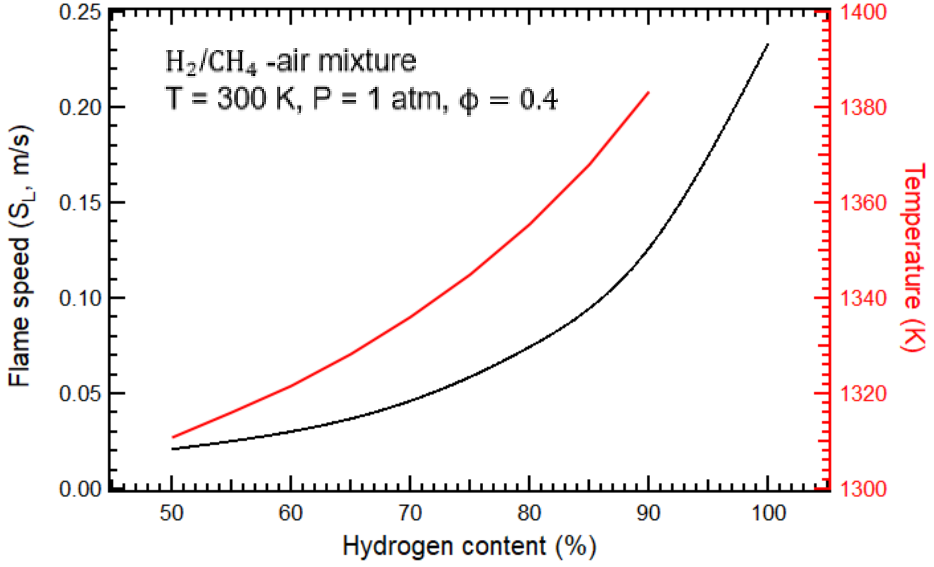
- **Motivational Factors and Background**
  - Issues with next-generation gas turbine systems
  - Hydrogen for energy transition
  - Potential of low swirl flames with hydrogen-enriched systems
- **Experimental Apparatuses**
  - High-repetition rate ns-pulse laser system
  - An optically accessible laboratory-scaled, swirl-stabilized burner
  - High-speed detection system
- **Results and Discussions**
  - Effects of variation of hydrogen content, pre-mixer velocity, and equivalence ratio
  - Characterization of low swirl-stabilized flame
  - Investigation of flame flashback events
- **More Ongoing Works**
  - Jet-in-cross fuel-injectors, computational fluid dynamics (CFD) modeling of optimized hydrogen injectors

Introduction

- Hydrogen – a clean and sustainable energy source, key enabler for energy transition [1]
  - Significantly different combustion characteristics compared to natural gas – higher flame speed and adiabatic temperature
  - Reduce carbon-based products – supporting net zero carbon policy; however, NO_x emissions pose a serious problem
  - Ultra-lean hydrogen combustion has a great NO_x reduction potential
  - Higher flame speed increases the risk of flashback and equipment damage

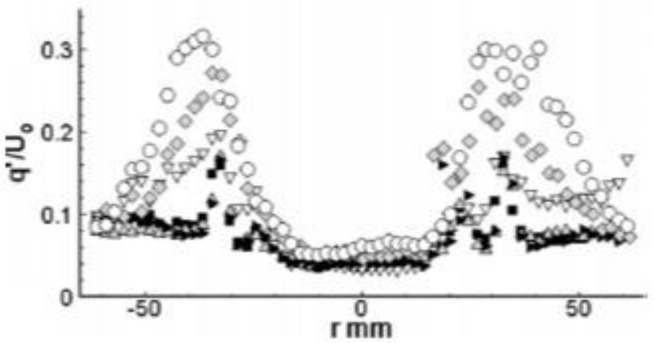


[1] Chapman et al., C&F (1995)

Source: GE Gas Power

Introduction

- Swirl-stabilized flames are well-known methods to stabilize premixed flames
  - Low swirl burners (LSB) have gained increasing attention for fundamental studies [1]
  - Increases flame intensity reducing the flame length
  - LSBs have non-swirling core surrounded by a swirling shroud and produce freely propagating lifted flames minimizing the heat transfer to the nozzle wall
- OH-PLIF diagnostic technique – a well-known laser diagnostic tool to gain insight into the LSB concept and 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]

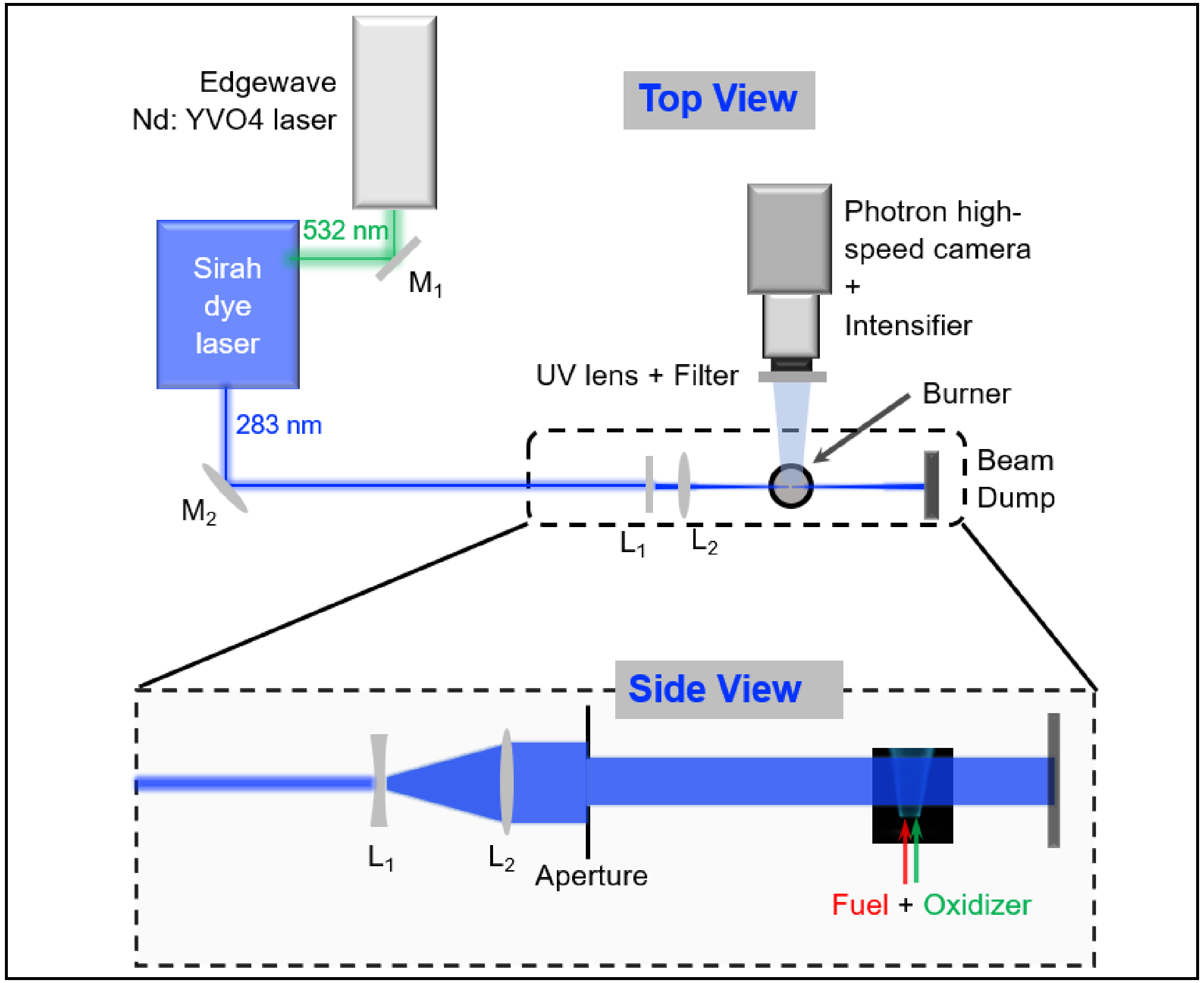
Objective of the current study:

