Sub Topic: Diagnostics

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Flame Flashback Investigations in Hydrogen-Enriched Low Swirl Burner using High-Speed Hydroxyl Planar Laser-Induced Fluorescence

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1. Introduction

Hydrogen and hydrogen-enriched fuels are considered a clean and sustainable energy source and are the key enabler of the energy transition to replace conventional fuels for the development of next-generation gas turbine engines [1-4]. The use of hydrogen-enriched fuels can significantly reduce the production of carbon-based products in the power generation industry. However, high-hydrogen flames are particularly susceptible to flashback which is one of the key issues in retrofitting natural gas turbine combustors. Flashback events occur when the flame front propagates upstream from the combustor into the premix section. Such events can cause the catastrophic failure of the combustor as the pre-mixing tubes are not designed to handle a high heat load. The propensity of flashback increases with the increase in hydrogen content of the reactant mixture due to faster kinetics and smaller quenching lengths of hydrogen-rich flames [5].

The successful design of next-generation gas turbine engine combustors requires a better fundamental understanding of flashback events. Currently, most gas turbine combustors include a swirling flow for flame stabilization and mixing process which requires a detailed study of flashback events. Swirl-stabilized flame methods are essential to lean-premixed combustion systems because of their significant benefits like increase in flame intensity, stability, as well as the combustor performance [6]. Low swirl burners (LSB) have gained increasing attention since they were originally developed by Cheng [7] for fundamental studies. LSB have a non-swirling core surrounded by a swirling shroud and utilize a flow divergence concept allowing the flame to freely propagate and stabilize at a position where the local flow velocity is equal and opposite to the flame speed [8]. Flashback becomes likely to occur if bulk flow velocity is reduced further as the velocity at the burner exit is close to the flame speed. Avoidance of such flashback events is critical to the design of hydrogen-safe gas turbine combustors; however, the lack of relevant fundamental knowledge of flashback modes in LSB and their underlying mechanism remains the major obstacle.

In this study, the flashback mechanism in low swirling flames is investigated in an optically accessible LSB via the visualization of spatiotemporally resolved hydroxyl (OH) radicals using

Planar Laser-Induced Fluorescence (PLIF). This study characterizes the swirl-stabilized flame and underlying flashback phenomena in a low swirl atmospheric pressure burner at the National Energy Technology Laboratory (NETL) and is an extension of previous work [9]. In the next section, a brief description of the optically accessible LSB, high-speed pulsed laser, and detection system are presented. Section 4 presents a series of single-laser-shot OH-PLIF images recorded while LSB is operated in a stable flame configuration and under flashback conditions. The detailed investigation of different inlet mixture parameters on lift-off length (L, defined as the distance from the burner rim to the base of the lifted flame) and flashback are studied and outlined.

2. Experimental Apparatuses – Laser and Burner System

The experimental setup for flashback measurements includes: (i) an optically accessible laboratory-scaled low-swirl burner, (ii) a high-repetition-rate ns-pulsed laser system, and (iii) a high-speed detection system. The details of the burner design, construction, and operation are explained elsewhere [10]. Briefly, it consists of H_2/CH_4/air mixtures fed into an optically accessible pre-mixer tube with swirler attached to it to create recirculation zones. Figure 1 depicts the optically accessible pre-mixer system along with design of the swirler used in this study. The swirler angle, α, and center-body hole diameter, d, of the swirler used are 26° and 1.16 mm, respectively. A thermocouple is inserted into the pre-mixing section of the burner via a tiny port just above the swirler to detect the flashback when it occurs. The laser system consists of a ns-duration Nd:YVO4 laser (Edgewave Innoslab, Model: IS400-2-L) emitting a 532 nm laser beam which pumps a frequency-tunable dye laser (Sirah, Model: CREDO-DYE-N). The dye laser generates ultraviolet radiation near 284 nm and is guided into the pre-mixer section of the LSB using a 45° mirror. A combination of a UV-coated fused silica cylindrical lens and a 750 mm focal length spherical lens is placed before the burner to generate a beam sheet ~ 30 mm tall. The OH-PLIF measurement of the flashback phenomena is collected using a high-speed intensifier (Invisible Vision, Model: UVi 1850- 10 S25) coupled to a high-speed CMOS camera (Photron, Model: FASTCAM SA-Z). A UV lens (Cerco, Objectif UV, f/1.8) was mounted to the intensifier and was used to focus the intensifier on the laser beam sheet. A set of Schott UG11 bandpass filters and laser line filters is placed in front of the UV lens to collect strong OH fluorescence emissions near 309 nm and block unwanted chemiluminescence interference and laser scattering.

