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INVESTIGATION OF CRITICAL OPERATING CONDITIONS FOR HYDROGEN FLAMES UNDER TYPICAL GAS TURBINE CONDITIONS

Holger Ax[1,*], Oliver Lammel[1], Rainer Lückerath[1], Joshua Gray[1], Benjamin Witzel[2], Lutz Blätte[2], Berthold Köstlin[2]

[1]German Aerospace Center (DLR), Institute of Combustion Technology
[2]Siemens Energy

ABSTRACT

The reliable operation of the core component of a modern jet-stabilized burner for large high-efficiency gas turbines with high power density and wide operating range was demonstrated in pressurized operation with 100% hydrogen.

High-pressure tests were performed at the high pressure combustor test rig HBK-S at the DLR Institute of Combustion Technology, mainly with hydrogen, but also with various hydrogen/natural gas mixtures. A single nozzle burner configuration, representative of modern jet-stabilized gas turbine combustion systems, was used for this purpose in a special optically accessible combustion chamber. Optical and laser-based combustion diagnostics was applied for flame characterization.

The investigation addressed the high reactivity of hydrogen and focused on operation at high pressures, high preheating temperatures and high flame temperatures, even beyond the specifications of state-of-the-art gas turbines, up to the operational limits regarding flashback. The influence of the operational parameters was investigated in detail on a generic configuration using a cylindrical quartz glass tube as mixing duct. Flame flashbacks could be directly observed within this optical mixing tube by high-speed OH chemiluminescence. Further tests were carried out with a newly developed metallic mixing duct, that was equipped with a special device to enhance the flashback resistance based on purge air.*

The results showed, for example, a strong dependence on the pressure. No flashbacks were observed in the investigated flame temperature range at low pressures (4–6 bar). Towards higher combustion chamber pressures, the operational limit in terms of flashback shows an asymptotic behavior. Higher jet velocities push the flashback resistance to higher adiabatic flame temperatures. The flashback prevention arrangement of the metallic mixing duct successfully extends the operational range at all conditions compared to the optical mixing duct.

*Corresponding author: holger.ax@dlr.de
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1. INTRODUCTION

The integration of hydrogen into gas turbine systems aligns with global CO_2 reduction targets, such as those outlined in the Paris Agreement, which aims to limit global warming to well below 2 degrees Celsius above pre-industrial levels. Many countries have set ambitious national targets for CO_2 reduction, often aiming for net-zero emissions by mid-century. The adoption of hydrogen as a fuel for gas turbines can significantly contribute to these goals by decarbonizing a substantial portion of the power generation sector.

In addition, real-world applications demand the capability to operate not only on pure hydrogen, but also on natural gas–hydrogen blends between 0% and 100% H_2 concentration in the foreseeable future. Innovative and reliable, state-of-the-art gas turbines, for example the Siemens SGT6-9000HL [1], are expected to play a crucial role in stabilizing the energy grid with their high load gradients and rotating mass while renewable energy sources continue to grow but remain volatile. They support sector coupling and enable the use of alternative fuels such as green hydrogen from power-to-X applications. Hence, hydrogen capable gas turbines are essential for a CO_2 reduced and ultimately CO_2-free electricity supply. The aim of the presented work is to develop a jet-stabilized combustion system for the next generation of gas turbines that meets the outlined requirements on fuel flexibility and maintains low emissions and high gas turbine efficiency at the same time.

However, the integration of hydrogen into gas turbine systems is not without challenges. Hydrogen's distinct combustion characteristics, such as its high flame speed, wide flammability range, and low ignition energy, necessitate fundamental modifications to traditional natural gas combustion systems. One of the main risks that arises with the use of hydrogen as fuel in (partially) premixed combustion systems is flame flashback due to increased reactivity [2–4]. The optimization of the gas injector concepts and mixing arrangements are crucial to control the combustion process, especially for realistic thermodynamic boundary conditions present in high preforming gas turbines with high pressures and adiabatic flame temperatures.

In the present study, combustion tests at gas turbine relevant conditions, i.e. elevated pressure and high preheat temperatures, were carried out on a single nozzle configuration for jet-stabilized flames at critical operation conditions regarding flashback. The single nozzle burner is a derivative of a multi-nozzle gas turbine combustor, but it reproduces the original mixing duct configuration and eliminates the influence of adjacent flames. Two different types of mixing ducts were used: first, a quartz glass cylinder with an original fuel injector was used as mixing duct in order to provide optical access to the upstream flame propagation within the mixing tube during flashback. Second, a metallic mixing duct was used together with the same injector, resembling the original configuration. The metallic mixing duct, however, was equipped with an additional device that shall prevent flashback or at least extent the operational limits to higher flame temperatures before flashback occurs. The primary influencing variables such as pressure, inlet temperature and jet velocity were systematically varied to characterize the flame behavior in general and, in the second step, to specifically provoke flame flashback into the mixing duct.

The paper structure continues with the description of the experimental setup, including the combustor, the different mixing ducts and the measurement techniques, that were applied. The following presentation and discussion of the results is separated into findings with the optical mixing duct and those with the metallic mixing duct.

2. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUES

The jet-stabilized single-nozzle burner was operated and tested in the high-pressure combustion chamber test rig (HBK-S) at the DLR Institute of Combustion Technology in Stuttgart. The test rig and the combustion chamber configuration with the burner are described in the following sections. Basic measurement techniques for flame characterisation were used during all measurements. These standard measurement techniques are also described in more detail below.

