September, 21st - 24th 2014

FLAME STRUCTURE 2014

8th International Seminar on Flame Structure

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Investigation of flame stabilization in premixed high momentum jet flames at elevated pressure by laser measurement techniques

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Abstract

The premixed turbulent flames of a jet stabilized generic burner with 3 nozzles were experimentally investigated with respect to flame stabilization mechanisms. The experiments were conducted at gas turbine relevant conditions at elevated pressure and with preheated air in a high-pressure test rig with optical access. Both natural gas (NG) and pure hydrogen (H2) were used as fuels, resulting in two different cases which are compared in this contribution. The flames and flow fields were characterized by OH*-chemiluminescence (OH*-CL), Particle Image Velocimetry (PIV) and laser Raman scattering. The measurements were conducted in the center plane of the combustor and evaluated on a single shot basis, which allows the comparison of mean values and fluctuations. While PIV results show that the flow velocity field is rather similar for the NG and the H2 flame, the flame position and shape revealed by OH*-CL and Raman measurements show large differences and indicate a fundamentally different coupling between flow field and chemical reactions for the two investigated cases.

Introduction

Jet stabilized combustion systems provide an interesting alternative for gas turbines replacing state of the art swirl stabilized combustors. These jet combustion systems, also termed FLOX®-combustor [1,2], have been shown to operate reliable, load-flexible and fuel-flexible with low pollutant emissions at gas turbine relevant conditions [3,4,5]. Key feature of a FLOX® burner is the large inner recirculation zone, which brings hot burnt gas back to the combustor nozzles, where it ignites the incoming high- momentum jet of fresh unburned fuel/air mixture and thus stabilizes the flame. However, the process of mixing, ignition and stabilization is not very well understood and offers many unanswered questions.1

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Especially the need for modern gas turbine combustion systems to operate with a variety of gaseous fuels like natural gases of different quality, low caloric gases from gasification, syngases with high hydrogen content or pure hydrogen alters the flame stabilization mechanisms and operating limits within one combustion system drastically. In particular, hydrogen poses major risks to the safe operation of a gas turbine due to its liability to flashback and undesired auto-ignition.

Experiments with advanced optical diagnostics can help in answering these questions. Therefore, a high-pressure experiment is described in the following sections, which provides a deeper insight into the turbulent flow and thermo-chemical states of natural gas and hydrogen flames. The results also provide an extensive data base for the validation of numerical simulations. Note that the results presented in this work only depict a fraction of the measured data, which offer additional evaluation and analysis in future.

Experimental Approach

High-Pressure Test Rig and Test Combustor

The experiments were conducted at the high-pressure combustion test rig (HBK-S) of the DLR Institute of Combustion Technology in Stuttgart (see [3,5] for details on this test rig).

The test carrier is a rectangular combustion chamber with a 3-nozzle jet combustor and is schematically shown in Figure 1.

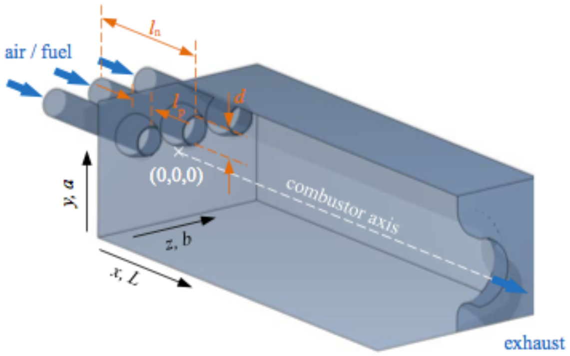

Figure 1: Test combustor with dimensioning

The nozzles are linearly arranged in *z-direction* and off- centered in *y-direction* to allow for the development of a recirculation zone, which is crucial for the flame stabilization in a FLOX®-burner. Thus, the test combustor design approximates a sector of a full FLOX® gas turbine burner. It is however strongly simplified and not considered to be a technologically relevant option. Also for the sake of simplification, the fuel was added to the air flow far upstream of the nozzles, so that the inflowing fuel/air mixture can be considered fully premixed and no influences of mixing need to be taken into account. The main dimensions of the test combustor are given in Table 1. The origin of the used coordinate system is located at the center of the burner front plate.

