Flashback Phenomena Associated with Lean Premixed Syngas Combustion at Gas Turbine Like Conditions

S. Daniele¹, P. Jansohn¹, K. Boulouchos²
1. Paul Scherrer Institut (PSI), Combustion Research Laboratory, 5232 Villigen PSI, Switzerland
2. Swiss Federal Institute of Technology (ETH), Aerothermochemistry and Combustion Systems Laboratory Sonneggstrasse 3, CH-8092 Zürich, Switzerland

1. Abstract

Integrated gasification combined cycle plants (IGCC) present new challenges for premixed gas turbine engines originally fuelled with natural gas. Through gasification, solid fuels are converted to syngases consisting in mixtures of mainly H₂ and CO containing different diluents (H₂, N₂, CO₂) according to the original feed stock and gasification process. The ratio of H₂ and CO can generally vary from one to two (in volume) reaching asymptotically 100% H₂. Within this work a fuel mixture of H₂ and CO in equal volume percent was investigated. High H₂-containing fuels are characterized by higher burning rates compared to natural gas, thus by a higher flash back propensity.

This paper presents experiments at gas turbine like conditions aimed to determine flash back limits and operability issues of a modern Gas Turbine engine. Dependence on the combustion parameters (pressure, inlet temperature and inlet velocity) is described and discussed.

2. Introduction

The term flashback defines the upstream propagation of the flame front into the fuel/air mixing section from its previous stabilization point in the combustion chamber. A general classification of the different mechanisms leading to flashback is given in [1]. In this work four categories have been listed:
- propagation in the core flow
- propagation in the boundary layer
- propagation due to “combustion induced vortex breakdown” (CIVB)
- propagation due to combustion instabilities.

The first two mechanisms are prompted when the flame speed locally overtakes the velocity of the incoming flow [2-4] CIVB derive from the coupling between turbulence and chemistry in swirled flows [5-7]. The last category of the list is populated by all the flashback events derived from various instabilities (e.g. thermoacoustic, entropy waves, etc.).

For H₂-rich fuels experiments at gas turbine relevant conditions with the goal of describing and understanding the flashback propensity are of value for combustor design. Performing flashback experiments is usually expensive due to the damages this phenomenon can provoke. In addition, these experiments necessitate higher attention to safety issues due to their dangerous nature. For this reasons facilities capable to operate such experiments are rare and there are not comprehensive data sets available in the literature.
This paper summarizes the experience gained in the Paul Scherrer Institut (PSI) when adapting the high pressure turbulent premixed facility, which was conventionally used for the study of hydrocarbon flames, to the operation with high H\textsubscript{2} containing fuels.

3. Experimental Set Up

The measurements were performed in a high pressure combustor shown in Figure 1. The combustor, specifically designed to study turbulent, lean premixed flames, is capable of operations at up to a pressure of 30 bars, with a maximum air flow rate of 1200 m\textsuperscript{3}/h and adiabatic flame temperatures up to 2000 K. The set up is described in details in [8].

![High-pressure combustor schematic.](image)

4. Operational Window

A fuel mixture of H\textsubscript{2} and CO in equal volumetric parts was used in this study for all the experiments. The measuring campaign whose results are summarized in this paper had the purpose of checking the feasibility of firing syngas in a test rig which was conventionally fired with CH\textsubscript{4}. A removal of all the potentially flame holders from the mixing section (perforated plates, static mixers) was needed. Then measurements were performed to obtain the operational window.

Figure 2 reports the operational window in terms of \( \Phi_{FB} \) versus Pressure. Lean blow out limits are also reported for completeness, the procedure for LBO detection is described in a detailed manner in [9], in which also their pressure dependence is analyzed and explained.

Results are shown for different inlet temperatures and different inlet velocities. The figure depicts how the operational window drastically narrows with increasing the pressure and/or the inlet temperature (no margin left for P>11 bar).

As the hypothesis of flashback through the core region was rejected, no analysis by means of the Peclet number correlations was performed like it was done by other authors [2; 10]. As it is explained in [2], this kind of analysis provides good insights for core flow flashbacks, because it doesn’t account for boundary layer conditions. In the same study, which also deals with boundary layer flashback, this analysis was applied demonstrating its inefficiency in this case.
The propagation of the flame front through the boundary layer is dependent on the possibility of the flame to propagate along a surface (quenching distance) and on a local balance between the flow velocity of the incoming fresh air/fuel mixture in the boundary layer and the local flame speed. Both velocities vary upon changes of pressure, inlet velocity and inlet temperature.

The dependence of $\Phi_{FB}$ on $T_0$ and $U_0$ is analyzed in the following sections. More insight on the dependence of $\Phi_{FB}$ on $P$ can be find in [8].

![Figure 2](image_url)

**Figure 2  Operational window**

5. FB Propensity: Inlet Velocity Dependence

In figure 2 data for different inlet velocities (circles, and diamonds; taken for 10 bar and 14 bar) highlight that variations of this parameter do not have a strong impact on the flashback propensity. On first sight increasing of the inlet velocity could be seen as an approach to avoid FB, i.e. trying to blow the flame further away from the burner lips. This strategy shows to have little effect.