Characterize the combustion chemistry and flashback events observed in a swirl-stabilized, atmospheric-pressure burner in hydrogen-enriched flames

[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 apparatuses**
  - 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)



Experimental Apparatuses – Burner System

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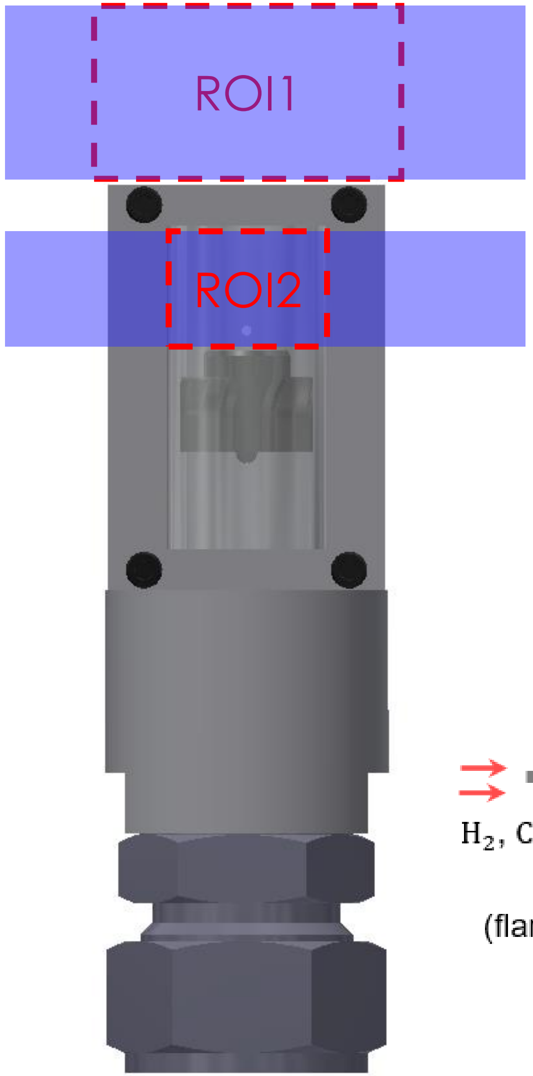
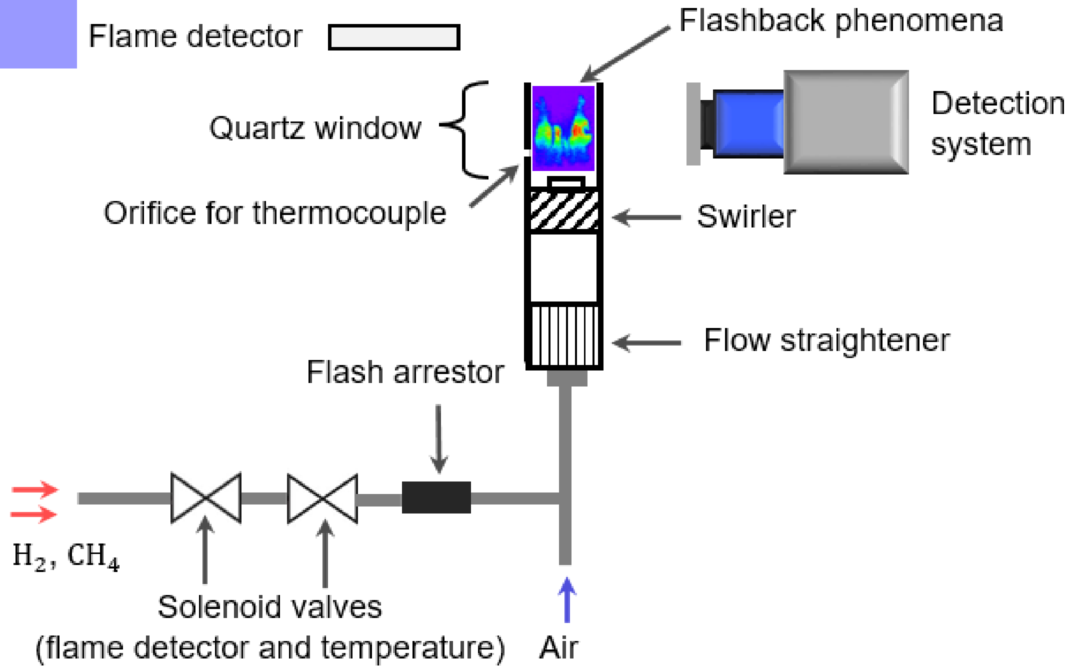
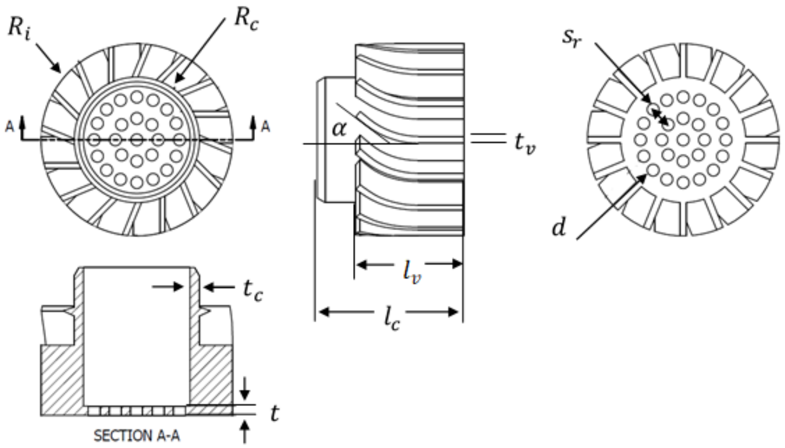


