EXPERIMENTAL ANALYSIS OF CONFINED JET FLAMES BY LASER MEASUREMENT TECHNIQUES

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ABSTRACT

An experimental analysis of confined premixed turbulent methane/air and hydrogen/air jet flames is presented. A generic lab scale burner for high-velocity preheated jets equipped with an optical combustion chamber was designed and set up. The size and operating conditions were configured to enable flame stabilization by recirculation of hot combustion products. The geometry of the rectangular confinement and an off-center positioning of the jet nozzle were chosen to resemble one burner nozzle of a FLOX®-based combustor. The off-center jet arrangement caused the formation of a pronounced lateral recirculation zone similar to the one in previously investigated FLOX[®]-combustors [1,2]. The analysis was accomplished by different laser measurement techniques. Flame structures were visualized by OH* chemiluminescence imaging and planar laser-induced fluorescence of the OH radical. Laser Raman scattering was used to determine concentrations of the major species and the temperature. Velocity fields were measured with particle image velocimetry. Results of measurements in two confined jet flames are shown. The mixing of fresh gas with recirculating combustion products and the stabilization of the methane flame are discussed in detail. The presented findings deliver important information for the understanding of confined jet flames operated with different fuels. The obtained data sets can be used for the validation of numerical simulations as well.

Keywords: Confined Jet Flame, FLOX[®], laser diagnostics, validation data set, jet flame stabilization, laser Raman scattering, OH* chemiluminescence imaging, planar laser-induced fluorescence, particle image velocimetry

INTRODUCTION

Stationary gas turbine (GT) combustors are frequently operated with lean premixed flames in order to avoid high thermal nitrogen oxide emissions [3–5]. In most cases, the flames are aero-dynamically stabilized by swirl which leads to compact flames over a wide tuning range. However, the liability to thermoacoustic instabilities, the risk of flashback, and the sensitivity with respect to changes of the fuel composition are limitations for a reliable operation of swirl stabilized GT burner systems [6–9]. On the other hand, FLOX[®]-based combustors [10] have proven to be an attractive alternative for reliable and fuel flexible low emission combustors [1, 11, 12] (also termed flameless [13, 14], volume or mild combustion [15, 16]).

Furthermore, enhanced FLOX[®] burners are promising concepts for fuel flexible GT combustors operating at high power densities and high flame temperatures [2]. The FLOX[®] principle is characterized by high momentum jets, which are discharged through orifices arranged on a circle into the combustion chamber. The axial high momentum jet flow provides strong recirculation in the combustion chamber and leads to an intense mixing of burnt gas with fresh fuel/air mixtures. High flashback resistance is obtained through the absence of low velocity zones, which favors this concept for multi-fuel applications (fuels with medium to high hydrogen content).

The understanding of jet stabilized flames plays an important role in the design process of novel gas turbine combustors based on the FLOX[®] concept. Although high pressure tests of realistic burner geometries can be combined with laser diagnostic measurements [2], the analysis of the flame stabilization of a FLOX[®]-like jet flame can be significantly improved by setting up a generic experiment with well defined boundary conditions. Therefore, a single burner nozzle was arranged in a rectangular confinement with optical access. The off-center positioning of the nozzle in between the surrounding quartz glass walls allowed the formation of a distinct recirculation zone on one side, which draws a link between this configuration and the strong inner recirculation zone of an enhanced FLOX[®] burner. This single nozzle experiment was operated at atmospheric pressure with perfectly premixed preheated methane/air and hydrogen/air mixtures, at flow rates providing realistic jet nozzle exit velocities up to 150 m/s.

For this basic experiment the influence of the mixing quality of fuel and combustion air prior to the inlet in the combustion chamber was eliminated by completely premixing of fuel and air upstream the combustor. Thus, the entrainment and recirculation inside the combustion chamber could be studied without considering effects of unmixedness of fuel and air. The decision of selecting one single nozzle led the focus to jet-confinementor jet-wall-interaction, neglecting jet-jet-interactions existing in a FLOX[®]-based combustor.

The attained results were used as validation data for numerical simulations as well. Di Domenico et al. are presenting a companion paper on *Numerical Simulations of Confined, Turbulent, Lean, Premixed Flames Using A Detailed Chemistry Combustion Model* [17].

EXPERIMENTAL SETUP

For the generic experiment on confined jet flames presented in this work a new laboratory setup was prepared. The arrangement was designed to enable an extensive experimental analysis and to provide a comprehensive data base for the validation of numerical simulations. Key points were thus well-defined boundary conditions, very good optical access, and mechanical and thermal stability over long measuring runs.

