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Experimentelle Untersuchung des Einflusses eines axialen Freistrahls auf drallstabilisierte, mager vorgemischte Wasserstoff-lammen

Experimental Investigation of the Impact of Axial Air Injection on Swirl-Stabilized, Lean Premixed Hydrogen Flames

Thoralf G. Reichel, C.O. Paschereit
Herman Foettinger Institut – Technische Universität Berlin
Müller-Breslau-Str. 8
10623 Berlin

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Abstract

Lean premixed combustion allows for fuel-efficient, low emission combustion and 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 flame flashback in the premixer can be overcome. We apply axial air injection in a swirl-stabilized burner in order to achieve a flow field that allows for flashback-proof combustion of premixed hydrogen. This is realized by introducing a non-swirling jet on the central axis of the radial swirl generator which reduces the deficit in axial velocity and influences the location of vortex breakdown. Excellent agreement is achieved for the Particle Image Velocimetry (PIV) investigation of the isothermal flow field in a water tunnel and an atmospheric combustion test rig. Subsequent atmospheric reacting tests reveal changes in the flow field due to the additional fuel momentum and the acceleration over the flame front. However, the positive effects of axial air injection are observed to be maintained in the presence of a flame. Moreover, the fuel momentum is indicated to positively influence flashback resistance. Accordingly, flashback-proof operation of the burner with axial injection at inlet temperatures up to 620K and up to stoichiometric conditions is verified by OH* chemiluminescence images, evidencing the flame to remain anchored in the combustion chamber.

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). The concept proposed in the AHEAD project is a contra-rotating turbofan engine with two sequential combustors, using two different fuels. The engine is operated on hydrogen in the first stage and bio fuel under flameless conditions in the second stage, aiming to reduce CO_2 and NO_x emission. The authors' focus is the hydrogen combustion carried out in the first stage.

Premixed combustion is chosen as the preferred combustion mode since it exhibits much lower flame temperatures in comparison to diffusion flames and, hence, offers the potential for very low NO_x emissions. Evaluating lean hydrogen combustion concepts for aero engines, Ziemann (Ziemann 1998) indicated the low NO_x potential of a premixed swirl-stabilized burner from preliminary tests. 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).

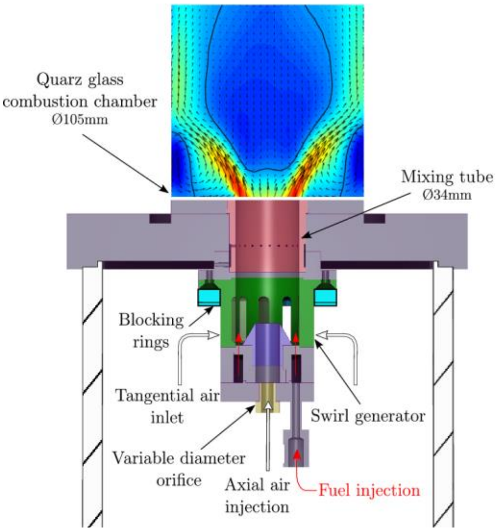

Figure 1: Schematic of burner configuration employing axial air injection

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 4a). 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. Earlier, the impact of axial air injection on the non-reacting (Midgley et al. 2005, Spencer et al. 2008, Reichel et al. 2013) and reacting flow field (Terhaar et al. 2013) in the case of methane has been investigated experimentally. However, the reacting flow field when applying hydrogen is inherently different to the methane case, due to the low Wobbe index (lower volumetric heating value and relative density) of hydrogen, resulting in a high fuel volume flow, whose additional momentum is suggested by Sangl et al. (Sangl et al. 2010) to positively affect flashback resistance.

The remainder of this paper is structured as follows. First, the impact of axial injection on the flow field is presented and evaluated with respect to achieving the required shape for flashback-proof operation. This is done by means of Particle Image Velocimetry (PIV) in a water tunnel. A configuration with long mixing tube and high swirl is tested in the absence and presence of a medium and high amount of axial air injection. Subsequently, the obtained results are compared to isothermal and reacting PIV measurements in the combustion test rig. Moreover, the postulated 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.