ROI = Region of interest



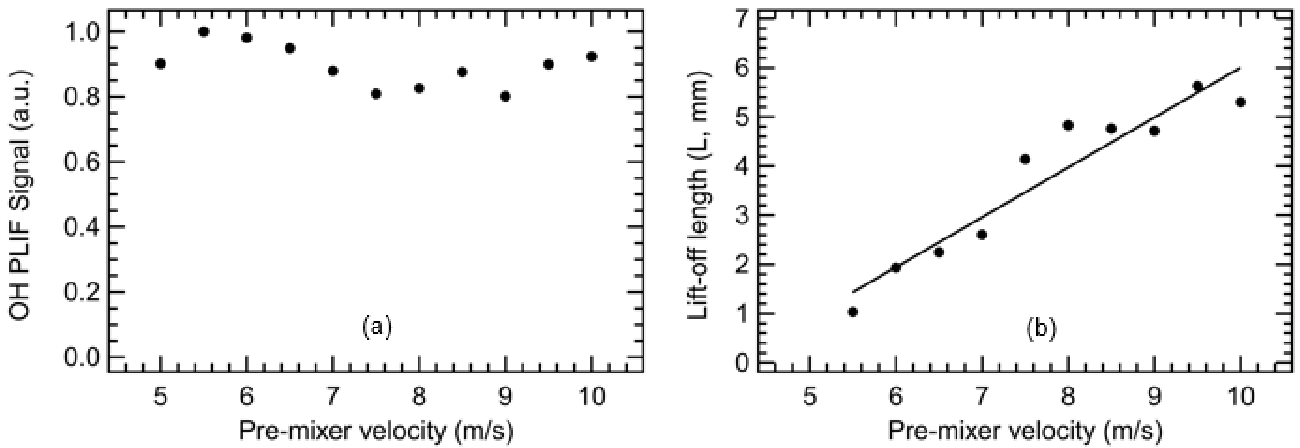
- **Burner configuration**
  - A 21.2-mm ID low swirl burner with optically accessible pre-mixer system
  - Fuel (H_2 and CH_4) with 50%–90% H_2 by mole
  - Thermocouple (inserted in pre-mixer unit) senses the rise in temperature and fuel shuts off
  - The blockage ratio and radius ratio of the swirler used are 0.75 and 0.65, respectively



Results and Discussions

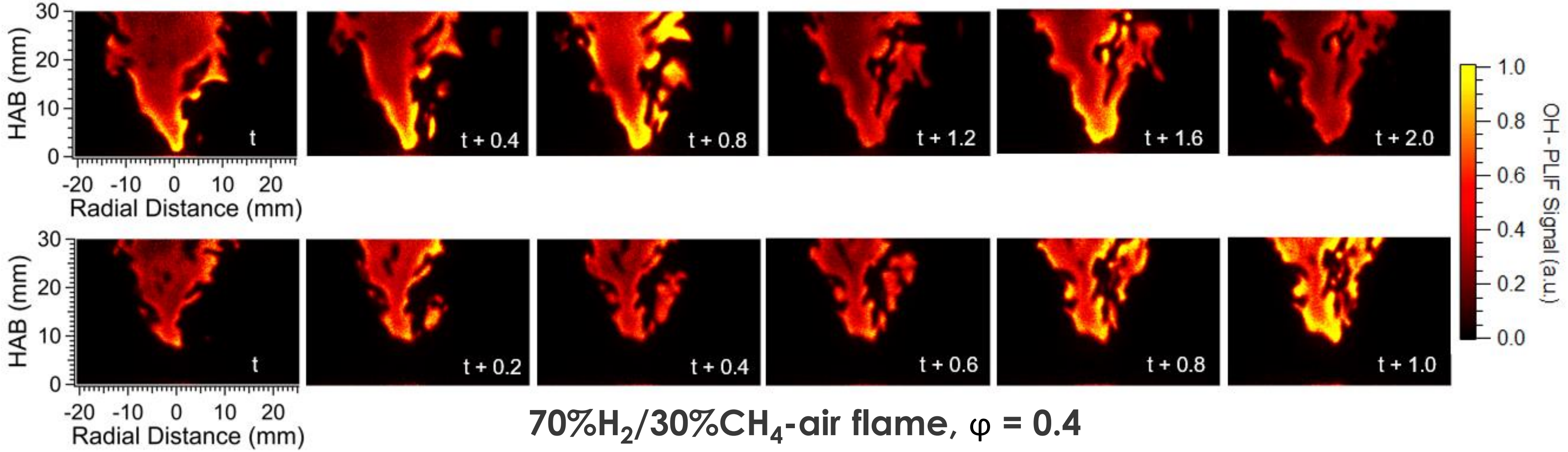
Characterization of Low Swirl Burner Flame

- **Effect of inlet pre-mixer velocity (V)**
  - OH-PLIF shows negligible variation with V
  - Lift-off length (L) tends to increase linearly with V
  - V varied from 5.5 m/s to 10 m/s
  - The local gas velocity is increased compared to flame speed and becomes less flashback prone