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Optical access is provided by 8 quartz glass windows.

nozzle diameter	d	20
nozzle length	l_n	109
nozzle protrusion	l_p	20
nozzle positions	$x; y; z_i$	20; 20; -40, 0, +40
comb. chamber length	L	320
comb. chamber outline	$a \times b$	100 × 140
diameter at outlet	e	50

Table 1: Dimensions of the combustor (in mm)

The fuel/air mixture was preheated to the temperature *Tpre* and entered the combustion chamber with a mean nozzle exit velocity *v* at elevated pressure *p*, in order to provide realistic gas turbine conditions. The investigated fuels were natural gas (NG) and pure hydrogen (H2). For this contribution, two flames are chosen and presented, one with pure NG and one with pure H2. The operating conditions for the two cases can be found in Table 2. The Reynolds number of the nozzle flow was Re = 300 000 for both cases.

fuel	p [bar]	v [m/s]	λ	T [K]	P_{th} [kW]	$\dot{m}_{air}$ [g/s]	$\dot{m}_{fuel}$ [g/s]
NG	8	120	1.5	673	908	468.0	19.38
H_2	8	120	3.0	673	234	468.6	4.55

Table 2: Operating Conditions

Measurements presented in this work were only performed in the center plane at $z = 0$ (see Figure 2). Thus, only the central jet flame is investigated, while the outer nozzles and flames assure proper boundary conditions in *z*- direction.

OH*-Chemiluminescence

OH radicals in the electronically excited state (OH*) are formed by chemical reactions in the reaction zone [6,7]. The subsequent transition to the ground state by spontaneous emission of light is called chemiluminescence (CL). The signal intensity depends on the concentration of OH*, which qualitatively correlates well with the heat release rate and therefore provides a good indication of the position and shape of the heat release zone [8].

The CL signal at 310 nm was imaged directly with an intensified CCD camera, equipped with a UV quartz glass lens and an interference filter. Note that the OH*-CL imaging is a line-of-sight technique, i.e. the signal is integrated in *z-direction*. 200 CL images were recorded per operation point with a frame rate of 3 Hz. Image corrections like background luminosity subtraction were applied to these sets and time series statistics like average images (revealing the characteristic flame shape by

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canceling out the turbulent fluctuations) and standard deviations (revealing the location and intensity of turbulent fluctuations) were derived.

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Particle Image Velocimetry

Two-dimensional two-component flow velocity fields were quantitatively measured using Particle Image Velocimetry (PIV). Titanium dioxide particles (d ≈ 1 µm) were added to the flow upstream of the combustor and two flashlamp- pumped Nd:YAG lasers (λ = 532 nm) were used to illuminate the particles with two consecutive laser sheets. The image pairs of the particle distribution were recorded with a CCD camera (1600 × 1200 pixels) at a repetition rate of 5 Hz.

From the image pairs, velocity fields were calculated using a multipass cross correlation algorithm. The spatial resolution for the resulting vector field was approximately 2 × 2 mm2. Additional information on the PIV setup and data processing can be found in [11].

For both flames PIV was applied at different planes within the combustion chamber; the plane presented in this work is the center plane at $z = 0$, schematically shown in Figure 2.

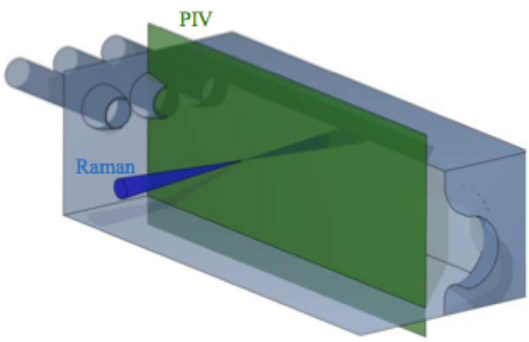

Figure 2: Measured plane for PIV and Raman spectroscopy

Laser Raman Spectroscopy

The major species concentrations (CO2, O2, CO, N2, NG, H2O, H2) and the temperature were quantitatively determined by one-dimensional vibrational laser Raman scattering. A mobile laser system combined the beams of five single shot lasers (wavelength 532 nm, pulse duration ~7 ns, repetition rate 10 Hz) to one beam by spatial overlay. The combined pulse with a total energy of around 800 mJ was stretched to a duration of around 350 ns by a pulse stretcher in order to avoid optical breakdown at the focus [9]. A section of 8.5 mm was imaged by an achromatic lens system onto the entrance slit of a spectrograph. The spectrally resolved signals of the major species were then relayed onto the chip of an image intensified CCD camera. NG was treated as one species since the C-H stretch vibration of all hydrocarbons contribute to the evaluated spectral interval [11].

