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COMBUSTION OF CH_4/H_2 MIXTURES IN GAS TURBINES – EFFECT OF MIXING ON RISK OF FLASHBACK

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ABSTRACT

Boundary layer flashback of hydrogen-methane-air flames is investigated experimentally in a model swirl combustor. The combustor is installed in a high-pressure test rig to study flashbacks up to a pressure of 7.5 bar. The present work focuses on the effect of technical premixing on flashback limits in comparison to perfectly premixed conditions. For technical premixing, fuel is injected in the premix section of the burner through ports in the vanes of the axial swirler. To achieve perfectly premixed conditions, fuel and air are already well mixed far upstream of the burner mixing section. The results show that for H_2-CH_4 air flames with a significant amount of H_2 (more than 50% by vol.), where flashback occurs at rather lean conditions, the risk for flashback increases significantly when fuel and air are not perfectly mixed. In contrast, if the amount of H_2 in the fuel mixture is low, unmixedness between fuel and air hardly effects the flashback propensity.

INTRODUCTION

As a consequence of the envisioned transition of energy systems all around the world towards a higher share of renewable energy sources combined with a significant reduction in the emission of greenhouse gases, hydrogen (H_2) is expected to play an important role as an energy carrier [1]. As it will take many years to ramp up H_2 production from renewable sources (mainly via water electrolysis) in order to provide the significant amounts required for a large-scale conversion, transition scenarios will play an important role in the years to come.

A vital part of such scenarios is the option of admixing large amounts of H_2 into natural gas (NG), either into the NG grid or at plant level. This in turn requires that the technologies currently using NG to provide electricity, heat and power to the grid and to industry are suited to run on such H_2-NG fuel mixtures across a wide range of H_2 content.

Gas turbines are well suited to play a vital role in this transition since they can provide power on a large scale and they are flexible in their operating profile such that they can complement fluctuating, renewable energy sources. Furthermore, retrofitting the large fleet of installed gas turbines with advanced burner hardware can strongly support a fast and affordable transition towards a low-carbon energy supply [2]. The challenge for existing burner technology, including gas turbine burners, is their capability to handle large, varying amounts of H_2 above 50% up to 100% H_2 while still maintaining a stable flame and adhering to the low NOx emissions. These low emissions are achieved with state-of-the-art Dry Low NOx (DLN) technology based on lean-premixed combustion.

Achieving stable, lean-premixed flames when the amount of H_2 is raised above 50% by vol. is challenging since these flames tend to flashback into the premix section of the burner. The main causes for flashback of hydrogen-rich flames at gas turbine conditions is flame propagation near walls (boundary layer flashback) and flashback due to the formation of auto-ignition kernels in the premix section [3,4].

However, detailed studies on flame flashback at gas turbine relevant conditions (elevated pressure and preheat temperature, reasonably high Reynolds numbers) to support advanced burner development are still sparse, especially for H_2-NG fuel mixtures [4–10].

The current study addresses one particular aspect of relevance for flashback in practical gas turbine burners, i.e. whether switching from “perfect premixing” to “technical premixing” has a strong effect on flashback limits for hydrogen-rich flames. Perfect premixing is often employed in fundamental flashback studies to reduce the complexity of the investigated phenomenon and isolate effects other than those resulting from fuel-air unmixedness [11,12]. On the other hand, some studies have introduced mixture stratification on purpose to study its effect on the flashback behaviour [13,14]. In the current work, we investigate flashback in a swirl burner with a commonly employed fuel injection strategy. The goal of this injection strategy is to achieve as good mixing as possible. However, just like in a real gas turbine burner, some unmixedness remains as the flow enters the combustion chamber. Its effect on the flashback propensity is investigated for hydrogen-methane-air flames.

EXPERIMENTAL SETUP

High-Pressure Rig and Swirl Burner

Flame flashback was investigated experimentally in a generic swirl burner installed in the high-pressure combustion test rig at the Paul Scherrer Institute [15,16]. The test rig, which has three windows to provide optical access to the combustion and the premix section of the burner, is shown in Figure 1. This setup allowed high-speed imaging of flashback events to clearly differentiate between flame flashback due to flame propagation in the boundary layer and flashback triggered by auto-ignition events.