V = 5.5 m/s

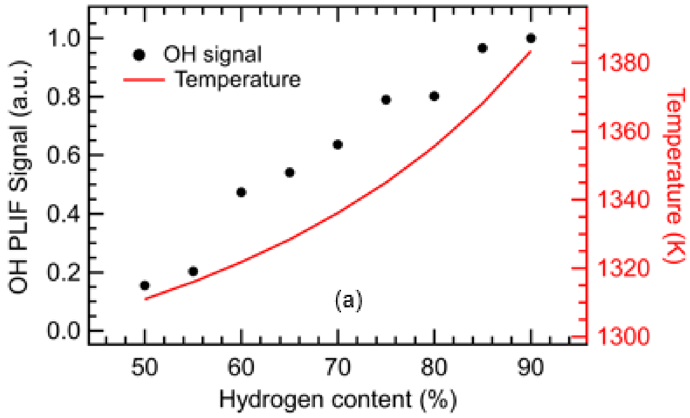
V = 10 m/s

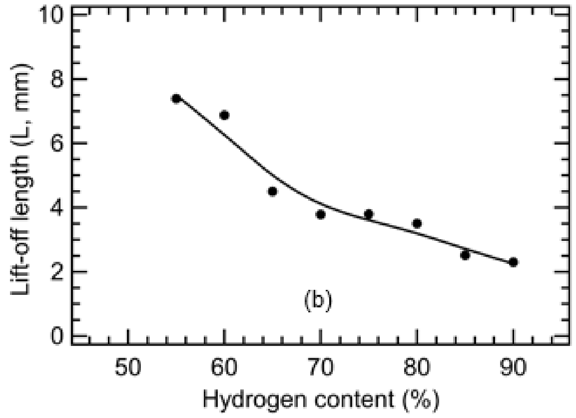


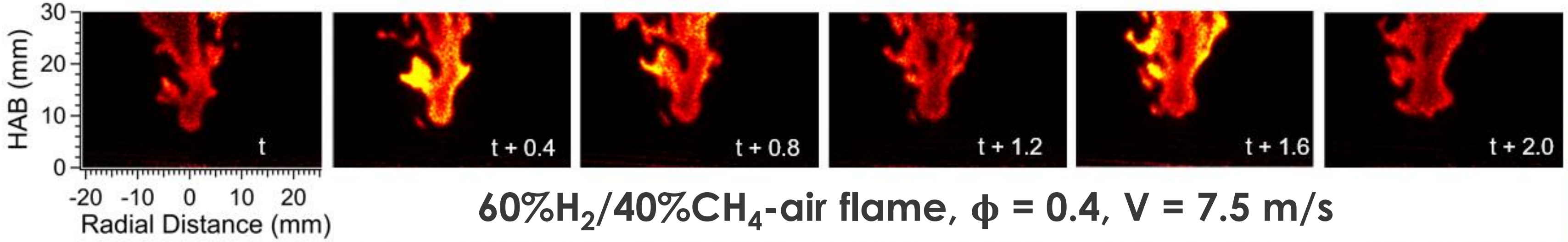
70%H_2/30%CH_4-air flame, φ = 0.4

Effect of Hydrogen Content (x_{H_2})

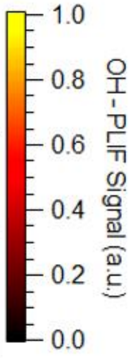
- A higher X_{H_2} increases OH concentration
- Expected rise of flame temperature as hydrogen flame is hotter than methane flame at same φ
- Increasing X_{H_2} tends to decrease lift-off length and increase the chances of flashback – due to a sudden rise in flame speed of hydrogen-enriched flame