2.1 Test Rig HBK-S and Burner

The high-pressure combustion test rig is designed for testing and analyzing scaled gas turbine burners or original burner components under technically relevant conditions. It is characterized by a large optical access for the application of optical and laser-based measurement techniques. This is made possible by up to 12 high-pressure windows, which can be mounted in 4 radial and 3 axial positions. The size of the windows at the first axial position is $441 \times 140\,mm^2$ and at the following two $160 \times 140\,mm^2$.

The jet-stabilized burner concept has proven to be an alternative for reliable and fuel-flexible burners with low emissions [5–7]. Initial feasibility studies have demonstrated its suitability for operation in modern gas turbines in terms of power density and high temperature combustion [8]. The burners of this early stage had only one combustion stage, as shown in Figure 1a in [9].

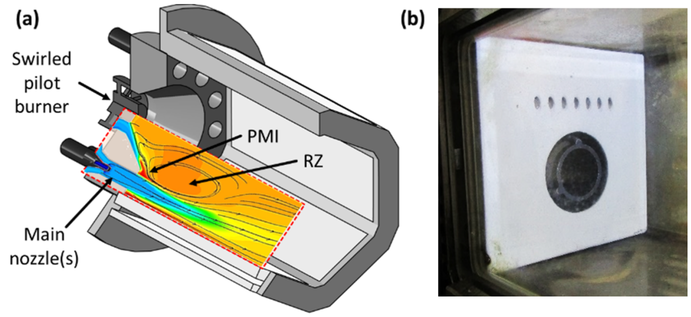

FIGURE 1: Left: Piloted jet-stabilized multi-nozzle combustor with typical mean flow field and temperature from numerical simulations; right: single nozzle configuration of presented work.

In the following, possibilities for an extension of the operating range were investigated [9, 10]. As a result, a combination of a jet-stabilized main stage and a proven swirl burner was selected as a pilot stage to push further the development for the application in large gas turbines (see Figure 1b in [9]). The next development step was the transition to burners with multiple combustion stages. Model burners of this type were investigated in optically accessible combustion chambers, including burners with nozzles in several rows and a central burner. In this way, radial, axial and sectoral staging concepts could be combined to achieve high degrees of operational flexibility. At the current stage of development, the scientific focus is on flexible multi-fuel injectors and downstream mixing. In order to gain the best possible access to all relevant parameters and to be able to obtain and compare results from both numerical simulation and high pressure tests using optical measurement techniques, a model burner featuring the key components was built. Based on the findings from earlier investigations on single nozzle burners [11–18] or burners with multiple nozzles [19], the modular burner combines the following features: (a) the jet nozzle is of original size, so that injectors, the mixing concept and partially additional equipment can be tested without modifications; (b) a pilot burner that can stabilize the main stage. These features are essential for the analysis of different mechanisms of flame stabilization with and without pilot flame.

The configuration of the piloted single nozzle is shown in Figure 1b) and represents a section of a jet stabilized gas turbine burner (Figure 1a)). The nozzle with a diameter of d_M is located off-centered by 10 mm in the square combustion chamber in order to give space for the pilot stage and to create a pronounced and stable recirculation zone on one side of the nozzle, which is a characteristic of jet-stabilized burners; the corresponding recirculation zone in the complete burner system is accordingly located in the center of the combustion chamber (see Figure 1a)). The corresponding flow field for a larger single nozzle is shown in Figures 6, 8 and 10 of [13].

The air supply line in front of the plenum of the main stage is deflected twice by 180°. The main nozzle (the mixing duct), the air deflection, the injector and some additional equipment are interchangeable. The injectors are located in the center of the mixing tube. The pilot stage consists of 7 nozzles with a shared air and fuel plenum. The pilot stage nozzles are inclined at an

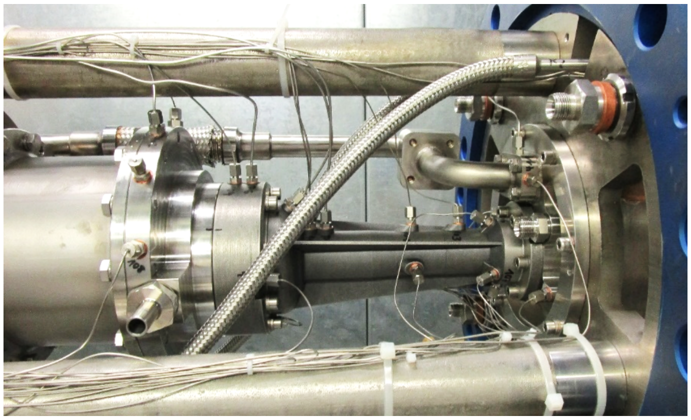

FIGURE 2: Metallic mixing duct, mounted to the combustion chamber on the right; air in-take to the left; supporting frame on top and bottom.

FIGURE 3: Optical mixing duct. Left: single nozzle with quartz glass mixing duct before mounting to combustion chamber; right: setup of high-speed OH* CL for flashback observation in the optical mixing duct.

angle of 60° to the main nozzle. Figure 1a) shows the area of interaction between the pilot stage and the main stage (PMI) for a whole burner with the swirl pilot burner set back (numerical simulation from earlier work [20]). The new model pilot burner was designed to have similar or identical characteristics: The jets of the inner nozzles of the pilot stage hit the jet of the main nozzle, while the outer ones are next to it. Furthermore, it was important that the pilot stage could be operated completely independent from the main stage, i.e. the air mass flow for the pilot stage was set and preheated separately via a separate line. In this way, both air and fuel for the pilot stage could be switched on and off during operation.