Experimental Setup

A detailed drawing of the investigated swirl burner is given in Figure 1. There are two ways for the main air flow to enter the cylindrical mixing tube (red). First, through the radial swirl generator (green), whereby a certain amount of swirl is imposed on the flow, depending on the number of blocking rings (light blue). Second, through an orifice of the diameter D_{or} on the central axis (yellow), constituting axial air injection. As suggested by Syred and Beer (Syred, Beer 1974), in this investigation a swirl number S is used which depends entirely on the burner geometry. The fuel is injected into the premixing section through sixteen injection ports located on an annular ring around the center body. The mixing tube is located downstream of the swirl generator and has an inner diameter of *D*=34 mm. A short (l_{mt} = 40 mm, displayed in the schematic) and a long (l_{mt} = 60 mm) mixing tube variant are tested. The purpose of the circumferentially distributed dilution holes in the mixing tube, is to reduce the near-wall equivalence ratio in order to prevent boundary layer flashback. For the water tunnel experiments a plexi glass model of the burner was designed that provided full optical access to the mixing tube.

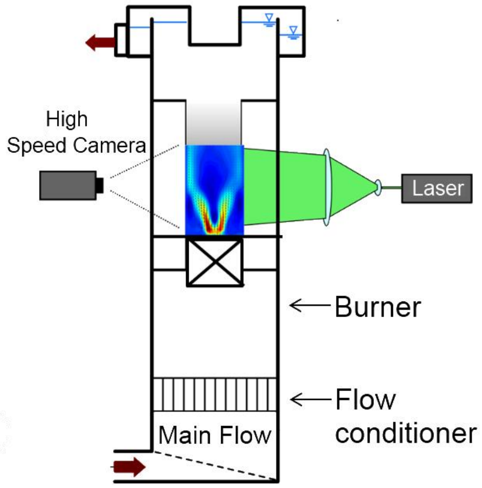

Figure 2: Schematic of water tunnel test rig with a 400x400mm test section and the experimental setups for PIV measurements

The 400 mm x 400 mm vertical test section of the water tunnel allows for optical access to the streamwise plane from four sides (Figure 2). In agreement with the gas-fired tests, the Reynolds number is set to 40’000 with respect to the diameter of the mixing tube *D*. To determine the velocity field, a high-speed PIV system with a double pulsed Nd:YLF laser with a wavelength of 527 nm and a pulse energy of 30 mJ per pulse is applied. Two cylindrical lenses are used to form a light sheet of 2 mm thickness illuminating the streamwise plane downstream of the burner exit. For seeding of the flow, silver coated hollow glass spheres with a nominal diameter of 15 μm are added to the water. The scattered light is detected by a CMOS camera. The pulse separation is set to 0.1 and to 0.2 ms depending on the volume flow. For the cross-correlation an interrogation area of 16x16 pixels and 50% overlapping is selected. The velocity fields are averaged over 1000 image pairs and normalized with the bulk velocity at the burner exit U_0. In order to minimize reflections, an adhesive tape is applied on roughly 40% of the inner wall of the combustion chamber as well as in the mixing tube. This tape shifts the incoming laser light’s wavelength. Accordingly, applying a PIV daylight filter in front of the camera lens allows for strong reduction of the recorded reflections.

A schematic drawing of the atmospheric combustor test rig used for the present investigations is given in Figure 3. At a mass flow of 180 kg/h, the air entering the swirl generator is preheated up to T_{in} = 620 K. Located downstream of the burner model 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 in order to agree with the Reynolds number of the water tunnel experiments.

Results and Discussion

The velocity field inside the mixing tube and in the combustion chamber is investigated in order to assess the concept of axial air injection with respect to establishing a flashback-proof flow field. A flow field is considered flashback-proof, when the deficit in axial velocity is overcome. The changes of the flow field in the absence and presence of a medium ($D_{or} = 8.0$ mm) and high amount ($D_{or} = 8.8$ mm) of axial air injection are revealed in Figure 4a-c, respectively. Under all investigated conditions vortex breakdown is established downstream of the area expansion. This leads to the typical flow field of swirl-stabilized combus-