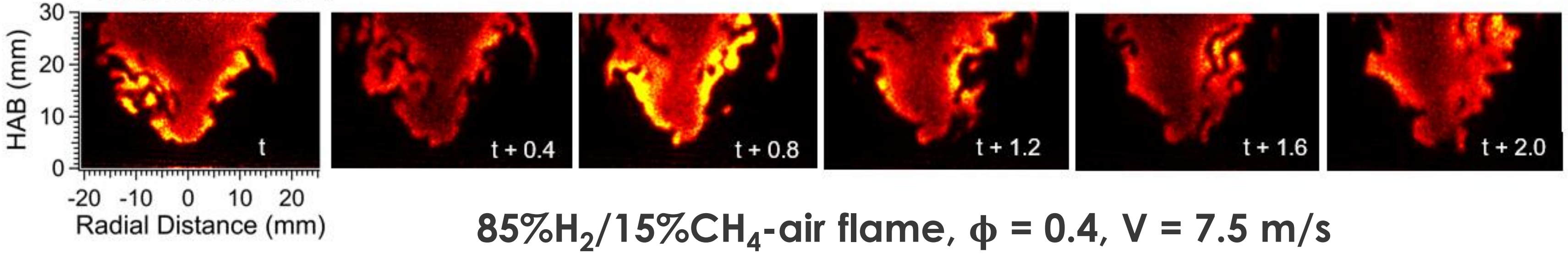




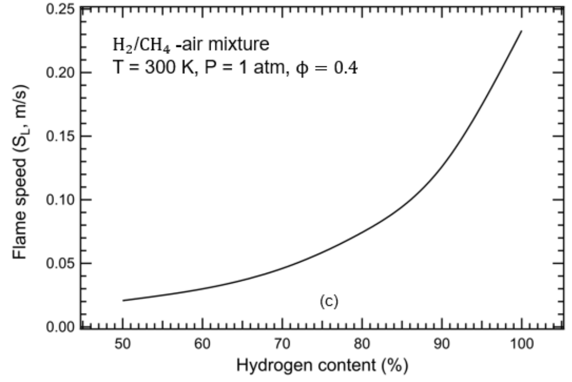


60%H_2/40%CH_4-air flame, ϕ = 0.4, V = 7.5 m/s



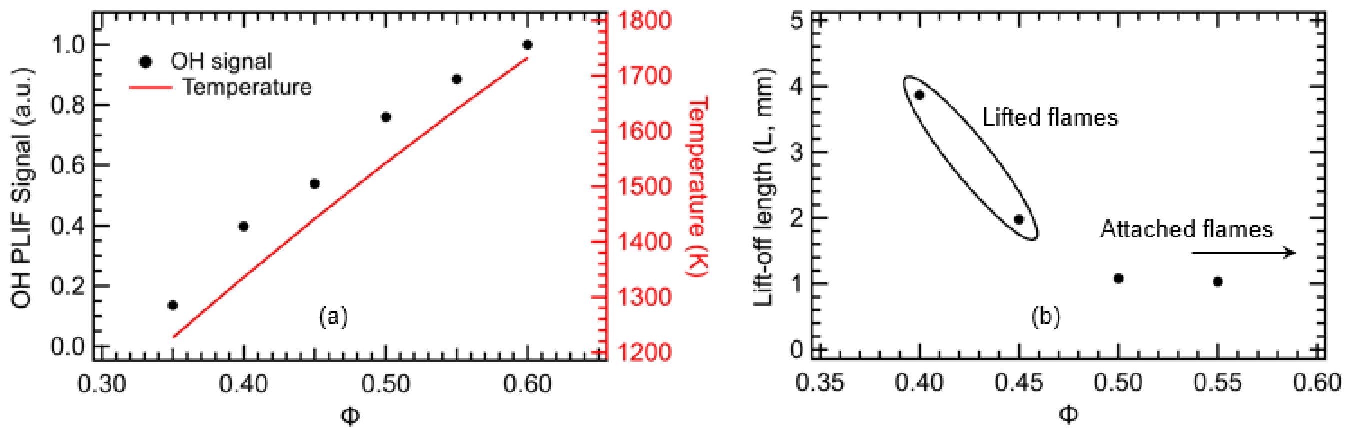


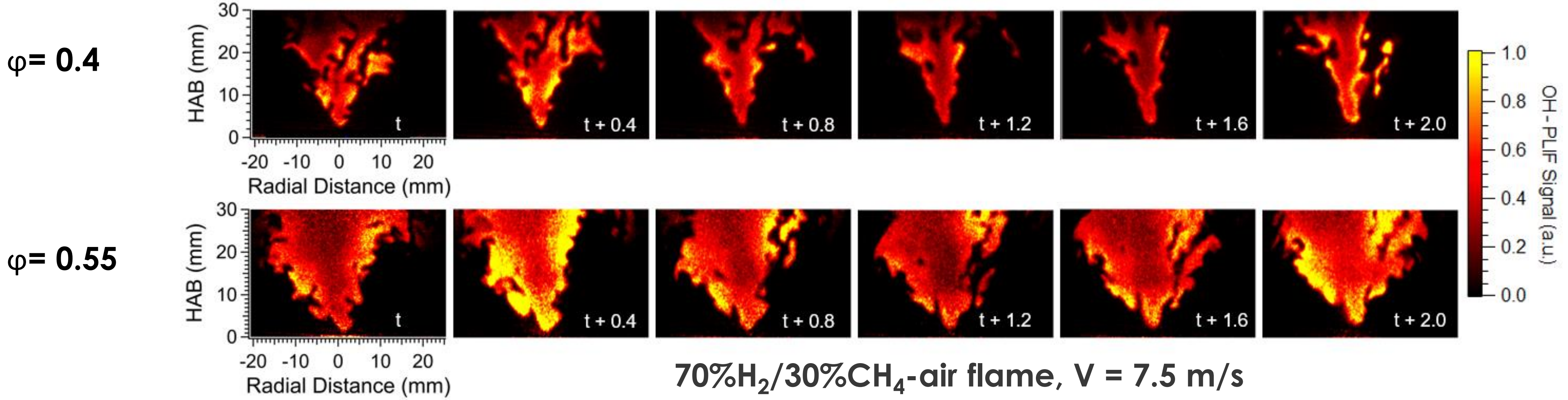
85%H_2/15%CH_4-air flame, ϕ = 0.4, V = 7.5 m/s



Effect of Equivalence Ratio (φ)

- OH-PLIF signal decays as φ is decreased
- Increasing φ decreases L, i.e., it brings the flame closer to the burner surface, increasing the risk of flashback
- Lifted-to-attach flame transition can be observed
- Increasing φ increases flame speed