The entire arrangement of mixing tube, injector, air inlet and additional equipment could be mounted in 2 axial positions, resulting in a mixing tube end in the combustion chamber flush with the burner front plate or protruding beyond the burner front, respectively.

2.2 Metallic Mixing Duct

The tube that forms the main nozzle, the injector and additional equipment are manufactured using the SLM process (selective laser melting). The contours and surfaces through or over which the flow passes are identical to those of the industrial partner Siemens Energy; this also applies to the dimensions.

Additional devices can also be installed in the metal mixing tube, including a device for influencing the flashback limits. This device can, for example, be supplied with a purge air whose quantity can be varied without changing the global flame conditions. In the optimum case, flashbacks in hydrogen operation can thus be avoided beyond the operating limits of the combustion system of the gas turbine. Numerous thermocouples are fitted around the circumference and along the length of the mixing duct to measure the wall temperature. The metallic mixing duct can be seen from the outside in Figure 2.

2.3 Optical Mixing Duct

The metallic mixing tube can be replaced by an optical mixing tube, which can be seen in Figure 3. This optical mixing duct is a cylindrical quartz glass tube with constant inner and outer diameters and was specially designed in order to directly observe flashbacks within the mixing duct. For this reason, the quartz glass tube is convectively cooled on the outside with a cooling air flow in order to enhance the resistance to high thermal loads. For the tests with the optical mixing duct, the combustion chamber is moved downstream so that the optically accessible area of the test carrier is no longer limited to the combustion chamber, but also covers the upstream burner assembly with the optical mixing tube.

Unlike the metallic mixing duct, the optical mixing tube has no additional device to prevent flashback. Accordingly, it comes close to the geometries of mixing tubes of earlier investigations, which were carried out, for example, with scaled, but complete jet-stabilized burner systems for hydrogen [8, 11]. However, there are important differences: (i) the fuel injector in the current investigations is the same as for the metallic mixing duct and, thus, an original component and significantly further developed; (ii) the technical mixing corresponds to the original; (iii) the mixing duct investigated in this study has a larger diameter, which results in longer physical length scales for flow formation and mixing.

An original (gas turbine typical) inner contour is no longer possible with the optical mixing tube. Additional equipment for the mixing pipe and wall-mounted thermocouples can also no longer be fitted. However, the fuel injector is still identical to the original.

2.4 Combustion Chamber

The combustion chamber is an assembly of metal and quartz glass with an internal square cross section of $95 \times 95\,\text{mm}^2$ and a length of 843 mm (see Figure 1). The length of the combustion chamber was chosen in order to achieve realistic residence times in the combustion chamber similar to those in a real gas turbine. At the outlet, the combustion chamber narrows to a round cross section with a diameter of 58.4 mm. Optical access is ensured by 5 rows of windows on each side of the combustion chamber, with one row of windows being shorter than the other four. The windows are cooled convectively by an air stream flowing through a gap between two superimposed panes. In this way, there is no need for cooling air to be channeled into the inside of the combustion chamber, which would influence the combustion process as false air. The innermost glass surfaces were therefore exposed to the high temperatures of the flames and were regularly replaced. The wall temperature inside the combustion chamber varies between 920–1450 K [21], depending on the operating conditions. The water-cooled metal frame only accounts for a small portion of the inner surface area (around 7%).

Pressure pulsations were measured with a fast (10 kHz) pressure transducers (Kistler, model 4045A50, piezo-resistive absolute pressure sensor for a measuring range of 0–50 bar). The signals were then amplified (Kistler, model 4603B00) and recorded at a sampling rate of 20 kHz.

2.5 Exhaust Gas Probes

The exhaust gas composition was measured by extracting the exhaust gases from the combustion chamber using an exhaust gas probe. The probe had three separate openings for sampling at different positions. The three independent lines allowed the flue gas to be routed to the measuring device either individually (measured one after the other) or together (mixed and measured integrally). The exhaust gas was quenched at the inlet of the probe holes by a pressure drop and by impacting a cold wall. Only results from integral measurements are presented in this report. The exhaust gas analysis is performed during operation with a system from ABB, which directs the exhaust gas through a cooler and then measures it in a dry state. The system was calibrated every day before and after measurements to prevent deviations and measurement inaccuracies. During operation, the exhaust gas analysis values are automatically stored at 5 s intervals.

2.6 Video Cameras

Several video camera systems are used at the test bench to monitor the flame, the fixtures in the optically accessible pressure vessel (i.e. burner, combustion chamber, etc.) and the test bench itself, thus, helping to ensure safe operation. Several of these non-scientific cameras (Bosch VBN-4075-C51, 1/3", 720TVL) are focused on the flames and provide a continuous image of the heat release. In operating conditions with (proportions of) natural gas in the fuel gas, these cameras without spectral filtering mainly register the glow of the CH* molecule (see also the following section), which emits in the blue spectral range. In the case of flames with 100% hydrogen, the radiance of water is recorded in the red spectral range on the one hand, and a spectrally broad background on the other; in this case, the eye sees a bluish glow again. This broadband luminescence can and is used (in addition to OH*) as a qualitative marker for the position and shape of the flame. In addition, the observation cameras record every emission that emanates from glowing metal surfaces.

