Experimental Investigation of Flame Stability of Swirl-Stabilized, Lean Premixed Hydrogen Flames

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Abstract

Since lean premixed combustion allows for fuel-efficiency and low emissions, it is nowadays state of the art in stationary gas turbines. In the long term, it is also a promising approach for aero engines, when safety issues like lean blowout (LBO) and flame flashback in the premixer can be overcome. While for the use of hydrogen the LBO limits are extended, the flashback propensity is increased. Thus, axial air injection is applied in order to eliminate flashback in a swirl-stabilized combustor burning premixed hydrogen. Axial injection constitutes a non-swirling jet on the central axis of the radial swirl generator which was shown to positively influence the flashback limit. The flame structure is measured using high-speed OH* chemiluminescence imaging. Simultaneous high-speed PIV measurements of the reacting flow provide insight in the time-resolved reacting flow field and indicate the flame location by evaluating the Mie scattering of the raw PIV images by the means of the Qualitative Light Sheet (QLS) technique.
For a high amount of axial air injection, the flame is proven to remain anchored in the combustion chamber under all operating conditions. While detached from the rim, the lift off height of the flame is noted to slightly increase with equivalence ratio, which is explained with the additional fuel momentum.

Introduction

Future demands on air transport systems dictate that aircraft should be less polluting, less noisy and more fuel efficient. In the long term, alternative fuels like bio fuels and hydrogen are likely to replace traditional jet fuel (Brand et al. 2003, Corchero, Montañés 2005, Haglind, Singh 2006). Experimental tests on a low NO_x hydrogen combustor for aero engines are conducted within the project Advanced Hybrid Engines for Aircraft Development (AHEAD).
Premixed combustion exhibits low flame temperatures and, hence, offers the potential for very low NO_x emissions. Swirl is imposed on the flow to allow for sufficient mixing and to create a central recirculation zone which provides for recirculation of hot gases and hence flame stability (Gupta et al. 1984). Applying aerodynamic, swirl-induced, vortex breakdown flame stabilization waives the necessity of a bluff body or center body which would potentially suffer from material degradation due to the high flame temperatures of hydrogen flames.
Accordingly, in the current study, a cylindrical mixing tube without center body is used in order to further enhance mixing. The swirling flow downstream of a mixing tube or nozzle without center body exhibits a flow field with a recirculation zone, whose vortex breakdown under most conditions is situated just at or upstream of the nozzle exit (Burmberger et al. 2006 and Figure 3a). Mayer et al. (Mayer et al. 2012) showed that without further effort such a flow field is prone to combustion induced flashback for high reactivity fuels. Burmberger and Sattelmayer (Burmberger, Sattelmeyer 2011) suggested to influence the position of the vortex breakdown by a non-swirling air flow exiting on the central axis of the radial swirl generator.

Experimental Setup

A detailed drawing of the investigated swirl burner is given in Figure 1. The mixing tube is located downstream of the swirl generator and has an inner diameter of D=34 mm. The combustor fires into a 105 mm diameter quartz glass combustions chamber

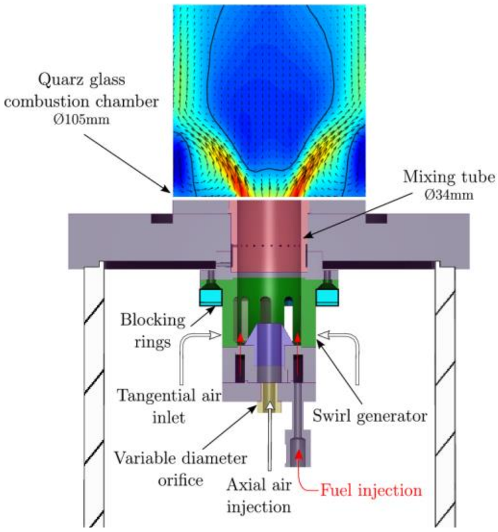

Figure 1: Schematic of burner configuration employing axial air injection

A schematic drawing of the atmospheric combustor test rig used for the present investigations is given in Figure 1. The air entering the radial swirl generator (green) is preheated up to T_{in} = 700 K. Located downstream of the burner and its 34 mm diameter mixing tube, separated by a sudden expansion, is the 105 mm diameter combustion chamber. It is made of quartz glass and, hence, optically accessible. The location of the flame is captured using a band-pass filtered intensified CCD camera for the chemiluminescence of the OH* radical, which correlates with the location of heat release. The Reynolds number during the experiments is set to 40’000.