The focus of this work has been on comparing two fuel injection strategies and their impact on flashback limits. The reference fuel injection system is referred to as “perfect premixing” where fuel was injected into the preheated air 430 mm upstream of the swirler through a cross-shaped tubing arrangement with 25 ports distributed across various radial and circumferential locations (Figure 1) [8]. In addition, a static mixture (STAMIXCO 18-315) was installed downstream of the fuel injection location to ensure fully premixed conditions already at the burner mixing tube inlet.

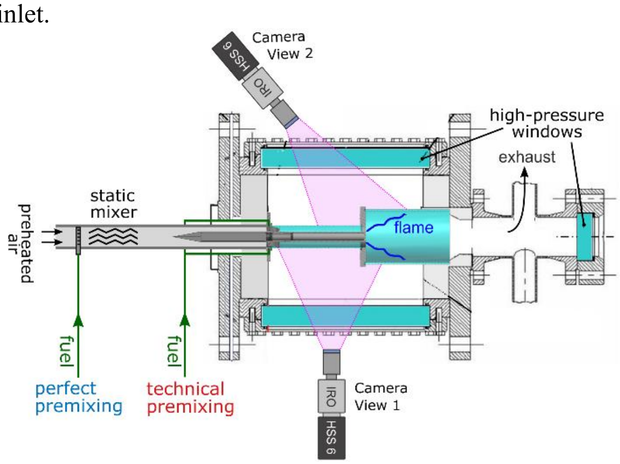

Figure 1: High-pressure test rig with swirl burner. The burner is operated with two different fuel injection strategies: "perfect premixing" and "technical premixing".

In the “technical premixing” fuel injection system, fuel was injected through ports in the vanes of the axial swirler. As in a lean-premixed gas turbine burner, fuel and air then mixed inside the premix section before reaching the combustion chamber with some remaining unmixedness.

The swirl burner and the axial swirler are shown in more detail in Figure 2. Swirl was imparted on the flow with an additively manufactured, axial swirler with eight blades. The blade angle with respect to the burner axis was 0° at the leading edge, 50° at the trailing edge and constant in the radial direction. The corresponding swirl number was about 0.7. The blade leading edges had an elliptical shape with radius 1.25 mm (minor axis, i.e. blade thickness) and 2.25 mm (major axis), respectively. The trailing edges were sharp.

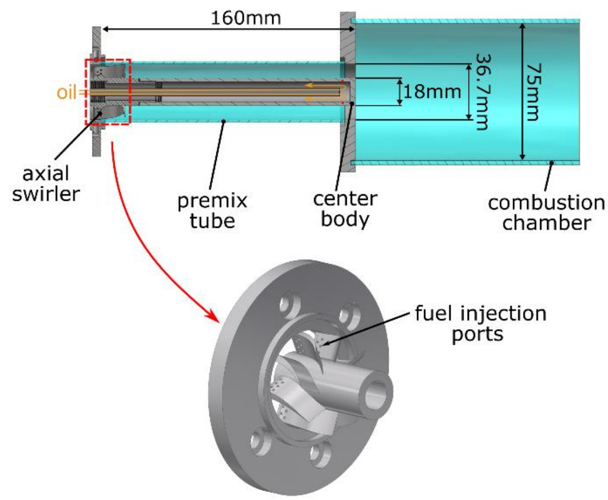

Figure 2: Swirl burner with axial swirler, temperature controlled center body and optical access to the premix section and combustion chamber.

In the technical premix operating mode, fuel was injected through a total of 96 holes: Six holes on the pressure and the suction side of each vane, staggered axially and radially. The injection hole diameters were 1 mm. The fuel flow was not choked for the operating conditions investigated in this work.

The center body ended flush with the mixing tube exit except for the data presented in Figure 8 labelled “CB short”, where the center body was shortened by 18 mm (corresponding to one center body diameter). The center body metal temperature was controlled with an internal oil cooling/heating circuit to achieve a well-defined thermal boundary condition on the wall [8].

The air flow rate through the burner, the hydrogen flow rate and the methane flow rate were each controlled with a mass flow controller. The burner was ignited with spark-ignited hydrogen jet flame positioned in the flange between premix section and combustion chamber.

Operating Conditions and Flashback Limit Measurement Procedure

Flashback limits were measured for a range of pressures from p = 1 to 7.5 bar and preheat temperatures of T_{pre} = 200°C and 300°C at the entrance to the combustion chamber. Fuel mixtures of hydrogen and methane (CH_4) were investigated as a surrogate for H_2-NG mixtures. A test with Swiss natural gas (main constituents: 92% methane, 5% ethane by vol.) showed a negligible difference on the measured flashback limits.