2.7 OH* Chemiluminescence (OH*-CL)

OH* chemiluminescence is based on the detection of the intrinsic luminescence of the electronically excited OH* radical, which emits a photon during relaxation. The signal strength of OH* CL depends primarily on the concentration of the OH* radical. These radicals are formed by chemical reactions during combustion, primarily via the reaction paths $CH + O_2 \rightarrow OH^* + CO$ [22] and $H + O + M \rightarrow OH^* + M$ [23] in hydrogen combustion in the region of maximum heat release. Due to the short lifetime of OH* at the present pressures, OH* CL only occurs in the flame zone, which is why this measurement technique is suitable for determining the shape and position of the flame zone. [24]

The chemiluminescence was recorded with different cameras. For continuous observation, two cameras with "low speed" frame rates (10–50 Hz) were used (LaVision Imager sCMOS, 1280 × 1080 pixels), each equipped with an image intensifier (LaVision IRO) and observing the flame from above and from the side, respectively. Different UV lenses (UV-Nikkor, focal length f = 105 mm; Halle Nachf., focal length f = 64 mm) were used with bandpass filters (312 ± 15 nm) for detection.

In addition, an image intensified camera with a high repetition rate (typically 5 kHz) was used to observe the movement and expansion of the flames before and during flashback events in the combustion chamber or within the mixing tube (LaVision HS camera 5, SN VC13-0105, with LaVision Highspeed IRO SN VZ08-0164). A UV lens (Halle Nachf.) with a focal length of f = 64 mm and a bandpass filter (312 ± 15 nm) were used for this purpose.

3. RESULTS

In the first section of this chapter, stable operating states are shown and the general operating parameter ranges are specified. In the second and third sections, observations of flame flashbacks from the measurements with the optical mixing tube and the investigation of influencing parameters are presented as examples. In the last section, the effectiveness of the measure for influencing the operating limits with the metallic mixing duct is discussed.

3.1 Measurement Procedure and Stable Operating States

Stable operation with natural gas and hydrogen in the burner with metallic mixing tube is shown in Figure 4 as single images from videos. A lifted flame can be seen at the top for pure natural gas operation, which is stabilized by recirculation without the pilot burner. On the recirculation side, the flame base is located further upstream where the flame reactions are induced in the shear layer between fresh gas and recirculated exhaust gas. In pure hydrogen operation, the flame is more cone-shaped, significantly shorter, and the flame stabilizes close to the nozzle orifice. The flame appears paler due to the lack of CH* CL.

Table 1 provides an overview of the investigated ranges of the main operating parameters; the table does not differentiate between metallic and optical mixing tubes.

TABLE 1: Overview of the operating conditions for both types of mixing tubes.

Parameter	Symbol	Unit	Range
Pressure	p	[bar]	4 ... 16
Inlet Temperature	T_{in}	[°C]	250 ... 550
Jet Velocity	v_{jet}	[m/s]	50 ... 150
Flame Temperature	T_{ad}	[K]	1550 ... 2487
Air Equivalence Ratio	λ		1.2 ... 2.7
Hydrogen Amount	H_2	[%]	0 ... 100

Initially, several test days were used to characterize the burner in order to carry out flame temperature variations (λ-sweeps) with

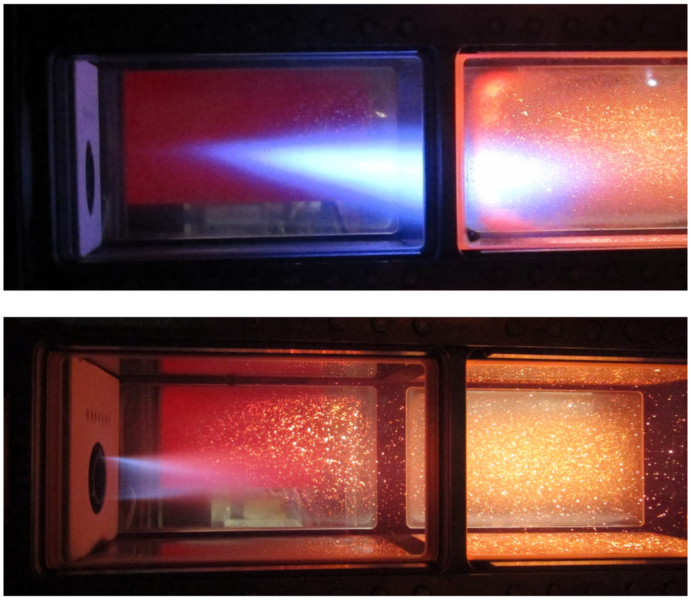

FIGURE 4: Video stills of a lifted natural gas flame (top) and a hydrogen flame (bottom) anchored close to the nozzle exit in the investigated single nozzle configuration.

natural gas and hydrogen and to record the flame position, exhaust gas emissions and thermal acoustics, together with all mass flows, pressures, differential pressures, media and material temperatures (by thermocouples). The additional device at the metallic tube to prevent flashbacks was in operation with a high proportion of purge air. There was no flashback into the mixing tube or self-ignition in the mixing tube observed.

Subsequently, series of tests were carried out, in which flashbacks were induced at the end (see the following sections). This was made possible by using either the optical mixing tube (which has no additional device to prevent flashback) or by varying the purging air in a wide range (from maximum to zero) in the metallic mixing tube. For the test series with natural gas, the burner was run at the target operating conditions to be analyzed (pressure, inlet temperature, jet velocity). The natural gas flame generally had a flame temperature of around 1700°C before the fuel was stepwise switched to 100% hydrogen. During the switching procedure, the flame temperature was lowered to values of $T_{ad} < 1400°C$ with increasing hydrogen content (increasing air-fuel equivalence ratio λ). The flame temperature of the hydrogen flame was then increased in steps; in most cases, the step size of the steps was $\Delta\lambda = -0.1$. Each step was either stabilized as an operating point and all standard measurement techniques were carried out, or several minutes were waited while the operating parameters remained stationary. If no flashback occurred during the waiting period, the measurement series was continued.