The measurement location inside the combustion chamber could be adjusted in axial, horizontal and vertical direction by a three-axis translation stage that simultaneously traversed the beam guiding and forming optics as well as the detection optics. 300 single shot measurements were recorded and evaluated on an average and single shot basis. The base for the quantitative evaluation forms a calibration data set that was established beforehand by measurements on electrically heated pure gases and in the equilibrium region of flat CH4/air- and H2/air-flames in the high pressure combustion test rig (see [9,10,11] for details).

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Results and Discussion

The averaged images of the OH*-CL recordings, which illustrate the flame shape and position, can be seen in Figure 3a (NG) and b (H2) in a black-red-yellow intensity scale. The most striking differences are the much larger extent and distribution of the NG flame compared to the H2 case. Also the NG flame is lifted from the nozzle exit (by approx. 40 mm) while the H2 flame is closely attached to the nozzle.

The averaged velocity fields obtained by PIV are shown in Figures 3c (NG) and d (H2). In contrast to the flame shapes, the velocity fields look very similar for both cases. The expanding high momentum jet and the large recirculation zone are clearly visible. For the H2 case, the jet expands a little bit stronger but is shorter in return, which was expected considering the earlier and more concentrated heat release in this case.

In order to get an insight into the turbulent nature of the flow, the standard deviations (RMS) of the velocity fields are displayed in Figures 3e and f, which can serve as a measure for the magnitude of turbulent fluctuations. Obviously, these fluctuations are highest in the shear layer between the jet and the surrounding hot gas, with the inner shear layer towards the recirculation zone being a little more pronounced than the outer one. The shear layer is likely to be crucial for flame stabilization, since it is responsible for the mixing of cold unburned fuel/air mixture with surrounding hot exhaust gases. In order to determine its role more accurately, contour levels are extracted from these plots and added to the OH*-CL images in subfigures 3a and b. The contour lines are drawn at 50 % (blue), 70 % (cyan) and 90 % (green) of the respective RMS maximum. These levels are chosen at elevated values, since there is an overall background noise of ≈ 30 % in the RMS fields.

The overlay of the OH*-CL images and the velocity-RMS contours show that the NG flame is located mainly within the shear layer and in particular where the shear layers merge and the turbulent jet profile becomes fully developed (at $x \approx 120$ *mm*). This indicates flame stabilization based on the mixing of fresh fuel/air mixture with hot burned gas from the recirculation zone followed by ignition. Thus, the flame cannot be called self- sustaining, but dependent on the recirculation of hot exhaust gas. Note that the low OH*-CL signal around the jet center up to $x \approx 100$ mm is most likely due to the line- of-sight integration of the three-dimensional flame immanent to the OH*-CL technique.

On the other hand the H2 flame is almost entirely located within the undisturbed parallel jet flow close to the nozzle, where hardly any influence of the shear layer is observed. Therefore, the flame seems to stabilize through flame propagation against the high velocity jet flow in this case. Figures 3g and h show interpolated contour plots of the mean fuel mole fraction (NG or H2) and Figures 3i and j the corresponding RMS values, evaluated from the Raman measurements. These plots support the stated arguments well: While fuel is mainly consumed within the shear layers in the NG case, almost all of the H2 is already burned before the flow on the jet axis is affected by turbulent mixing in the H2 case. The dependence of the NG flame on the shear layer becomes even more obvious in the RMS plot of the NG mole fraction, where the fluctuations of NG correlate almost perfectly with the velocity fluctuations, while the H2 fluctuations take place in the center of the undisturbed jet.

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Conclusions

The presented results suggest fundamentally different flame stabilization mechanisms for the chosen test cases of NG and H2 flames under gas turbine relevant conditions. While the NG flame is most likely stabilized by auto- igniting mixtures of fresh and burned gas in the shear layer, the H2 flame is quite obviously dominated by flame propagation. Especially the NG case demands for further data analysis, since it is still unclear whether the process of recirculation and ignition happens in small scales within the shear layer (which would rather be called turbulent flame propagation) or in large scales throughout the entire recirculation zone (true auto-ignition).