The thermal power was limited by the allowable heat load on the burner hardware during a flashback event. This limited the investigated flow rates and thus bulk flow velocities in the premix section (u_{bulk}) to about 30 m/s for H_2-CH_4-air flames and to about 40 m/s for H_2-air flames.

Below about 50% H_2, generally no flashback occurred even at stoichiometric conditions for the investigated operating conditions and burner geometry. For instance, to trigger a flashback with a fuel mixture of 30% H_2 and 70% CH_4 by vol., the bulk flow velocity had to be lowered to 10 m/s ($T_{pre} \approx$ 300°C, p = 5 bar).

Flashbacks were triggered by first establishing a lean flame at a desired nominal operating point (p, T_{pre}, u_{bulk}, X_{H2}) followed by increasing the equivalence ratio ϕ at a constant, slow rate of $\Delta\phi = 0.1$ per minute. The equivalence ratio is the reciprocal of the air number λ, i.e. the ratio of the actual to the stoichiometric fuel-to-air ratio (FAR): $\phi = 1/\lambda = FAR/FAR^{stoich}$.

The LabView based control system increased ϕ by simultaneously increasing the H_2 and CH_4 fuel mass flows and the air flow rate to keep p, T_{pre}, u_{bulk} and X_{H2} constant when the flashback limit was approached.

The flashback limit was defined as the equivalence ratio at which the flame propagated through the entire premix tube up to the swirler. Such "complete" flashbacks (as opposed to an intermittent penetration of the flame into the premix section by only a few centimeters) were typically followed by flame holding.

Perfectly premixed flames typically anchored in the wakes of the swirler vanes following a flashback event. For moderate pressures up to 5 bar and H_2 contents up to about 85%, it was possible to recover a stable flame in the combustion chamber by quickly reducing the H_2 mass flow and thus the overall equivalence ratio. Only for the higher pressures (> 5 bar) and high H_2 contents (> 80%), the flame remained at the swirler up to the lean-blowout limit. Sometimes, the flame even managed to propagate beyond the swirler and stabilized in the static mixer upstream of the burner. In those cases, a fuel shut-off was required.

Technically premixed flames anchored slightly farther upstream on the metal swirler vanes rather than immediately downstream of the vane trailing edges in the wakes. Therefore, flushing out such a flame and recovering it in the combustion chamber was more difficult (only possibly for moderate conditions p < 2.5 bar, X_{H2} < 60%).

RESULTS

Modes of Flashback and Flame Holding

The common mode of flashback in the current burner for most of the investigated operating conditions was upstream flame propagation along the center body wall. As an example, a chemiluminescence image sequence obtained with a high-speed, intensified camera is shown in Figure 3 (left column). The corresponding field-of-view is indicated in Figure 1. The camera was equipped with a narrow band-pass filter targeting the emission of the OH* radical. The grey scale images were converted to false-colors in a post-processing step. This particular flashback occurred at 5 bar, 300°C preheat temperature and 60% H_2 (image sequence reproduced from [9]).

Flashback along the outer wall is only possible for low swirl numbers, for which the outer boundary layer thickness is comparable to the inner one. The time scale associated with such boundary layer flashbacks was ~100 ms.