Figure 5 shows hydrogen flames at a combustion chamber pressure of 8 bar in a flame temperature range of 1365–1581°C. The hydrogen flames do not show any significant changes in shape over the course of the series; on average (column on the left hand side), they are consistently conical and are hardly lifted from the rim of the mixing tube. The colder flame (top row) stabilizes slightly closer to the nozzle on the side facing the recirculation

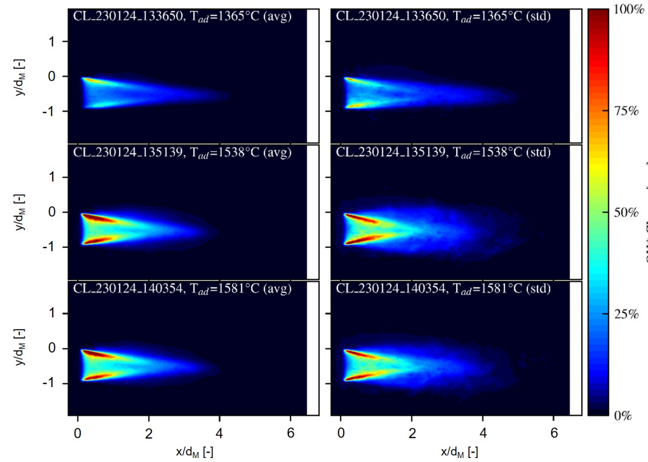

FIGURE 5: Flame shapes and positions of hydrogen flames at different flame temperatures from OH* CL. Left column: averaged OH* distribution (avg); right column: according standard deviation (std); all images scaled to a common maximum, intensity of fluctuations multiplied by a factor of 3.

zone. The length of the flames hardly changes. By increasing the fuel quantity, the OH* CL signal increases due to an increase in heat release. The areas of maximum reactions lie in the shear layer between the fresh gas jet and hot burned gas; the fluctuations are also high in the same regions (column on the right hand side). The tip of the cone shows less heat release and less fluctuations. For the higher temperature flames, it can be seen that the areas, in which heat release fluctuations can be observed, broaden at the tip of the cone.

Several of such flame states were stabilized and investigated in the multi-dimensional parameter space (pressure, inlet temperature, jet velocity, mixing tube type and purge air volume if applicable). In this context, it is important to note that none of the operating conditions exhibited significant thermoacoustic instabilities; the amplitudes of the measured dynamic pressure all remained below the usual limit values for the individual nozzle investigations.

3.2 Flashback in the Optical Mixing Tube

Observation of the Flashback. In order to investigate the flame propagation within the optical mixing duct during flashback in more detail, an image intensified high-speed camera was used to record the OH* CL signal of hydrogen flames. In most cases, a repetition rate of 5 kHz was selected for a temporal resolution of 200 µs. This allowed for the utilization of the full resolution and size of the camera chip. Figure 6 shows an exemplary result for measurements at 8 bar with the mixing tube flush with the combustion chamber. The top two images are two randomly selected images of OH* CL. They show the typical shape and signal distribution of a hydrogen flame that burns in the combustion chamber as described above. The burner end plate (and thus the end of the mixing tube) is marked with a blue line; the mixing tube is located upstream of the line. As can be seen in Figure 3, the optical mixing tube requires a holder on the combustion chamber side, which restricts the optically accessible area: the region of

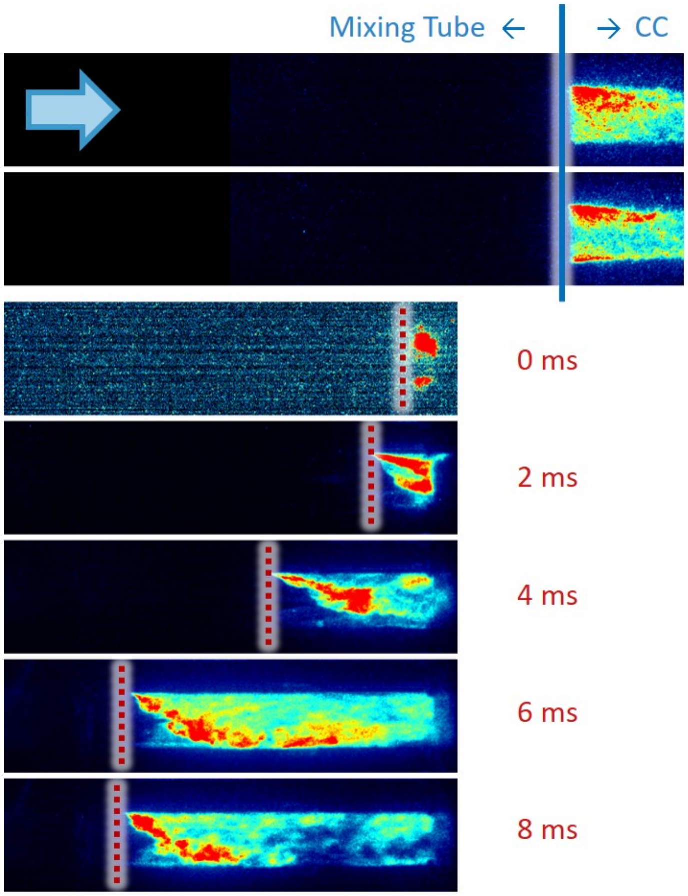

FIGURE 6: Direct observation of a propagating flashback in the optical mixing duct by high-speed OH* CL (5 kHz). Upper two images: stable hydrogen flame in the combustion chamber, random single images. Lower 5 images: propagating flashback in optical mixing duct, every 10th image shown.