The minor difference in the FB limits is accompanied by a low sensibility of the flame front position on the inlet velocity as it was highlighted in [11]. This is explained by the increase of the Reynolds number at higher velocities, i.e. different turbulent characteristics, which enhance the overall flame surface by adding wrinkling. This enhancement leads to a higher fuel consumption rate. As result of this effect, the flashback propensity stays almost unchanged.

The balance between $S_T$ and $U_0$, expressed as $S_T/U_0$, undergoes a very little variation as depicted by figure 3, where the ratio $S_T/U_0$ is plotted versus $U_0$ for inlet velocities up to 150 m/s (data are compared at fixed $\Phi=0.42$). Increase of $U_0$ of almost a factor of 4 yields to a decrease of $S_T/U_0$ of about 5% only. This decrease is probably due to stretching effects and consequent local extinctions increasing with the increase in the Re number.
The magnitude of variation in $\Phi_{FB}$ in figure 2 of the curves representative for the $U_0$ variation (circles for 45 m/s and diamonds for 60 m/s) is in very good agreement with the magnitude of the variation of $S_T/U_0$ for the same inlet velocities which can be estimated from figure 3. The good matching of these two values leads to the conclusion that the slight reduced flashback propensity for higher inlet velocities must be totally attributed to the growth of the importance of stretching effects and their influence on the turbulent flame speed.

![Graph](image)

Fig. 3 Variation of $S_T$ for different $U_0$. P=5bar, $\Phi=0.42$.

6. FB Propensity: Inlet Temperature Dependence

It was found that FB propensity is significantly mitigated by reducing the inlet temperature. The variation of the inlet temperature at constant pressure has an impact on the reactivity of the mixture, summarized in the laminar flame speed, and on the turbulence conditions due to the correspondent variation in the Reynolds number. For the temperature variation described in this paper [573K -673K], changes in the turbulence conditions have been neglected (Re varies of about 20%).

The left hand side of figure 4 reports the same data points already presented in figure 2 for 10 bar and different inlet temperatures. In the current diagram data are plotted in the form of $1/\Phi_{FB}$ versus $T_0$. As highlighted in this figure flashback propensity increases by rising the inlet temperature with a power exponent of 4 (the solid line is the power fit).

In order to correlate the flashback propensity with the $S_L$, the temperature exponents of the law $S_L \sim T_0^x$ have been calculated (using GRI 3.0 as reaction mechanism) for a pressure of 10 bar and for different values of $\Phi$. The results are reported on the right hand side of figure 4 with filled symbols; the linear interpolation of those results is represented by the solid line. As shown here the dependence of $S_L$ on $T_0$ varies upon the equivalence ratio showing that lean flames are more sensible to inlet temperature variations. This observation suggests that using an inlet temperature reduction strategy against flashback is a favorable option for syngases. For these gas mixtures the design operative condition is leaner then for hydrocarbon flames; this is clear when comparing the adiabatic temperature for CH4 and syngas as it was done for example in our previous work [9].
The non filled symbols in the same figure represent the power exponent of the law $1/\Phi_{FB} \sim T_0^x$ calculated from the points on the left hand side diagram. For example “(1,2,3)” represents the power exponent calculated by using the points “(1)”,”(2)” and “(3)”.

The average exponent “(1,2,3)” of $1/\Phi_{FB} \sim T_0^x$ is in very good agreement with the trend of the exponents of $S_L \sim T_0^x$ (solid line on RHS), the other exponents show a small deviation.

Unfortunately there are no more data points available for a more accurate analysis.

The agreement leads to the conclusion that $S_L$ is the main parameter influencing FB propensity when varying the $T_0$.

![Figure 4](image)

**Figure 4** Dependence of FB propensity on $T_0$ (left). Power exponents “x” of the law $S_L \sim T_0^x$ for different $\Phi$ (right).

### 7. Conclusions

An investigation on flashback propensity for syngas mixtures was done at operative conditions typical for gas turbine applications. The boundary layer flashback mechanism is believed to apply for the actual experimental configuration. Dependence of flashback on pressure, inlet temperature and inlet velocity was described. Interpretations of the described behaviors were proposed.

The results show strong pressure dependence; the pressure trend narrows dramatically the operational window for high pressures and highlights the needing of experiments at these conditions.

Flashback propensity was found almost independent on $U_0$, showing that increasing $U_0$ when fighting (boundary layer) flashback is not a good strategy.

With the aim of mitigating flashback propensity, the most encouraging results were obtained by reducing the inlet temperature. In this case flashback propensity has been observed to scale like the laminar flame speed. Due to the strong power exponent (~4) especially for ultra-lean conditions, a local reduction of the inlet temperature is particularly suggested for syngas applications as for these fuels the operative conditions must be leaner than the ones typical for natural gas combustion.
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9. References