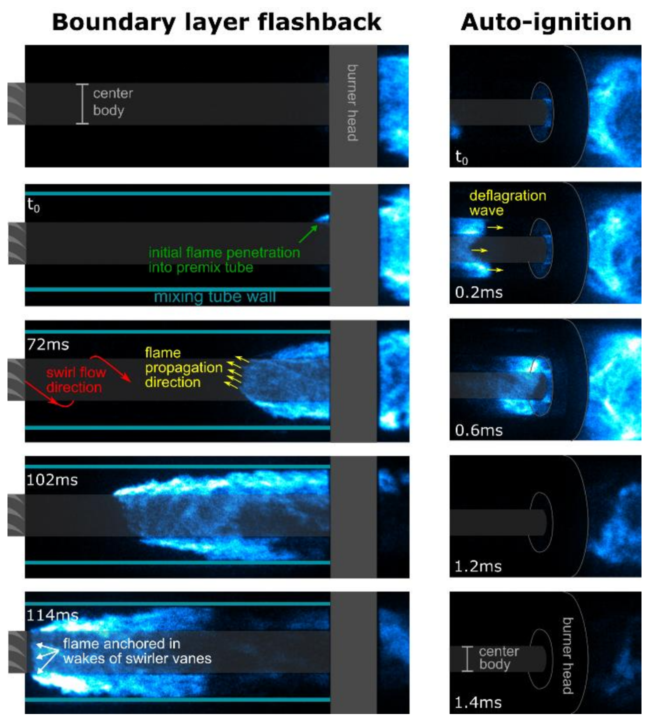

Figure 3: Flashback types observed in the current burner. Left (Camera View 1): Boundary layer flashback along the center body wall followed by flame holding in the wakes of the swirler vanes. Right (Camera View 2): Flame holding in the test rig mixing section (not seen in the images) due to auto-ignition followed by the downstream propagation of a deflagration wave causing a flame-out.

Starting at about 5 bar and 300°C preheat temperature, auto-ignition began to dominate over flame propagation type flashback for perfectly premixed flames with X_{H2} > 80%. In such cases, the formation of an auto-ignition kernel triggered flame holding even upstream of the swirler inside the test rig mixing section. Once ignited, a deflagration wave superimposed on the flow travelled downstream as shown in Figure 3 (right column). Once this deflagration wave reached the combustion chamber, the main flame was essentially extinct. At this point, all reactants were consumed by the flame anchored in the test rig mixing section and only combustion products reached the combustion chamber. Such auto-ignition triggered flame-outs of the main flame occurred very suddenly since the deflagration wave and the flow propagated in the same direction (downstream) and reached the combustion chamber within milliseconds.

Auto-ignition was not observed in combination with the technical premixing fuel injection strategy for the operating conditions investigated in this work. The auto-ignition time scales were sufficiently large compared to the convective time-scale between the fuel injection locations in the swirler vanes and the combustion chamber.

Effect of Hydrogen Content on Flashback Limit

In a previous study, we have quantified the increase in flashback propensity as more and more hydrogen is admixed to a H_2-CH_4-air flame for perfect premix conditions [8]. These reference data points (blue squares) are shown in Figure 4 for a pressure of 2.5 bar, a preheat temperature of 200°C and an averaged bulk flow velocity in the premix section of 20 m/s. Error bars indicate the precision based on at least five measured flashback limit data points at each nominal operating condition.

In the current work, fuel was instead injected in the burner mixing section as is done in a real gas turbine (technical premixing). In this particular burner, fuel can be injected through ports in the swirler vanes as described in the EXPERIMENTAL SETUP section.

The corresponding measured flashback limits are shown in Figure 4 as red stars. Here, each symbol corresponds to one measured flashback limit. The results reveal that the flashback propensity increases significantly in the case of technical premixing for hydrogen contents above about 65% where flashback occurs at lean conditions (equivalence ratios of 0.5 and lower). The offset remains approximately constant all the way up to 100% H_2.

At 62% H_2 content, the equivalence ratio was increased up to $\phi = 0.80$ (at this point the heat load limit on the combustor hardware was reached) and still no flashback occurred. The dashed grey line indicates the hypothetical flashback limit trend line below 65% H_2.

These results clearly show that technical premixing strongly affects the flashback limit above a critical amount of hydrogen admixed to the fuel. In contrast, flashback limits for low H_2 contents are hardly affected. This is despite the fact that the "technical premixing" fuel injection strategy in this work was realized with a large number of well-distributed fuel injection ports combined with a long mixing tube such that a rather well-mixed fuel-air mixture can be assumed even for this case.

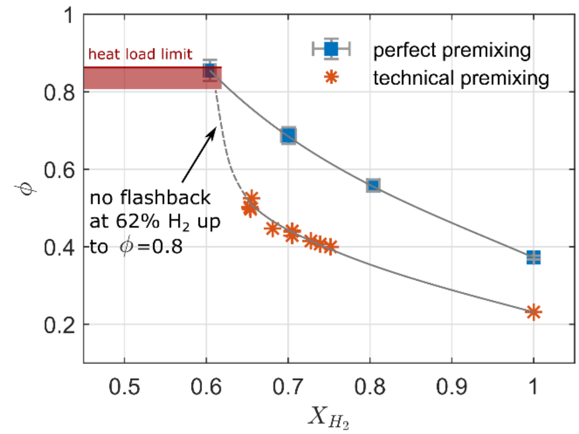

Figure 4: Flashback limits for perfectly and technically premixed flames at p = 2.5 bar and T_{pre} = 200°C, expressed in terms of the equivalence ratio ϕ at which flashback occurred.