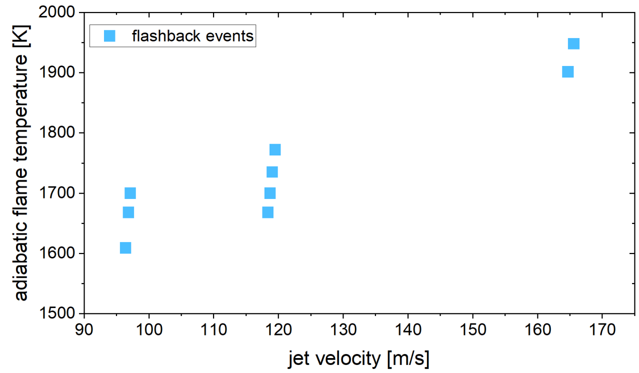

FIGURE 7: Operational limits for jet-stabilized hydrogen flames using the optical mixing tube: dependence of flashback on the jet velocity.

the mixing tube directly upstream of the combustion chamber cannot be seen when installed flush.

Proceeding with the method described above, a flashback is initiated in the following. The high-speed camera was focused exclusively on the mixing tube and recorded continuously, even while operation was still stable. As soon as a flashback was observed, the fuel supply was (manually) stopped as soon as possible with a quick-action stop valve and the last 3 seconds of the high-speed camera series were saved. This results in image series such as in the lower 5 OH* CL single images of Fig. 6. Due to limited space here, only every tenth image is shown. The images shown are scaled to the intensity maximum of each single image. In the image labeled 0.0 ms, the upstream flame front of the hydrogen flame reaches the optically accessible area of the mixing tube. In the following, the flame passes through the mixing tube within 6 ms close to the fuel injector. This corresponds to an upstream propagation velocities of around 15 m/s with downstream flow velocities (of the nozzle block profile) of around 100 m/s.

As it can be seen in the image sequence, the leading flame root propagates along the wall of the mixing tube. This was observed in most of the cases as far as it could be judged by OH*-CL images; no flashback was detected spreading through the center of the mixing tube. This observation supports the understanding in the literature, that flashback in jet flames is predominantly driven by the mechanism of boundary layer flashback [3, 4, 25]. In a few cases, the leading flame root was not observed to propagate along the upper or lower wall. However, due to the line-of-sight nature of CL, and the short period of time until the fuel is switched off, it is not possible to reliably distinguish whether the flame is burning in the full volume of the mixing tube. After the upstream flame lingers briefly at the end of the injector, the flame often moves to the fuel openings within a few ms and finally anchors there.

No detailed investigations have yet been carried out to determine whether a flashback that has already started can still be interrupted by intervening in the operating parameters of the combustion system without switching off the fuel. The optical mixing tube can only be used to a limited extent for this purpose due to operational safety concerns. In anticipation of the following sections, it should be noted that the metal mixing tube was already damaged within a few seconds after flashback due to the high flame temperatures; the optical mixing tube, on the other hand, could be operated for a longer period even with a flame within.

Influence of Jet Speed and Pressure. The optical mixing tube was used to determine the primary dependencies of flashback tendency on operating parameters for jet-stabilized systems. The influence of jet velocity, inlet temperature and pressure on the operating limits can thus be analyzed.

Figure 7 shows the adiabatic flame temperatures of the operating points, at which flashbacks occurred, in dependence of the jet velocity. The pressure in the combustion chamber was kept constant at 8 bar and the air preheat temperature at $T_{in} = 400\,°C$. Several flashback tests were carried out at different velocities in order to enhance the statistical significance. Each test series started at flame temperatures of around 1550 K, which means, that the flames were stable in the region below the plotted samples, i.e. at lower flame temperatures. As a general trend, it can be seen that flashback events occur only at higher flame temperatures with increasing jet velocity. This is in agreement with the understanding of boundary layer flashback, that the burning velocity

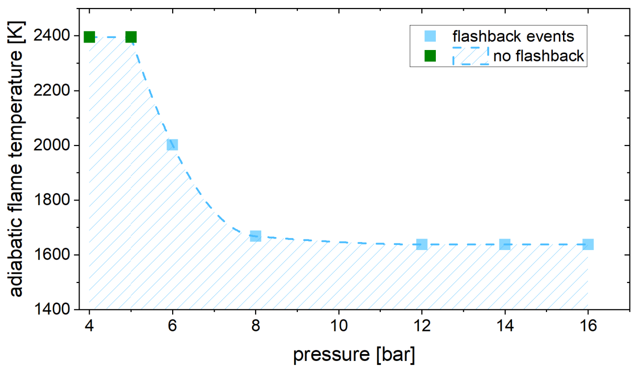

FIGURE 8: Operational limits for jet-stabilized hydrogen flames using the optical mixing tube: dependence of flashback on the combustion chamber pressure.