Flashback resistance is proven in gas-fired tests. The flame is verified by OH* imaging to remain anchored in the combustion chamber at all investigated operating conditions. The results of this study show the feasibility of axial air injection for flashback-proof combustion of hydrogen.

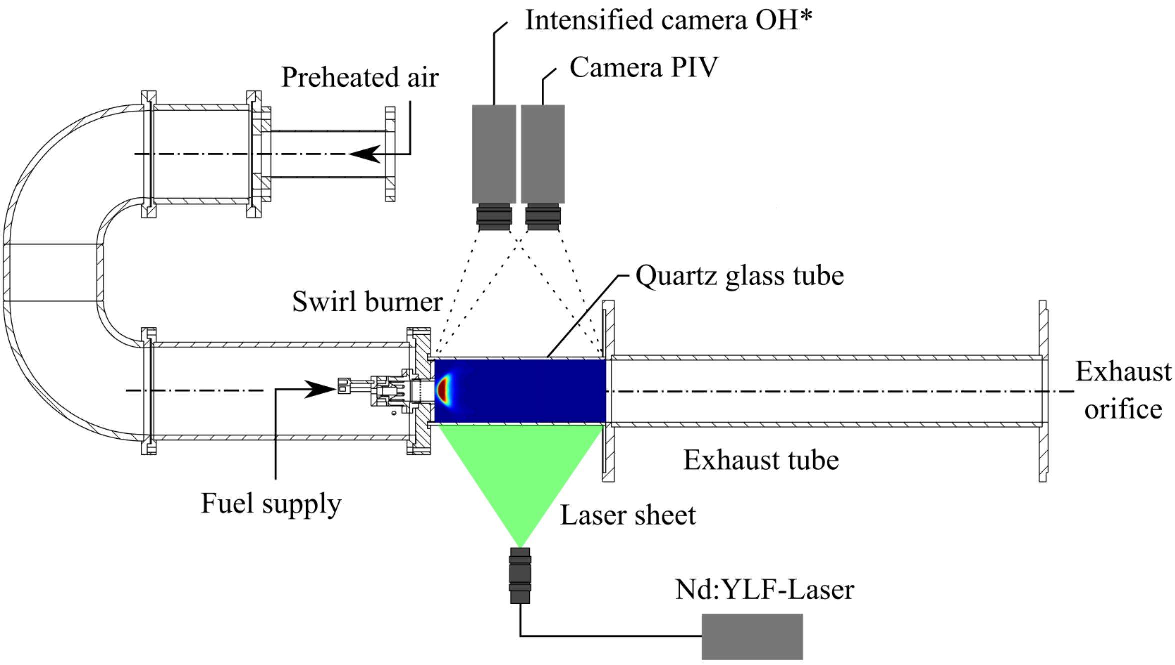

Figure 2: Schematic of the experimental setup for gas-fired atmospheric tests applying high-speed PIV and OH* imaging

Results and Discussion

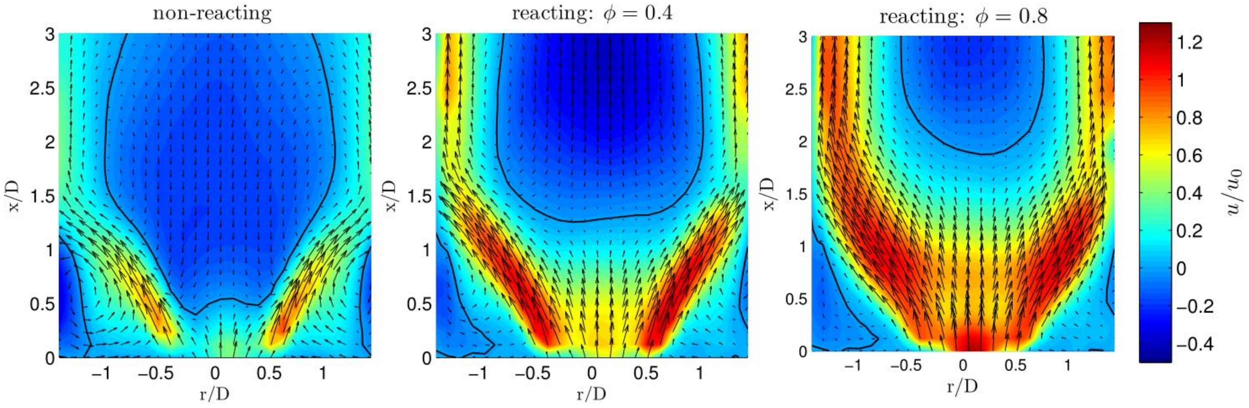

Figure 3: Time-averaged velocity vectors superimposed on the normalized axial velocity to visualize the impact of equivalence ratio on the flow field.