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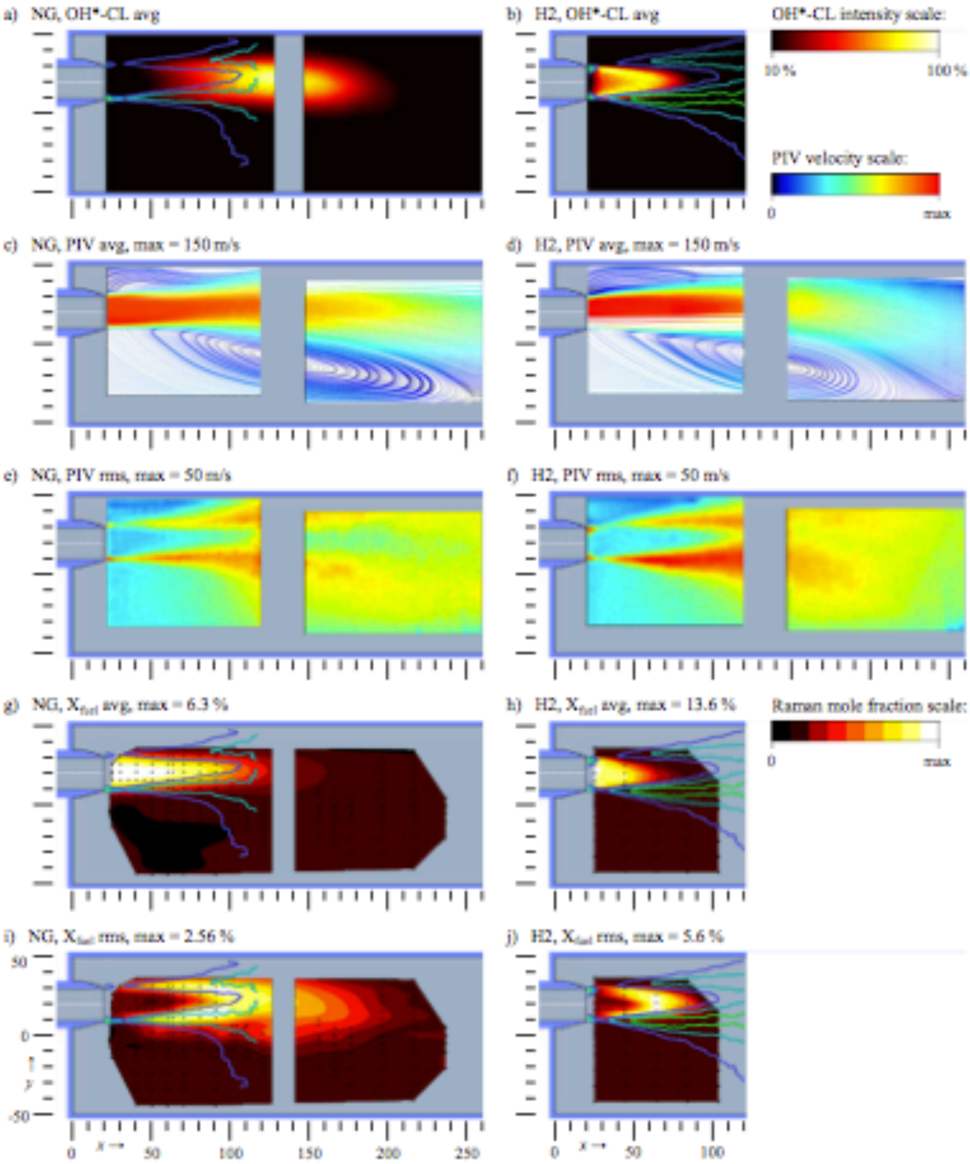

Figure 3: Results of OH*-CL (a – b), PIV (c – f) and Raman measurements (g – j) for the NG (left) and H_2 case (right). Overlayed contour lines are extracted from the PIV rms plots and indicate 50 % (blue), 70 % (cyan) and 90 % (green) of the rms maximum. *x* and *y* scales are in mm.

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