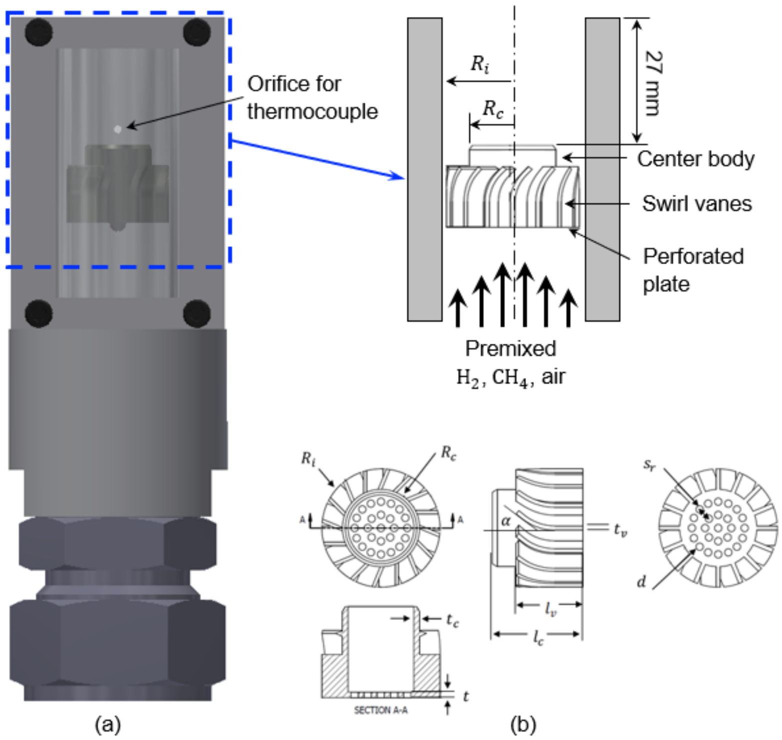

Figure 1: Design of (a) an optically accessible pre-mixer system (b) a swirler used in the present study.

3. Results and Discussion

The LSB was operated in two different configurations—stable flame configuration and under flashback mode, and ns OH-PLIF measurements were performed at 20 kHz and 1 kHz repetition rate, respectively. During the experiment, the initial temperature and pressure of the gaseous mixture were set at 300 K and 1 atm, respectively. The laser wavelength was tuned to 283.9 nm and the laser beam energy was held constant at ~ 0.05 mJ/pulse to avoid the saturation effects. The intensifier gate and gain were set at 100 ns and 45%, respectively.

3.1 Low Swirl Stabilized Flame Characterization

To investigate the hydrogen-enriched flame dynamics, the OH-PLIF signal was recorded as a function of flame equivalence ratio (ϕ), hydrogen content (X_{H_2}), and inlet pre-mixer velocities (V). In the stable flame configuration, several single-shot OH-PLIF images were acquired and 500 such individual frames were averaged together, and lift-off length was calculated during post-processing. An increase in lift-off length with increasing inlet velocities, decreasing X_{H_2}, and decreasing ϕ was observed and is displayed in Figure 2. Higher inlet velocities as compared to the flame speed push the combustion zone further downstream and the risk of flashback is minimized. Another significant observation is that an increase in flame width at high X_{H_2} or ϕ is strongly affected by the burning of the outer recirculation zone which pulls the flame close to the burner exit where the turbulent intensities are higher. This process increases the flashback propensity of the flame.