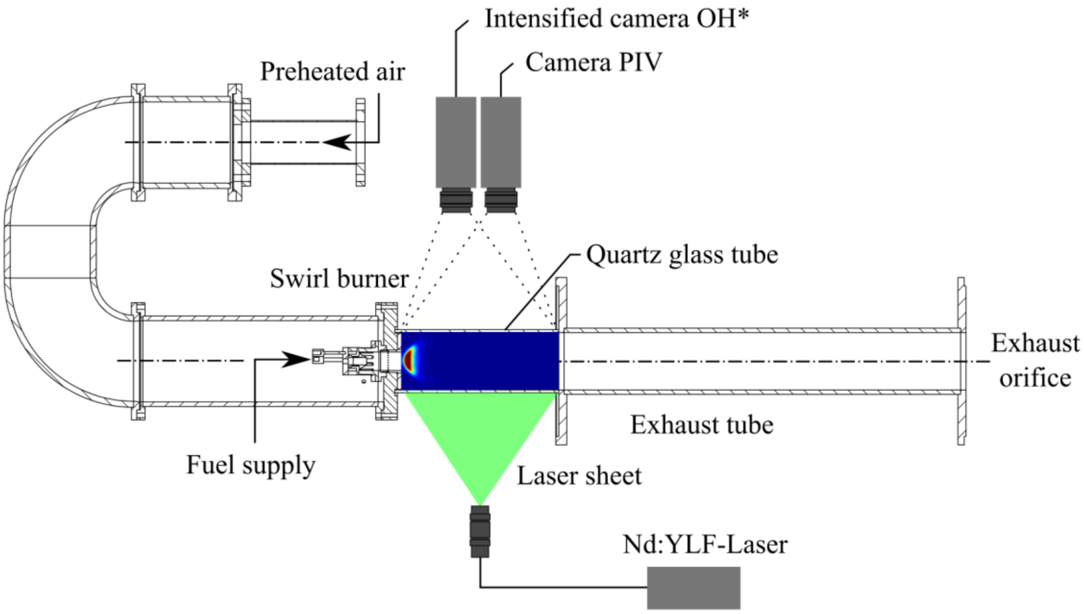

Figure 3: Schematic of the experimental setup for gas-fired atmospheric tests applying PIV and OH* imaging

tors which constitutes in an inner recirculation zone (IRZ), enveloped by an annular jet, and an outer recirculation zone (ORZ) between the annular jet and the bounding walls. It is observed that in the absence of axial air injection, the IRZ extends upstream up to the nozzle outlet Figure 4a). The line of zero axial velocity, indicated by the solid black line, is, on the central axis, located directly at the nozzle exit ($x/D < 0.1$). The flow field inside the mixing tube exhibits a deficit in axial velocity towards the center line for the entire length of the mixing tube. As revealed in gas-fired tests reported below, such a flow field does not allow for flame stabilization downstream of the nozzle exit, when combusting hydrogen.

In case of a medium amount of axial air injection, the flow field in the combustion chamber remains nearly unaffected (Figure 4b). However, strong changes are observed in the mixing tube. Here the deficit in axial velocity on the central axis is overcome and the axial injection yields a more homogenous radial distribution of axial velocity along the mixing tube.

Further increasing the amount of axial air injection to a high amount eventually yields flow field changes in the combustion chamber (Figure 4c). As desired for flashback resistance, we observe a downstream-shift of the stagnation point on the central axis. Its new location is $x/D = 0.7$. Inside the mixing tube, strong radial gradients in axial velocity due to the central jet are detected. However, they decline along the path through the premixing section, nearly achieving a plug flow shape at the nozzle exit.

Gas-fired tests in the atmospheric combustion test rig revealed that for all configurations at least a medium amount of axial air injection ($D_{or} = 8.0\,\text{mm}$) is necessary to operate on a high reactivity fuel like hydrogen, as otherwise flashback would occur. However, as predicted from water tunnel testing, applying a medium amount, for the short mixing tubes, and a high amount of axial air injection for the long mixing tubes, no flashback is observed over a wide range of operating conditions, namely inlet temperatures up to T_{in}=620 K and equivalence ratios up to stochiometric conditions. The flame is proven by OH* imaging to remain anchored in the combustion chamber at all operating conditions (Figure 7). A comparison of the isothermal flow field from water tunnel and combustion test rig (Figure 5) shows an excellent agreement of axial and radial velocities as well as of the location of vortex breakdown. Figure 6 reveals that, in spite of a slightly smaller IRZ and increased jet velocities due to the density decrease over the flame front, the main features of axial air injection are maintained for the