These findings suggest that lean, hydrogen-rich flames react more strongly to equivalence ratio stratification (richer and leaner streaks in the mixing field) at the entrance to the combustion chamber than methane or natural gas flames.

A similar comparison was repeated at a chamber pressure of 5 bar and a preheat temperature of 300°C (same bulk flow velocity of 20 m/s), shown in Figure 5. At these operating conditions, flashback limits for perfect premix conditions (blue squares) could only be measured up to a hydrogen content of 80%. Beyond 80% H_2, flashback occurred due to auto-ignition (verified by high-speed chemiluminescence imaging of the premix section as shown in Figure 3) instead of flame propagation in the boundary layer. Therefore, the true flashback propensity for this burner and for perfectly premix conditions increased significantly above 80% H_2 due to auto-ignition. In contrast, whereas the theoretical flashback limit due to boundary layer flashback (BLF) is expected to increase approximately linearly up to 100% H_2 as indicated by the grey dashed line in Figure 5.

As before, technical premixing strongly increased the flashback propensity. At this pressure and preheat temperature, the critical hydrogen content above which the flashback limits shifted to significant leaner conditions was about 55%. The corresponding equivalence ratio at which flashback occurred at this critical hydrogen content was again $\phi \approx 0.5$, which is similar to the previously discussed 2.5 bar case. At 52% H_2 content, no flashback occurred up to $\phi = 0.71$, at which the heat load limit on the test rig was reached.

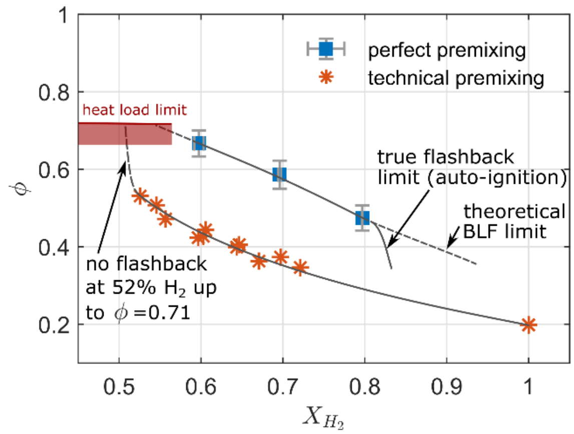

Figure 5: Flashback limits for perfectly and technically premixed flames at p = 5 bar and T_{pre} = 300°C.

These findings show that for hydrogen-rich H_2-CH_4-air flames, where flashback occurs already at rather lean conditions, achieving close to perfect premix conditions is significantly more important in order to prevent boundary layer flashback compared burners operated on methane (or natural gas) with merely low amounts of H_2 contained in the fuel.

The data suggest that there is not a single hydrogen content, at which the strong increase in flashback propensity kicks in. Instead, it is the combination of having a significant amount of H_2 in the fuel *and* an operating condition where flashback for the hydrogen-rich flame already occurs at rather lean conditions. This can be explained by the fact that the farther away the global (spatially averaged) equivalence ratio from stoichiometric conditions, the stronger the effect of having richer and leaner pockets locally due to imperfect mixing.

Another factor, which may play a role in the current experiments and needs to be investigated further, is that the degree of unmixedness between fuel and air may change as the amount of hydrogen in the fuel is changed. First, the diffusivity of hydrogen is higher compared to methane. Second, since the cross-section of the small fuel injection ports in the swirler vanes is fixed (like in a real gas-turbine burner), the jet-in-cross flow conditions and thus the mixing behaviour changes as the H_2 content in the fuel is altered. Increasing the amount of H_2 changes the flashback limit and therefore the volumetric fuel flow rate through the injection ports as well as the fuel density. Both parameters affect the fuel-to-air momentum ratio, which characterizes the jet-in-cross flow behaviour. Evaluating the jet penetration distance with a common correlation [17] for the current burner and the flashback conditions presented in Figure 5 suggests that the jet penetration distance decreases by about 40% as we move from a 50% H_2-CH_4 mixture to 100% H_2.