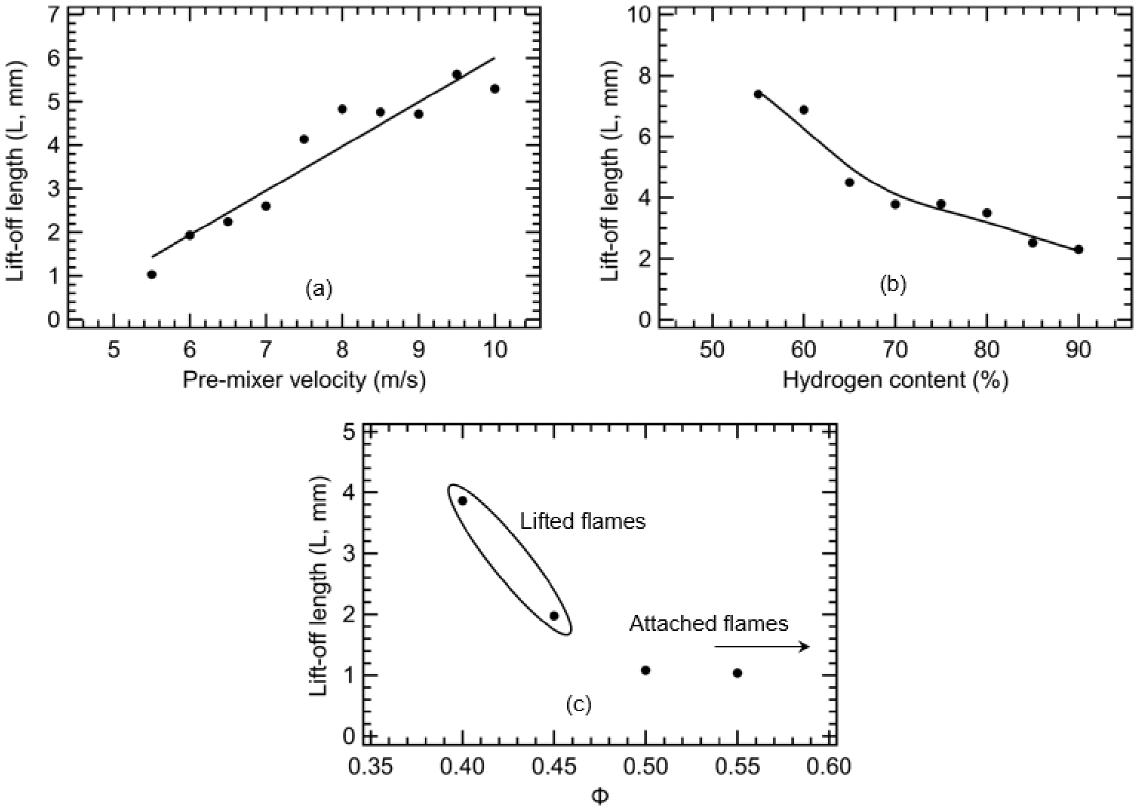

Figure 2: Variation of lift-off length (L) as a function of (a) pre-mixer velocity, (b) hydrogen content of the reactant mixture, and (c) flame equivalence ratio.

3.2 Flame Flashback Investigations

Figure 3a shows the dependence of flashback ϕ (ϕ_{FB}) on the proportion of X_{H_2} in reactant mixtures for three different V (5, 7.5, and 10 m/s). It is observed that ϕ_{FB} decreases linearly with an increase in X_{H_2} in the reactant mixture at a constant V. As X_{H_2} increases, the overall flame speed of the reactant mixture increases compared to the local gas velocity [11-13], and the flame flashback is more likely to occur. This statement is further supported by the decrease in lift-off length at higher X_{H_2}, displayed in Fig. 2b. At higher V, the flashback resistance of the burner system increases as the local fuel velocity grows larger relative to the flame speed of the mixture. This dependence of ϕ_{FB} on V at constant X_{H_2} was found to be linear as indicated in Fig. 3b. The error bar for the V of 7.5 m/s for 70%H_2/30%CH_4-air flame represents a 2-sigma standard deviation of ϕ_{FB} obtained from six different experimental tests.