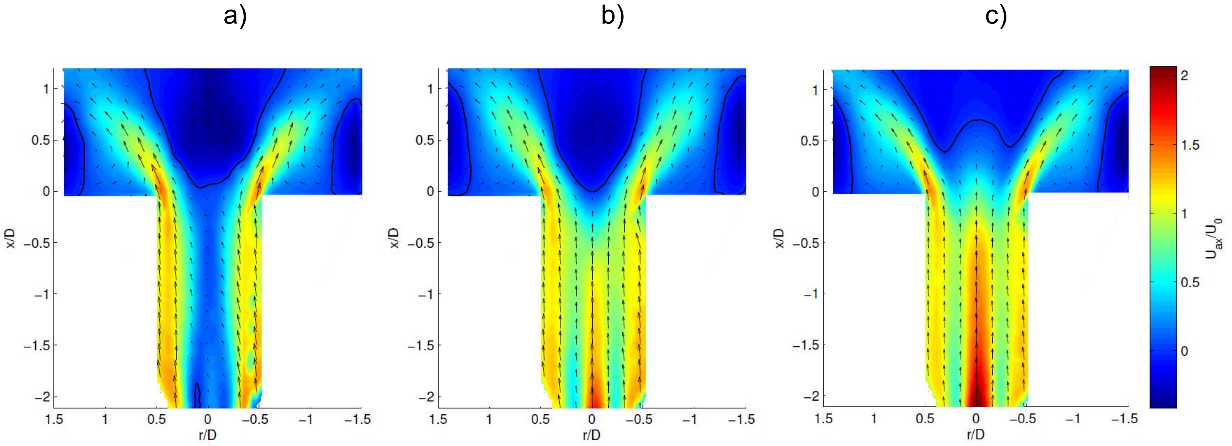

Figure 4: Time-averaged velocity vectors superimposed on the normalized axial velocity to visualize the impact of axial air injection in the long mixing tube, at high swirl (S=0.9). From left to right in the absence a) and presence of a medium b) and high (c) amount of swirl

reacting case: The velocity deficit at the nozzle exit is overcome and the vortex breakdown is shifted downstream.

The OH* images indicate the flame to be located close to the nozzle exit and exhibit a small streamwise expansion (Figure 7) , which is typical for hydrogen flames due to the high burning velocity in comparison to say, methane. Moreover, the distance of the flame from the nozzle exit seems to be increased, although burning velocities of lean premixed hydrogen flames increase with increasing equivalence ratio. This can be explained by the elevated bulk velocity at the nozzle exit which is caused by the high axial momentum introduced by the fuel. At T_{in}=620 K and Φ=0.4 the volume flow of hydrogen V_{H2}, which is injected in axial direction, corresponds to 8% of the main air volume flow $V_{air.}$ The share goes up to 20% of V_{air} at Φ=1.0. Hence, the bulk velocity at the nozzle exit is increased from U_0=70 m/s at isothermal conditions, over U_0=78 m/s at Φ=0.6, up to U_0=85 m/s at stoichiometric conditions. This effect, which is not observed for methane, is due to the lower Wobbe index of hydrogen in comparison to methane.

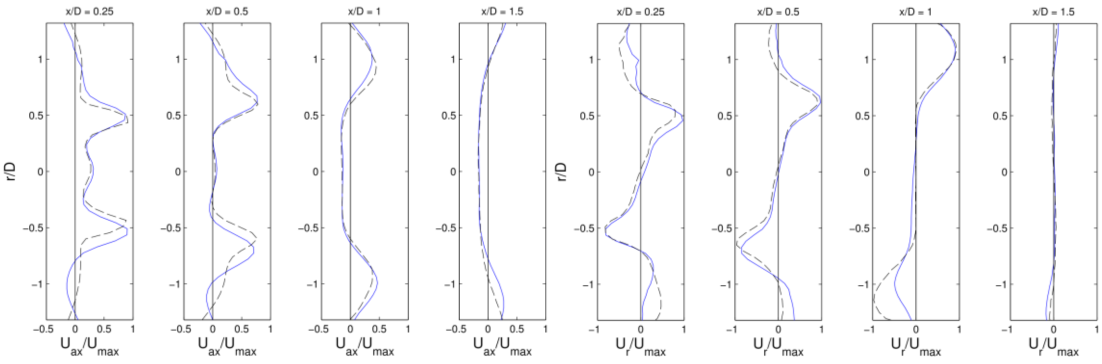

Figure 5: Normalized axial (left) and radial (right) velocity of the isothermal flow field from water tunnel (solid line) and atmospheric combustor test rig (dashed line)