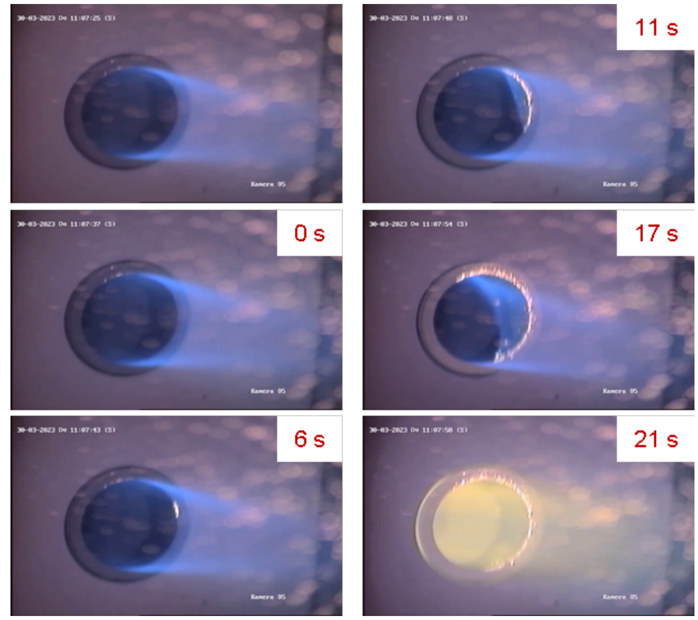

FIGURE 9: Observations before a flashback in the optical mixing duct (video stills). Image 1: stable flame (no label). Images 2–6: Change of flame root at nozzle exit with time scale as label, full flashback in shown the last image.

close to the wall has to outbalance the flow velocity to propagate upstream within the mixing tube. It can also be seen, that there is a certain scatter of flashback events for similar jet velocities. For example, the samples at a jet velocity of around 120 m/s were all taken at the same operation conditions, i.e. with the same amount of fuel. However, the adiabatic flame temperature, at which flashback occurred, varied in a range of around 100 K. The specified jet velocity was calculated from the air and fuel volume flow, which is the reason why for each cluster of samples around the same jet velocity, the samples with a higher adiabatic flame temperature also show a slightly higher jet velocity.

Figure 8 shows the adiabatic flame temperatures of operating points, at which flashbacks occurred, versus the pressure parameter. These measurements were taken at a constant inlet temperature of 400°C and a constant air velocity of 110 m/s. As before, the shaded area below the symbols indicates stable, reliable operation; the limit line is a spline interpolation of the measured operating limits. According to this result, the operating limits of jet-stabilized flames depend on the pressure, with a differently strong dependence in certain pressure ranges. At high pressures, the curve flattens out asymptotically and the limit of stable operation is hardly worsened by increasing the pressure. At medium pressures, there is a steep drop in flashback temperatures. At low pressures (green points), on the other hand, no flashback occurred, even at adiabatic flame temperatures above the specifications of state-of-the-art combustion systems (measurements up to around 2060°C). Higher temperatures were not tested since they were out of technical relevance.

Observations before the Flashback. The operating strategy for carrying out the tests was to interrupt the fuel flow as quickly as possible after the flashback was detected in order to prevent damage to the burner components. Thermocouples were installed along the metal mixing tube, which detected temperature changes close to the inner wall of the mixing tube. An additional thermocouple was installed in the tip of the fuel injector, which was present in both burner assemblies (glass and metal). All thermocouples in the mixing tube and in the injector showed abrupt rises of temperatures during a flashback. Two basic levels of material temperature were assumed: the inlet temperature (further upstream) or an equilibrium temperature of inlet temperature and flame operation (near the nozzle exit). The amplitude of the temperature rise also depends on the axial position of the respective thermocouple (ΔT_{TCx} = 30–150 K) and is limited by the duration of the event. All thermocouples could be used (simultaneously) in the burner control system to automatically interrupt the fuel mass flow by means of an individual limit value. At the same time, a person was deployed whose (sole) task was to visually detect a flashback and switch off the fuel flow under manual control. The most obvious signs of this were (i) a change in the flame position or the recognizable flame length in the combustion chamber and (ii) the end of the mixing tube lighting up, especially in the case of the metal mixing tube. After several tests, it was found that the "flame observer" method was faster than the thermocouples.

At the same time, it was found that there was (very often to almost always) a kind of pre-announcement of the flashback. This is shown for the optical mixing tube in Fig. 9. It shows video stills of the hydrogen flame in stable operation in the top left of the first image. Despite unclear reaction paths, the blue chemiluminescence is probably a good marker for the flame reaction. The subsequent images (column to column) show phenomena at the flame root, the time scale of which is labeled on each partial image. First, there is a (white, slightly orange) glow at the inner edge of the mixing tube rim, usually only at a spatially very limited segment of a few millimeters (see 6 s). From there, longer spatial sections of the inner edge of the nozzle rim light up, the end points of which appear to be connected by a line of the flame front (11 s, 17 s). The flame appears to move slowly into the interior of the mixing tube. Then the complete flame flashback occurs abruptly (21 s); the fuel flow is then interrupted. High-speed recordings show that the flashback through the mixing tube only occurs on a millisecond time scale in every case (as already shown above).

This second time scale of several seconds of advance notice of the flashback has been repeatedly observed for the optical mixing tube; however, further evaluation of the measurement data is still required. Measurement results not shown here revealed that the environment of the optical mixing tube (holder on the burner front, mixing tube flush or protruding into the combustion chamber) has a significant influence on the timing. The phenomenon was similarly observed for the metallic mixing tube and used to manually switch off the fuel in the event of a flashback. After identifying the phenomenon shown in Fig. 9, a dedicated camera was used to visualize it (viewing direction, image section), which had previously not been used for this purpose in all test series. Further investigations are necessary in order to be able to make reliable statements for the metallic mixing tube.

One possible explanation of the phenomenon: at the limit operating conditions for flashback, there is initially only a slight change in the flame (e.g. distance to the material; small-scale local heat release possibly at damage or unevennesses that influence the flow locally), which leads to a change in temperatures in the surrounding solid material, whereby heat dissipation plays a role. This change then leads to boundary conditions that favor flashback.