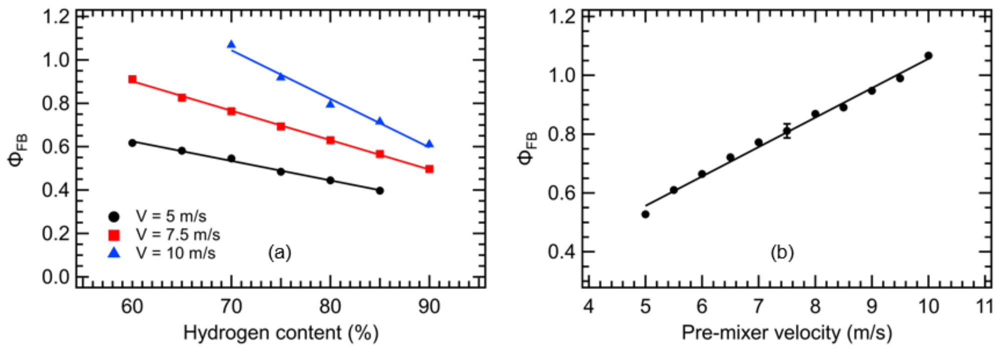

Figure 3: Dependence of ϕ_{FB} upon (a) X_{H_2} for three different Vs (5, 7.5, and 10 m/s), and (b) V for 70%H_2/30%CH_4-air flame at reactants temperature 300 K and pressure 1 atm.

A series of spatially resolved representative OH-PLIF images recorded for a 90%H_2/10%CH_4-air flame is illustrated in Fig. 4. The focus is on the flame-flow interaction inside the pre-mixing section as the flame propagates upstream. The horizontal axis represents the radial distance in "mm" with zero indicating the axis of the burner tube. Similarly, the vertical axis represents the depth below the burner rim in "mm." The location of the swirler is shown in the bottom row images for better visualization of the location of flashback events. These images were recorded by keeping the V constant at 7.5 m/s and slowly increasing ϕ until the occurrence of flashback (whenever applicable). The $\frac{d\phi}{dt}$ defined by the change in ϕ with respect to time, t was set at 0.001, i.e., for each 1-s time interval, ϕ was increased by 0.001 and was dictated via the mass flow controllers. As ϕ is increased the flame speed increases compared to the local gas velocity and the flame becomes more susceptible to flashback. Once ϕ_{FB} is reached, the flame propagates further upstream into the pre-mixer tube until it reaches flame stabilization mode. The spatiotemporally resolved OH-PLIF images revealed the occurrence of flashback-to-flame holding transition within 30–40 ms of the entrance for all the fuel combinations tested during this study. At first, the flame tongue starts interacting with flammable mixtures in the pre-mixing tube. The flame structures interact strongly with the fresh unburnt flow around it and appear to rapidly grow in size within a few milliseconds.

As the propagating flame structures reach closer to the swirler they bifurcate into two leading tips (from a 2D perspective). After a certain duration, these structures anchor inside the mixing tube, likely on the back of the perforated plate and continue fluctuating from frame to frame between the swirling and non-swirling regions of the LSB once anchored. Potential explanations for the sustained flame anchoring in the mixing tube could be: the continuous presence of fresh unburnt mixture inside the tube, heating of the inner wall of the mixing tube, and the center body reducing quenching distance and wakes behind the perforated plate. The two V-shaped flame structures formed by the central non-swirling core surrounded by a swirling shroud are merged in the downstream flow during the flame anchoring process forming a distorted conical flame front. The flame front is characterized by wrinkles, especially in the top part and fluctuates from frame to frame as shown in Fig. 4. It further illustrates that the height of the flame front decreases as X_{H_2} increases in the reactant mixture. Chen et al. [14] observed a similar effect of X_{H_2} on flame front height while investigating hydrogen-fueled reactant mixtures but the study was conducted in a stable, laminar premixed liquefied petroleum gas-hydrogen flame. This shorter flame front for increasing X_{H_2} is associated with the increase in the flame speed of the reactant mixture due to high X_{H_2}. As mentioned earlier, a thermocouple inserted into the pre-mixing section above the swirler senses the rise in temperature due to anchored flame and the incoming fuel is shut off. Approximately 300–500 ms of such flashback events and flame-holding transitions within the tube were captured before it was extinguished.