These factors impact how well the different fuels have mixed with air by the time the mixture reaches the exit of the premix section. Therefore, the quantitative downward shift of the flashback limit curves (Δϕ of about 0.2 to 0.3 in Figure 4 and Figure 5) may also be affected by this unequal degree of unmixedness as a function of the hydrogen content. Nonetheless, the general finding that technical premixing raises the boundary layer flashback propensity significantly for lean, hydrogen-rich flames remains.

Effect of Pressure on Flashback Limits

In a previous study on perfectly premixed H_2-CH_4-air flames, we found that raising pressure strongly increases the flashback propensity from atmospheric conditions up to about 3 bar [8]. Beyond 3 bar, only a weak pressure effect on the flashback limit has been found. As an example, the data set at T_{pre} = 300°C, u_{bulk} = 20m/s and for a hydrogen content of 60% is included in Figure 6 as a reference (blue squares).

In the current work, the pressure dependence was investigated for nominally the same operating conditions (read stars), but now with the previously described technical premixing injection strategy. The data show the same behaviour: Changing pressure most strongly affects flashback limits between 1 and 3 bar.

It is interesting to note that the effect of technical premixing (downward shift in ϕ to leaner conditions) becomes weaker for pressures below 2 bar where flashback occurs at equivalence ratios above 0.6. This supports the argument made in the previous section that it is not the hydrogen content by itself that determines whether technical premixing lowers the flashback margin. Instead, it appears to be the combination of a hydrogen-rich flame and flashback occurring at globally lean conditions. In other words, for flames with significant amounts of hydrogen, the flashback limit shifts to very lean conditions, which it turn strengthens the effect that non-perfect premixing has on the flashback limit.

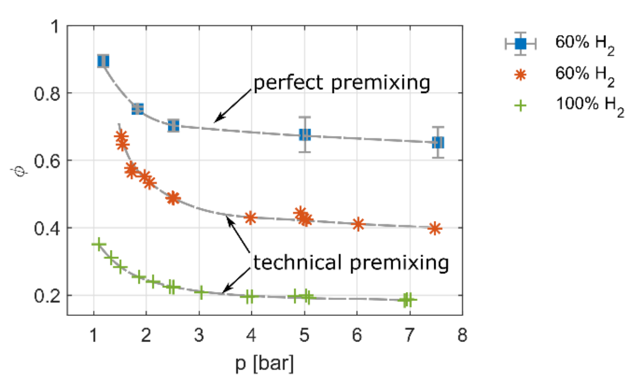

Figure 6: Effect of pressure on flashback limits at 300°C preheat temperature for a H_2-CH_4 fuel mixture with 60% H_2 and for a pure H_2-air flame.

The Flashback Challenge of Lean-Premixed H_2-air flames: High Resistance to Strong Shear

One of the main strategies to prevent flame flashback in lean-premixed burners is to choose a sufficiently high flow velocity in the premix section. This strategy is effective for burners operated on natural gas and even for burners operated on H_2-CH_4 mixture with significant amounts of H_2 above 50% by volume. However, the higher the hydrogen content in the fuel and the leaner conditions at which flashback occurs, the less effective it is to prevent boundary layer flashback by raising the bulk flow velocity.

In the current work, flashback limits for pure, technically premixed H_2-air flames were measured for two bulk flow velocities in the premix section. The flashback limit hardly improved when the velocity was doubled from 20 to 40 m/s as shown in Figure 7. This finding is in agreement with previous studies on non-swirling flame flashbacks, which also showed a week improvement in the flashback propensity for hydrogen flames when the flow velocity was increased [4].

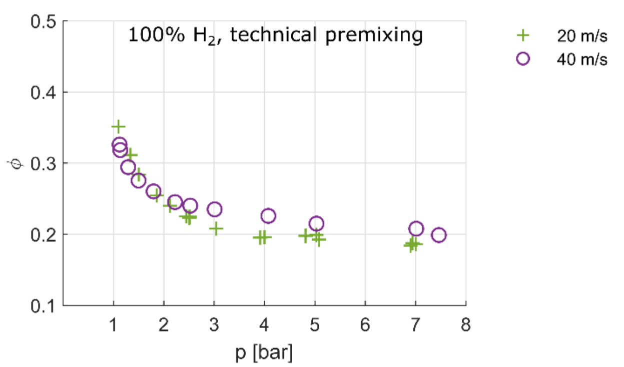

Figure 7: Effect of raising the bulk flow velocity on flashback limits of technically premixed H_2-air flames at T_{pre} = 300°C.