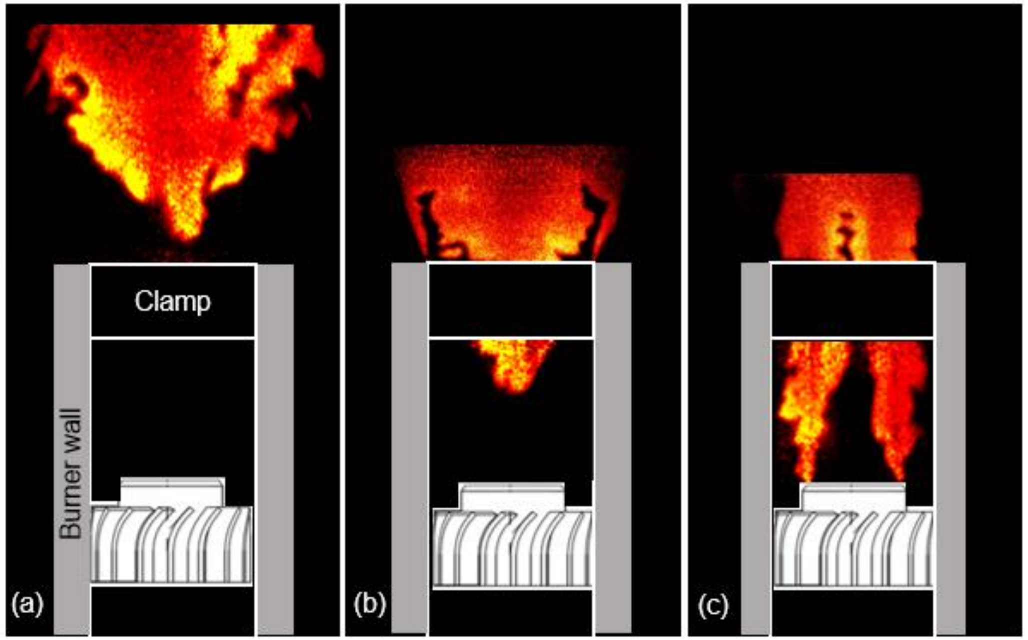




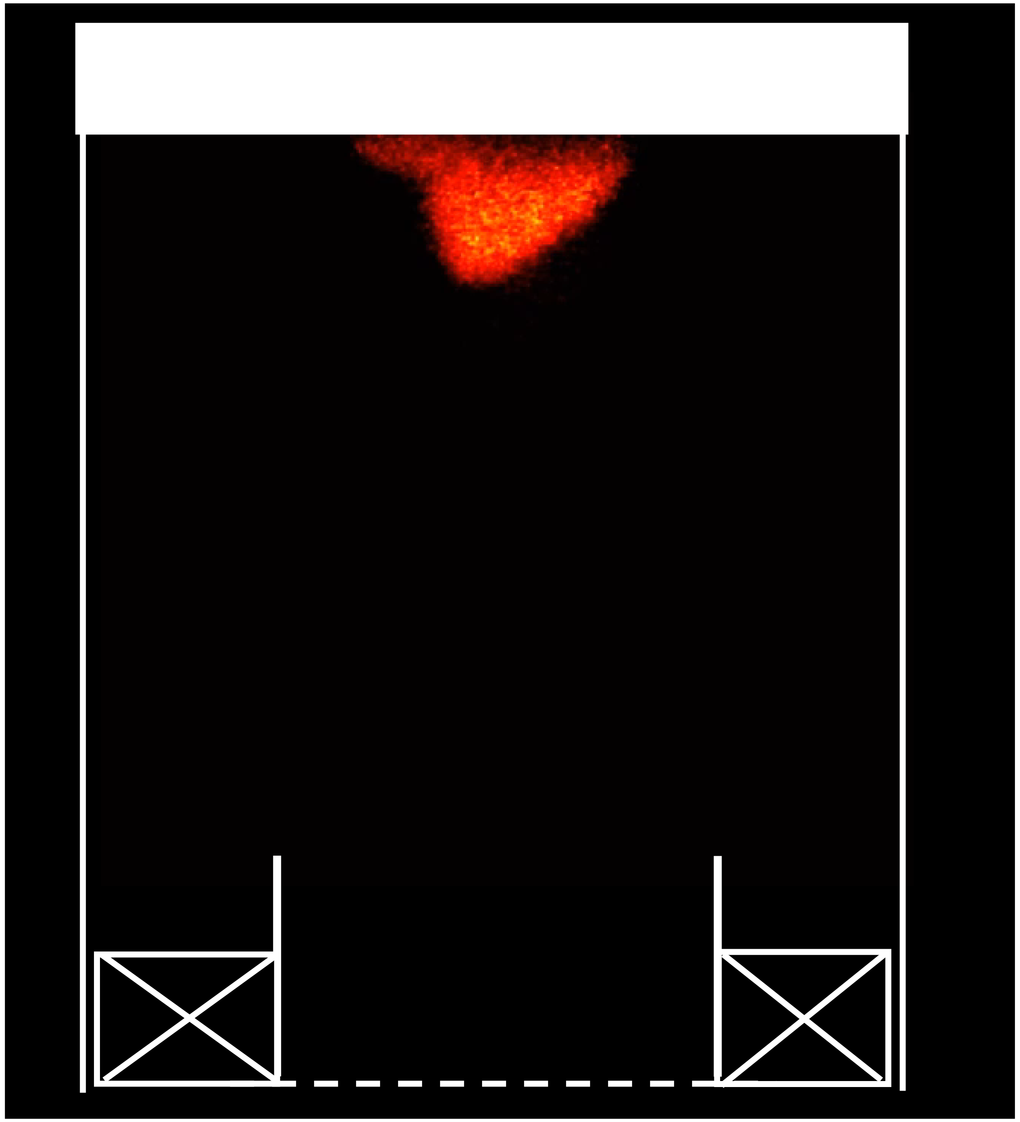
70%H_2/30%CH_4-air flame, V = 7.5 m/s

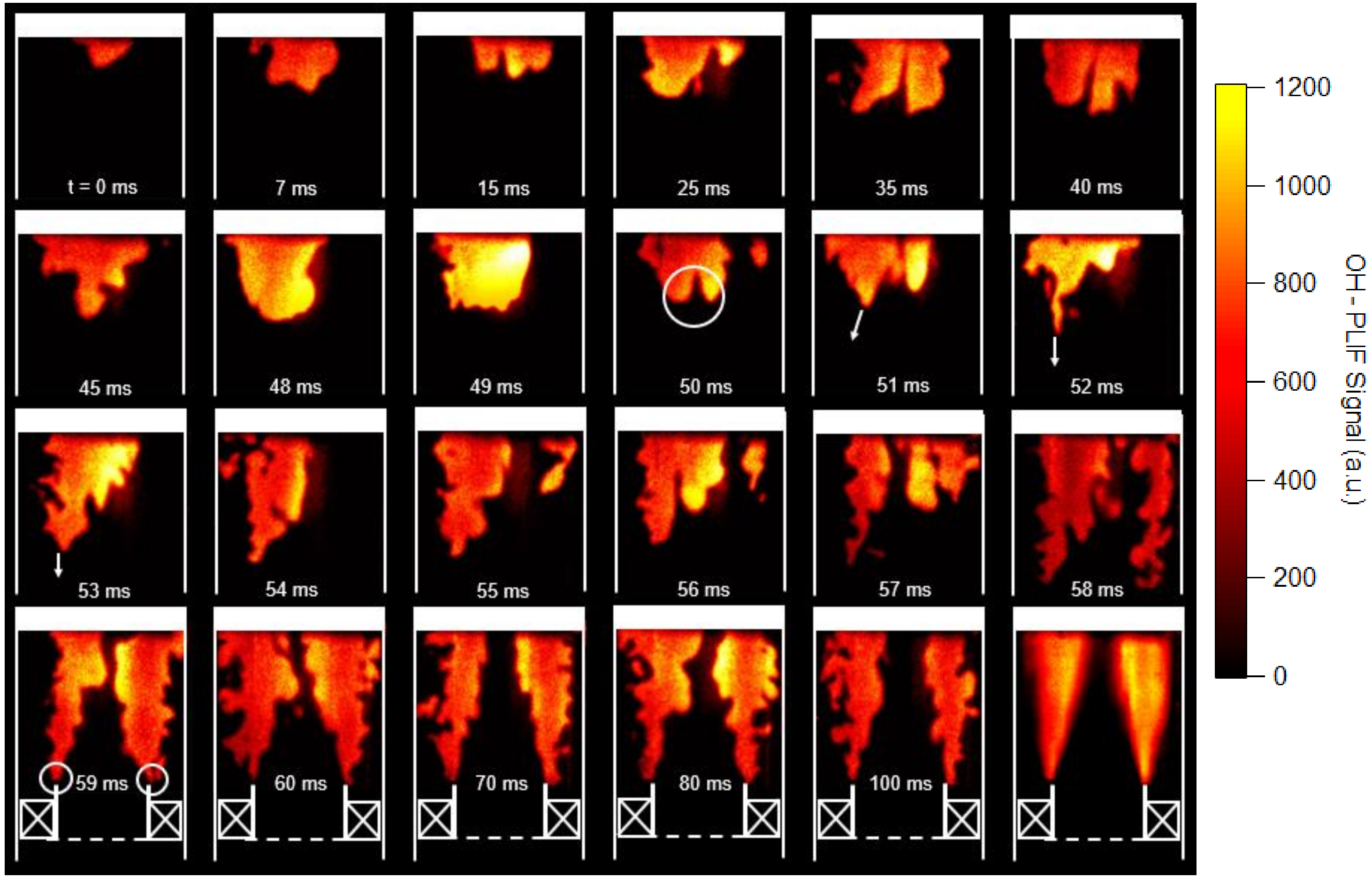
Investigation of Flame Flashback Events

- A series of spatially resolved OH-PLIF images recorded at 1 kHz repetition rate
- The occurrence of flashback-to-flame holding transition within 30–40 ms of the entrance into pre-mixer tube
- The flame structures anchor inside the mixing tube between the swirling and non-swirling regions
- The potential reasons for the sustained flame anchoring could be:
  - Continuous supply of fresh unburnt mixture
  - Reduction in quenching distance due to heated inner wall



Investigation of Flame Flashback Events

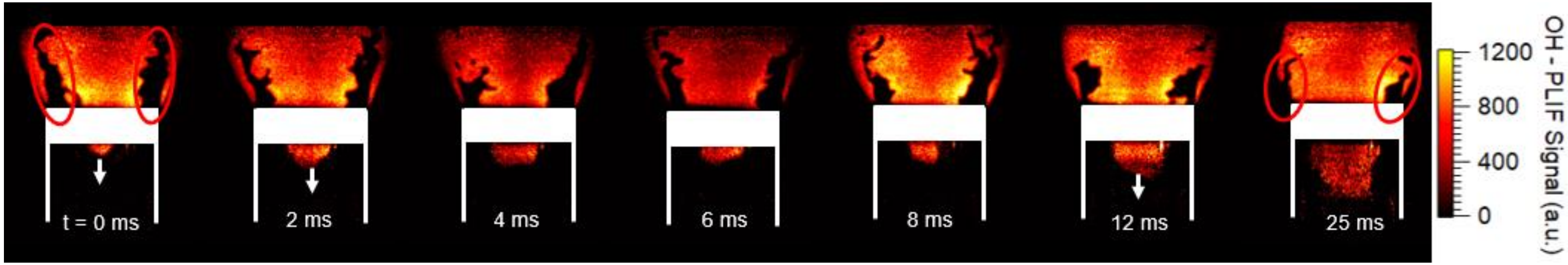




$70\%H_2/30\%CH_4$-air flame, V = 7.5 m/s

Investigation of Flame Flashback Events

- Flashback initiation
  - Burning of outer shear layer pulls the flame upstream into the nozzle
- Flashback propagation
  - Inner shear layer above the center channel wall (between swirled and unswirled flows) facilitating upstream flame propagation inside the nozzle
- Post-flashback flame holding
  - Once a part of flame is attached to the rim, it ignites the incoming fresh mixture (likely along the inner shear layer) forming a conical flame