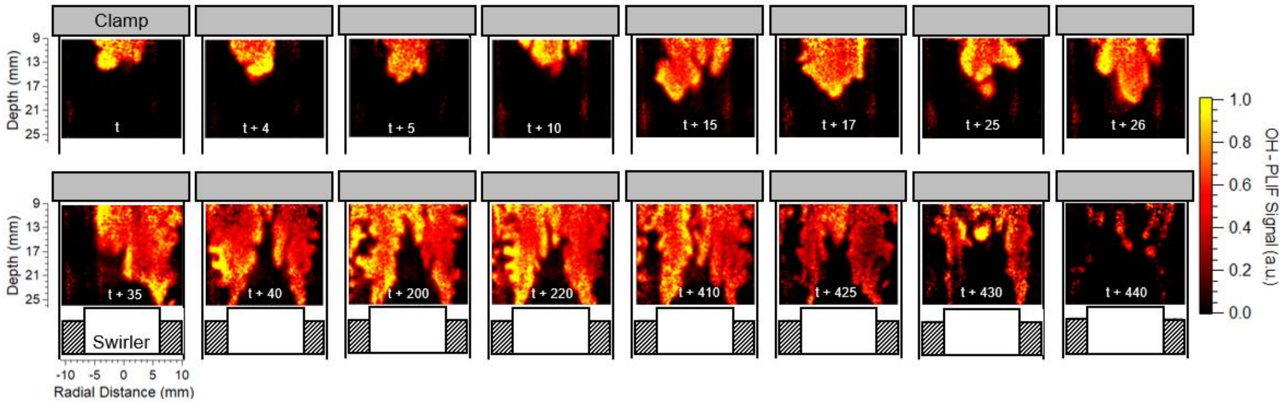

Figure 4: Sequence of single-shot OH-PLIF images showing temporal evolution of flashback events inside the pre-mixer tube for 90%H_2/10%CH_4-air flame at V = 7.5 m/s. The time stamp for the occurrence of each event is shown on the bottom right corner of each frame in ms.

4. Conclusions

In this study, a ns-pulsed OH-PLIF diagnostic technique was applied to visualize stabilized flame dynamics and flashback phenomena in a premixed LSB configuration at atmospheric conditions. The inlet fuel-air mixtures were varied systematically with respect to ϕ, X_{H_2} in a hydrogen-methane mixture, and V and the experiments were performed on a burner modified to provide optical access to the pre-mixing section. The burner was operated in a stable flame configuration and detailed investigations on the effects of different parameters on flame lift-off length were performed. The lift-off length measurement via averaged OH-PLIF images recorded at the 20 kHz repetition rate showed dependence on each of these parameters and hence OH fluorescence emission near 309 nm provides an excellent marker of the lift-off length. Flashback ϕ showed an expected linearly increasing trend with increasing V and decreasing X_{H_2}, and the conclusions agreed well with the detailed lift-off length investigation performed in the stable flame configuration. The burner was also operated in flashback mode and the OH-PLIF images were recorded at a 1 kHz repetition rate showing the flame-flow interaction in the pre-mixing region. The propagating flame anchored likely on the back side of the perforated plate within 30–40 ms of the entrance forming the distorted conical flame front. Such flame flashback events and other flame characteristics like flame breakages, growth, and flame curvature as well as the main reaction zone of the combustion region were well characterized. Spatially and temporally resolved kHz-rate OH-PLIF is a promising technique to observe rapidly occurring flashback events and it can be applied to validate turbulence-chemistry interaction models of swirling flames. The fundamentals of flashback and a detailed picture of flashback and flame holding of hydrogen-enriched low-swirl flames were presented in this study. The insights gained by these studies can be augmented by computational fluid dynamics simulations or simultaneous velocimetry and PLIF diagnostics which are the subject of future study.