3.3 Metallic Mixing Tube with Flashback Arrestor

As discussed in Chapter 2 and in the previous sections, the technical details of the optical and metallic mixing tubes are different. Above all, the metallic mixing tube has an additional device with purging air to prevent flashbacks. The effectiveness of this additional device is illustrated in Fig. 10. The data is limited to tests at a combustion chamber pressure of 8 bar and jet velocities < 120 m/s, but different inlet temperatures and jet velocities are shown.

An arbitrary test number is shown on the x-axis. Tests with the optical mixing tube (red diamonds) are used as a baseline, for which the adiabatic flame temperature of the flashback limits is shown. The black squares summarize extensive measurements with the metallic mixing tube in which no flashbacks could be found up to the specified flame temperatures. Higher flame temperatures were not tested. Flashbacks could effectively be prevented because the purge air volume for the flashback arrestor was maximum and above the currently possible gas turbine operating parameters. It is immediately recognizable that this additional device can shift flashback limits very effectively.

The green triangles, the cyan triangle and the blue dots show data for configurations in which the additional device was operated with intermediate amounts of purging air, given as fractions of the maximum purge air in the legend; the plotted points are measured flashback arrestor limits (flashback events). Even a low volume of purging air shifts the limits of stable operation towards higher flame temperatures and is therefore in the relevant range for modern gas turbines (green triangles). Measurements with about a tenth of the maximum purge air (blue dots), on the other hand, showed no significant influence on the flashback propensity compared to the optical mixing duct (red diamonds) without purge at similar operating conditions. It's worth noting,

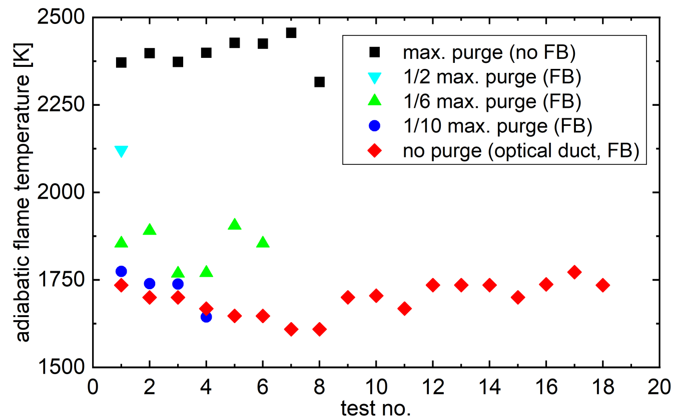

FIGURE 10: Comparison of flashback limits for the optical mixing duct and the metallic mixing duct with additional purge air device (legend: FB = flashback).

however, that the different materials of the optical mixing duct (quartz glass) and the metallic mixing duct also have in influence on the occurrence of flashback. Due to a higher tip temperature of quartz glass tubes compared to stainless steel, the flashback propensity is higher for the optical mixing tube [26].

The expression of the flashback propensity as a turbulent boundary layer gradient for the presentation of the results is not suitable in this case, since the application of the purge air device leads to a deviation from the typical velocity profile of a fully developed turbulent flow in the mixing duct, which is a primary assumption for the theoretical prediction of a critical velocity gradient [4, 25, 26].

4. SUMMARY

Jet-stabilized burners are a modern solution for gas turbines, characterized by fuel and load flexibility, low emissions and high reliability. Single nozzle tests offer an adequate and already proven means for this, as they use original components under defined boundary conditions and allow detailed investigations in optical combustion chambers.

In these investigations, operating limits for various operating states of hydrogen flames under realistic gas turbine conditions were tested, whereby influencing variables such as pressure, inlet temperature and jet velocity were systematically varied. A strong dependence on pressure was observed, with no flame flashbacks at very low pressures in the investigated flame temperature range and an asymptotic behavior of the operating limit at higher pressures. Higher jet velocities shift the limits of stable combustor operation towards higher adiabatic flame temperatures, as well as lower preheat temperatures.

Flame observations with high-speed OH* CL within the optical mixing duct showed that flashbacks happen in only few milliseconds and mostly occur along the wall. This supports the understanding that boundary layer flashback is the primary mechanism in this type of jet-stabilized burner configuration. Self-ignition was not observed. The flashbacks were preceded by the lighting up of small spots at the rim of the nozzle exit, both with the optical and the metallic mixing duct.

The additional device in the metallic mixing duct to prevent flashback based on purge air has proven a reliable measure to shift the operational limits to higher flame temperatures.

5. CONCLUSION

The feasibility of operation with 100% hydrogen at gas turbine relevant conditions has been confirmed, but this requires intensive reliability testing, particularly with regard to flashback and auto-ignition due to the high reactivity of hydrogen. The investigations presented here determined the operational limits for various operating conditions for hydrogen flames in a single nozzle configuration. However, a transfer of the results to multi-nozzle gas turbine burners regarding the operation conditions at which flashback occur is difficult, since the heat transfer from adjacent flames into the material of the burner front surrounding the nozzles has an impact on the flashback propensity.

On the other hand, there is still need of more investigations on fundamental aspects that affect flashback, such as the surface roughness of the mixing duct or the observed local increase of heat transfer on the nozzle rim preceding flashbacks. Even at well defined lab-scale conditions, the occurrence of flashback shows a statistical scatter regarding the operation conditions. More tests could increase the significance of the results and the reliability as validation data for the development of numerical models.

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