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

Effects of Fuel Compositions

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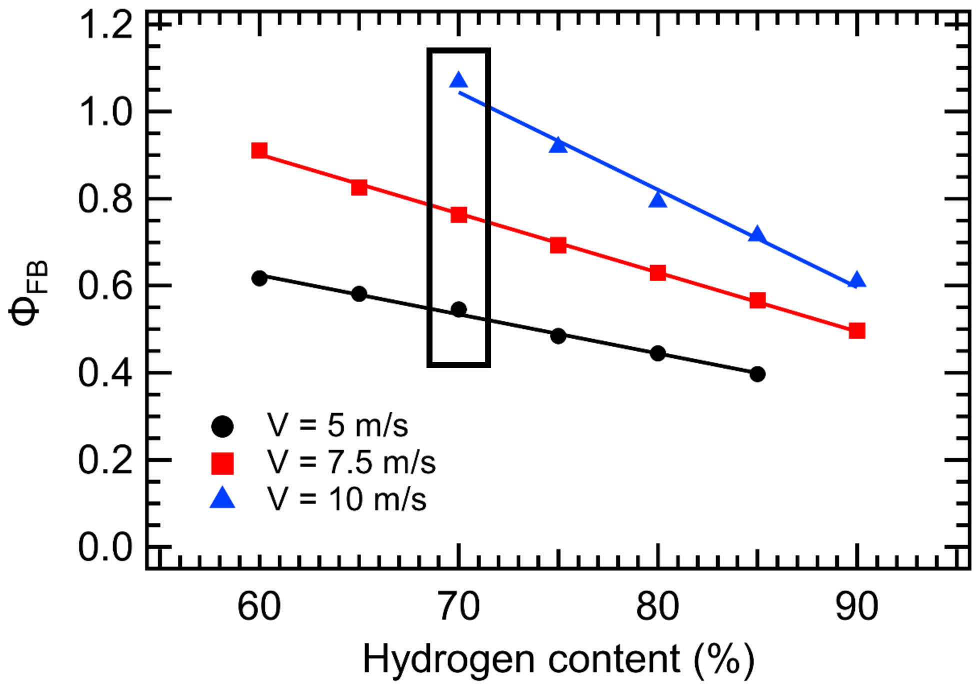
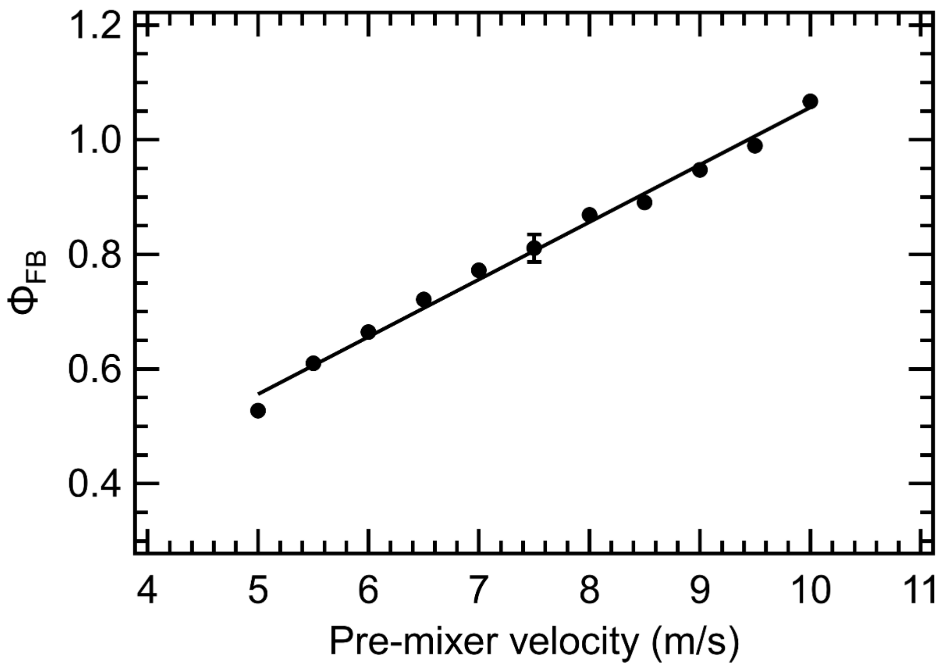
- As X_{H_2} increases, the burner system is more prone to flashback
- φ_{FB} decreases linearly with an increase in X_{H_2} in the reactant mixture





- As V increases, the flashback resistance of the burner system increases
- φ_{FB} increases linearly with an increase in pre-mixer velocity of the reactant mixture
- The error bar represents a 2-sigma standard deviation of φ_{FB} obtained from six different experimental tests