5. Acknowledgements

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6. Disclaimer

7. References

[1] A. Chapman, K. Itaoka, H. Farabi-Asl, Y. Fujii, M. Nakahara, Societal penetration of hydrogen into the future energy system: Impacts of policy, technology and carbon targets, International Journal of Hydrogen Energy 45 (2020) 3883-3898. doi: https://doi.org/10.1016/j.ijhydene.2019.12.112.

[2] D. Cecere, E. Giacomazzi, A. Ingenito, A review on hydrogen industrial aerospace applications, International Journal of Hydrogen Energy 39 (2014) 10731-10747. doi: https://doi.org/10.1016/j.ijhydene.2014.04.126.

[3] M. Ball, M. Wietschel, The future of hydrogen – opportunities and challenges, International Journal of Hydrogen Energy 34 (2009) 615-627. doi: https://doi.org/10.1016/j.ijhydene.2008.11.014.

[4] J. Krishnan Unni, P. Govindappa, L.M. Das, Development of hydrogen fuelled transport engine and field tests on vehicles, International Journal of Hydrogen Energy 42 (2017) 643-651. doi: https://doi.org/10.1016/j.ijhydene.2016.09.107.

[5] S. Verhelst, T. Wallner, Hydrogen-fueled internal combustion engines, Progress in Energy and Combustion Science 35 (2009) 490-527. doi: https://doi.org/10.1016/j.pecs.2009.08.001.

[6] Y. Xiao, Z. Cao, C. Wang, Flame stability limits of premixed low-swirl combustion, Advances in Mechanical Engineering 10 (2018) 1687814018790878. doi: https://doi.org/10.1177/1687814018790878.

[7] R.K. Cheng, Velocity and scalar characteristics of premixed turbulent flames stabilized by weak swirl, Combustion and Flame 101 (1995) 1-14. doi: https://doi.org/10.1016/0010-2180(94)00196-Y.

[8] R.K. Cheng, Low Swirl Combustion. The Gas Turbine Handbook, R. Dennis, U.S. Department of Energy, National Energy Technology Laboratory, 2006.

[9] M. Searle, P. Strakey, Flashback of Hydrogen-Methane Mistures in a Fixed-vane, Low-swirl Burner at Atmospheric Pressure, Proceedings of ASME Turbo Expo 2023, Boston, Massachusetts, June 26-30, 2023.

[10] P. Parajuli, P. Strakey, Flashback Studies of High-Hydrogen Flames using High-Speed OH Planar Laser-Induced Fluorescence, AIAA SCITECH 2024 Forum, Orlando, FL, 2024. doi: https://doi.org/10.2514/6.2024-0394.

[11] M. Ilbas, A.P. Crayford, İ. Yılmaz, P.J. Bowen, N. Syred, Laminar-burning velocities of hydrogen–air and hydrogen–methane–air mixtures: An experimental study, International Journal of Hydrogen Energy 31 (2006) 1768-1779. doi: https://doi.org/10.1016/j.ijhydene.2005.12.007.

[12] The path towards a zero-carbon gas turbine. Hydrogen Gas Turbines, European Turbine Network (ETN) Global, Brussels, Belgium, 2020.
[13] J. Goldmeer, Fuel flexible gas turbines as enablers for a low or reduced carbon energy ecosystem, Electrify Europe: Vienna, Austria (2018).
[14] H.S. Zhen, C.S. Cheung, C.W. Leung, Y.S. Choy, Effects of hydrogen concentration on the emission and heat transfer of a premixed LPG-hydrogen flame, International Journal of Hydrogen Energy 37 (2012) 6097-6105. doi: https://doi.org/10.1016/j.ijhydene.2011.12.130.