The weak effect of bulk flow velocity on the flashback limit can be explained by the high extinction strain rate of lean, convex-shaped hydrogen-air flames [18]. This property allows hydrogen flames to withstand the strong shear present in the thin boundary layers inside a premix tube. In a recent study, it was shown that the extinction strain rate plays an important role in determining flashback limits for lean H_2-CH_4-air flames [9].

Effect of a Recessed Center Body on Flashback Limits

It is common practice in gas turbine burners with a central fuel lance to recess the center body tip relative to the entry section to the combustion chamber. Thereby, the flame root is spatially separated from the tip of the center body and excessive heat load on the metal is prevented ensuring reasonable lifetime of the burner hardware.

We have briefly verified the findings in the current work for a burner with a recessed center body. For that purpose, the center body was shortened by 18 mm (equal to one center body diameter).

We found that the flame anchored to the recessed center body tip long before a complete flashback occured, i.e. at equivalence ratios well below the flashback limit. Therefore, in addition to the flame being stabilized in the combustion chamber (detached from the center body), a secondary stable flame location exists, where the flame is anchored to the rim of the center body inside the premix section but without flashback farther upstream along the center body wall.

The corresponding flashback limit results are shown in Figure 8. The results show that in general, the flashback limit at which the flame flashes back along the center body wall is slightly shifted to richer conditions both for perfect and for technical premixing. This may be explained by more favourable near-wall velocity profiles in the vicinity of the shortened center body tip.

However, the finding that technical premixing increases the flashback propensity for lean, hydrogen-rich flames remains valid also for a burner with a recessed center body.

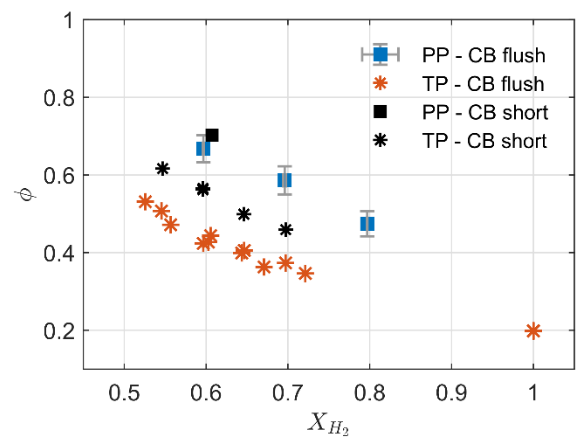

Figure 8: Effect of recessing the center body (CB) tip by one CB diameter (labelled "CB short"). PP: Perfect premixing. TP: Technical premixing.

SUMMARY AND CONCLUSION

Flame flashback of lean H_2-CH_4-air flames has been investigated experimentally in a generic swirl burner at elevated pressure and preheat temperature. The focus has been on technical premixing in comparison to perfectly premixed flame flashback reported previously.

The investigated flames show that once the hydrogen content is raised above 50% and 60%, respectively, technical premixing leads to a significantly higher risk of flashback. In contrast, for low H_2 contents, non-perfect mixing in the premix section does not significantly affect the flashback limit.

Raising the pressure from atmospheric conditions to about 3 bar drastically increases the danger of flashback by flame propagation in the boundary layer. The same behaviour was previously observed for perfectly premixed flames. Beyond about 3 bar, the effect of pressure on the boundary layer flashback limit is weak independent of the degree of remaining unmixedness. Instead, at some flame and burner dependant pressure level, the effect of pressure on the risk of flashback due to auto-ignition starts to dominate over its effect on the boundary layer flashback limit.

Testing flashback limits of pure H_2-air flames for two different bulk flow velocities highlighted why flames of H_2-rich fuels are particularly prone to boundary layer flashback. Very high velocities leading to extreme shear levels in the boundary layer are required to extinct such flames and thus prevent flashback. These conditions are typically achieved in micro-mixing type burner designs. Alternatively, tailored equivalence ratio profiles seem promising such that the shear in the boundary layer is sufficiently high to overcome the extinction strain rate of flames even for more moderate bulk flow velocities commonly found in burner premix sections.

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