Effects of Varying Geometries

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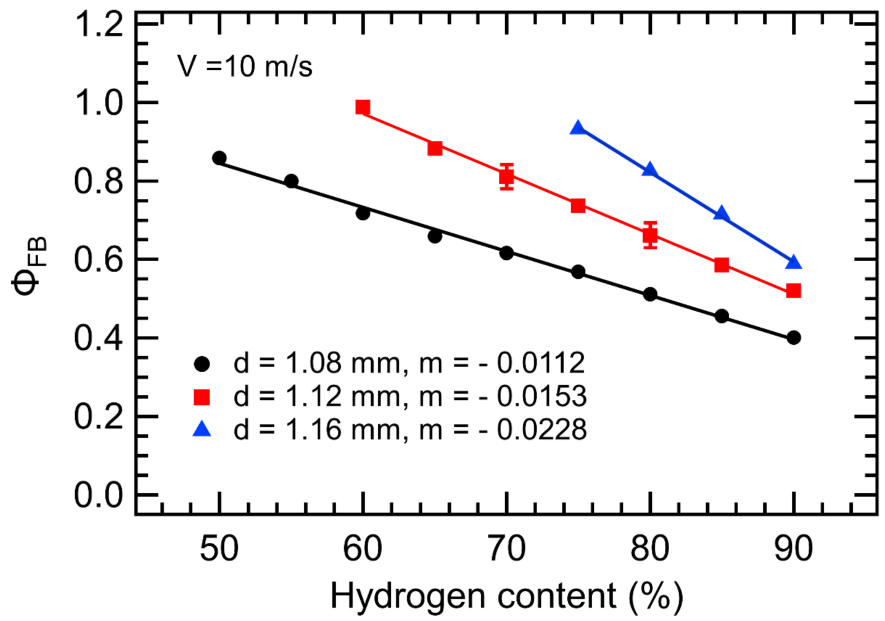
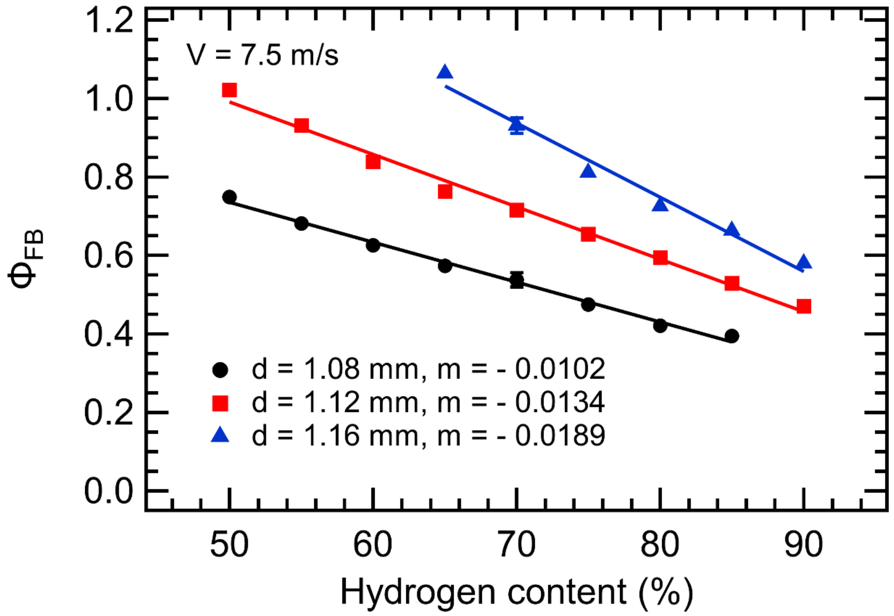
- Dependence of φ_{FB} on X_{H_2} for three different perforated plated hole diameters (d)
- An increase in d decreases the blockage ratio which increases the flow via the center-body and the burner system becomes less flashback prone





- 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 Geometries

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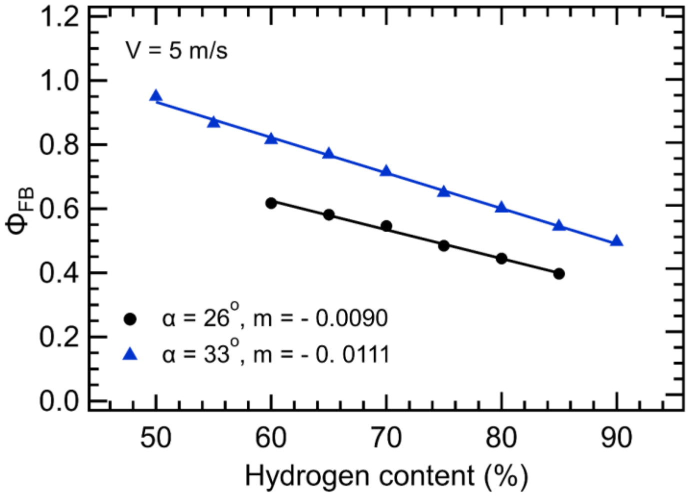
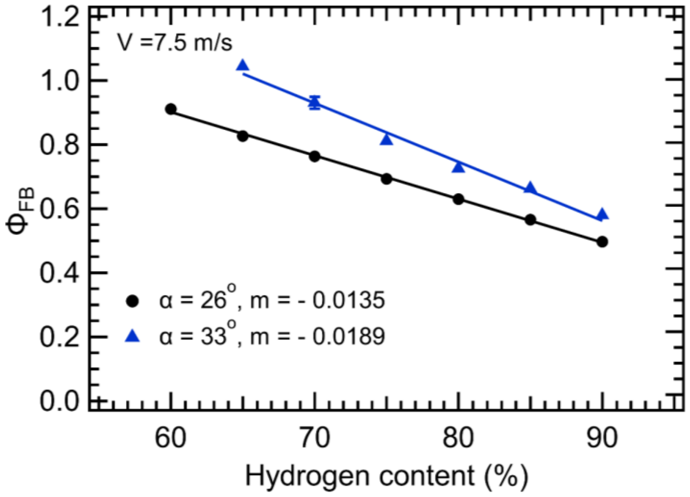
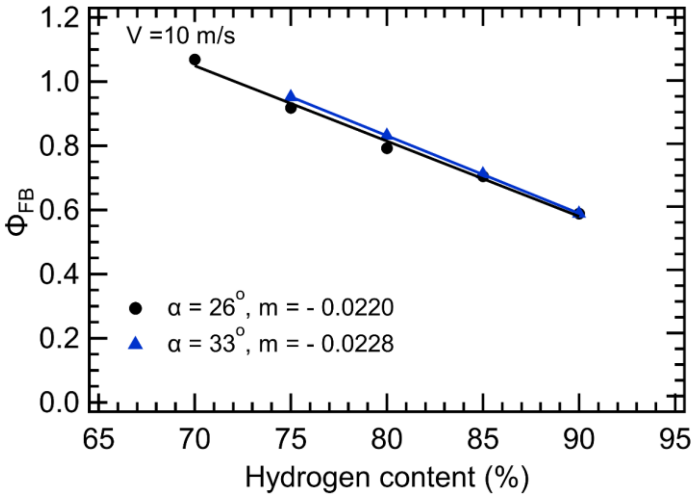
- An increase in *a* increases the flashback resistance of the burner system especially at lower pre-mixer velocities of 5 and 7.5 m/s.
- An increase in d decreases the blockage ratio which increases the flow via the center-body and the burner system becomes less flashback prone.







- As the inlet pre-mixer velocity increases, the cold inlet flow tends to push the flame downstream; however, the larger swirler angle induces strong swirling intensity preventing further flame push to downstream and changes the characteristics of recirculation zone and flame structure.

Summary and Ongoing Work

- Characterization of stabilized flame dynamics and flashback phenomena in a premixed low swirl burner configuration was performed.
- Effect of flame φ, hydrogen content and pre-mixer velocities on OH-PLIF signal and flame lift-off length was investigated.
- OH-PLIF fluorescence signal provides an excellent marker of the lift-off length.
- Flashback φ showed linearly increasing trend with increasing pre-mixer velocities and decreasing hydrogen content supporting the claim made during detailed lift-off length investigation.
- The flashback-to-flame holding transition was observed between the swirling and non-swirling regions with distorted conical flame front.
- Additional work will include testing for jet-in-cross fuel injector configuration, and injector design optimization via computational modeling.

Acknowledgments

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