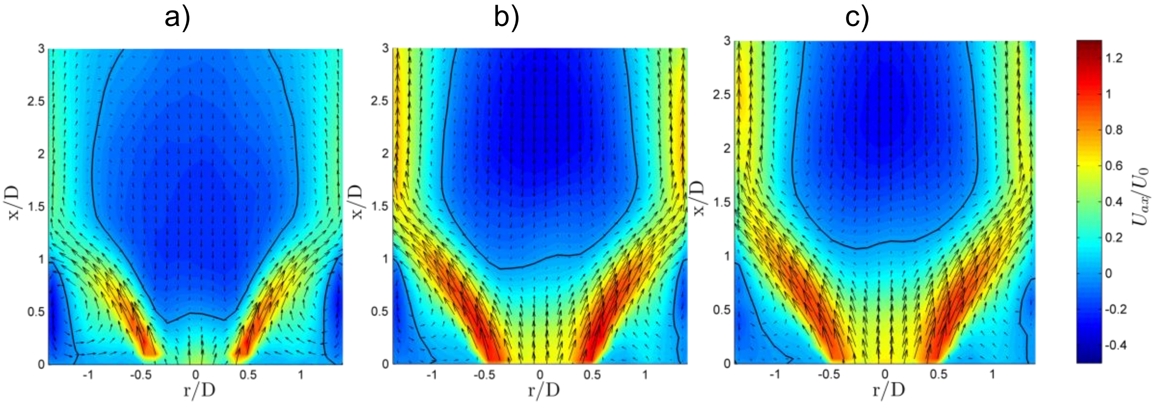

Figure 6: Time-averaged velocity vectors superimposed on the normalized axial velocity to compare the isothermal (a) and reacting velocity field. In the reacting case for φ=0.4 (b) and φ=0.6 (c). Note, U_0 increases with increasing equivalence ratio, due to the high volume flow of hydrogen as fuel.

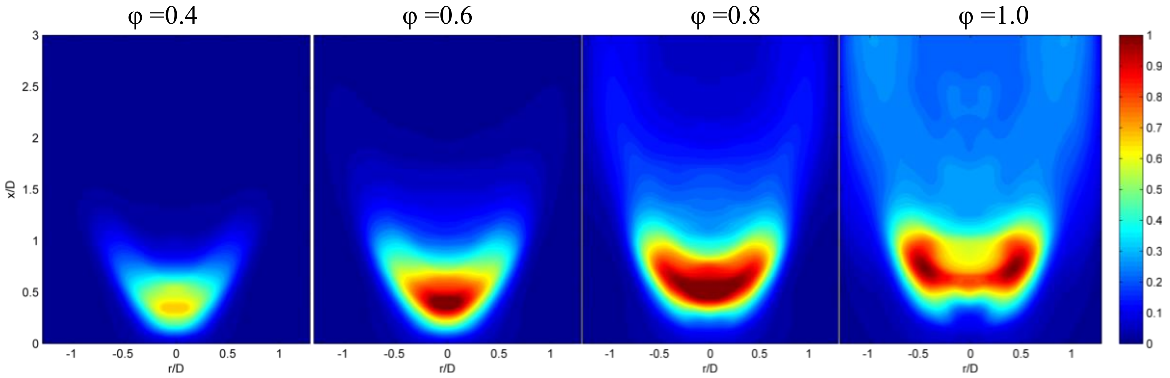

Figure 7: Abel-deconvoluted time-averaged OH* images normalized by maximum intensity of φ=1, indicating location of heat release. Images recorded at a mass flow of 180 kg/h and an inlet temperature of 620 K for configuration with long mixing tube and high swirl.

Conclusion

The flow field of a swirl-stabilized burner operating on lean premixed hydrogen is successfully tailored by means of axial air injection to exhibit a flashback-proof flow field, overcoming the deficit in axial velocity on the central axis and shifting vortex breakdown further downstream. Excellent agreement of the isothermal flow field from the water tunnel and combustion test rig for the configuration with long mixing tube and high swirl is shown by PIV measurements. An investigation of the reacting flow field by means of PIV proves the positive aspects of axial air injection to be maintained in the presence of a flame. Gas-fired tests revealed that the concept of axial air injection allows for flashback-proof swirl-stabilized combustion of technically premixed hydrogen mixtures. Note, that at least a medium amount of axial injection was mandatory to operate the burner on undiluted hydrogen. However, in the presence of a high amount of axial air injection, no occurrence of flashback was observed at the investigated conditions, namely inlet temperatures up to 620K and stoichiometric conditions. A downstream shift of the time-averaged flame location is indicated by the OH* images, which could be explained by the increased bulk velocity with increasing equivalence ratio due to the low Wobbe index of hydrogen.

Acknowledgments

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