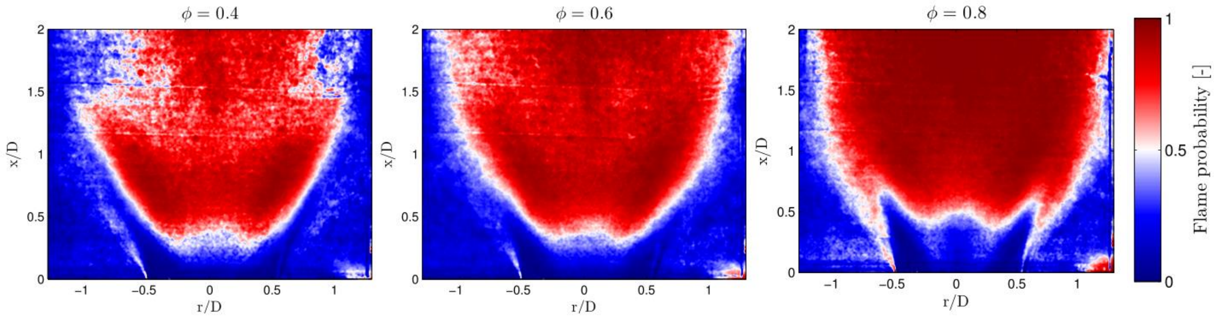

Figure 4: Flame probability indicating the location of maximum flame front likelihood, thus, allowing to determine the upstream flame shape (Re = 75 000).

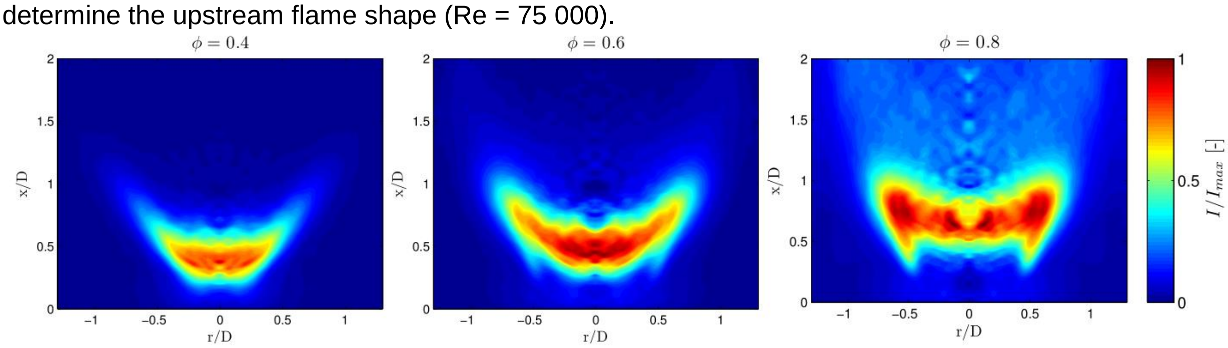

Figure 5: Abel-deconvoluted time-averaged OH* images normalized by maximum intensity of φ=1, indicating location of heat release. Images recorded at a mass flow of 180 kg/h and an inlet temperature of 620 K for configuration with long mixing tube and high swirl.

Conclusion

OH* chemiluminescence and the QLS measurement techniques have been used to determine the location of flame anchoring. For a high amount of axial air injection, the flame is proven to remain anchored in the combustion chamber under all operating conditions. While detached from the rim, the lift off height of the flame is noted to slightly increase with equivalence ratio, which is explained with the additional fuel momentum. An increase in fuel momentum causes both, a reduction in primary swirl number and elevation of the overall velocity level, resulting in a slight downstream shift of the flame front.

The results prove axial air injection to significantly increase flashback safety and hence the operational range of lean premixed hydrogen combustion. At high amounts of axial air injection no flashback occurred.

Acknowledgments

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