Burner and Combustion Chamber

The burner consisted of a single stainless steel tube with an inner diameter d as shown in Figs. 1b and c. The tip was slightly chamfered at the outer contour and rised 2 d above the stainless steel burner base plate. The nozzle was positioned at 3.5 d distance from the combustion chamber wall referring to the longer side a, and centered at 2 d distance in perpendicular direction. The off-center arrangement was selected to obtain a pronounced recirculation on one side of the jet flow, thereby shaping a flow field in analogy to the inner recirculation zone of a FLOX[®] combustor.

The combustion chamber had a rectangular cross section with edge lengths of $a \times b = 5 d \times 4 d$ (Fig. 1b). It consisted of 3 segments with a length of 20 d each, mounted together to an overall height of h = 60 d (Fig. 1a). The walls of the combus-



FIGURE 1. Burner and Combustion Chamber.

tion chamber were quartz glass plates with reasonable thickness to minimize heat exchange with the surrounding. At top and bottom of these segments stainless steel plates were placed for stability and assembly reasons, with a very small height compared to the glass section length. As a result, the confined jet flames had mainly contact with hot glass walls, providing a very good optical access in addition. Each segment was also equipped with a water-cooled supporting frame (not shown in Fig. 1).

Both burner and combustion chamber were mounted on a base plate and could be positioned relatively to the stationary laser measurement setups with a 3-axis translation stage. The laser sheet section plane for 2-dimensional measurement techniques (PIV, OH-PLIF) is indicated in Fig.1b; the locations for the Raman point measurements lay in the same plane. The width of the short side of the combustion chamber of b = 4 d was chosen as a minimum distance of the glass walls for Raman measurements; smaller gaps would result in damaging the quartz glass due to the used high laser power densities.

Infrastructure

Figure 2 shows a schematic diagram of a part of the equipment necessary for operating and measuring the confined jet flames. Dry combustion air was fed into an electrical preheater consisting of a Leister heating cartridge mounted in an isolated pressure housing [18]; the heating element was adapted to the desired air mass flows. The cartridge's phase angle control loop achieved a temperature stability of $\Delta T_{\rm ph} < 2$ K. Behind the preheater, a separat air flow loaded with seeding particles for the velocity measurements could be added to the combustion air mass flow. During the velocity field measurements the sum mass flow and temperature were kept constant at the level of the operating conditions of the unseeded experiment.



FIGURE 2. Infrastructure. TC1: permanent thermocouple, TC2: removable thermocouple

The fuels methane and hydrogen were added to the combustion air inside a static mixer (Sulzer SMI DN 25 [19]) by a radial injection in the mass flow. The used static mixer was laid-out for the operating conditions of the flames presented in this work. A thermocouple was mounted at the end of the settling section of the mixer (TC1 in Fig. 2). Subsequent to the mixer the premixed methane/air or hydrogen/air mass flow was piped by a flexible tube (length 1 m). The straight and un-narrowed section below the burner nozzle exit had a length of $l_{tube} > 40 d$. Mixer, hose and the adjacent straight tube were thermally isolated.

Both the seeding air and the fuels were added with room temperature to the air mass flow. A second removable thermocouple was positioned at the jet nozzle exit (TC2 in Fig. 2). Prior to each test series the designated preheat temperature $T_{\rm ph}$ was adjusted at TC2 with all mass flows at operating conditions, and a setpoint value for TC1 was thus determined. TC2 was dismounted before the ignition of the flame.

Flame Stabilization and Operating Conditions

The confined jet methane/air flames can only be operated in a restricted stoichiometry region at atmospheric pressure. The stability ranges of the flames were investigated for different preheat temperatures $T_{\rm ph}$ (jet exit temperatures) of 473 K, 573 K and 673 K, and varying jet velocities $v_{\rm jet} = 90 - 150$ m/s. The corresponding Reynolds numbers calculated for an air jet flow cover the range from 13,983 to 42,410.

Starting at stoichiometric conditions ($\lambda = \phi = 1$) the fuel mass flow was decreased until the flames started to become unstable or the lean blow out limit was reached. In Tab. 1 the stability limits are specified.

Thermo-acoustic pulsations were not observed at any of the operating conditions studied. Slightly above the lean blow out limits ($\phi > \phi_{LBO}$) the methane/air flames started a periodic movement of the axial position of the flame with periods of several seconds; the corresponding equivalence ratios are indicated in brackets in Tab. 1.

TABLE 1. Flame Stabilization. Matrix for lean blow out limits ϕ_{LBO} and stability limits ϕ_{st} writen in (). Preheat temperature values T_{ph} in (K) arranged from left to right, nozzle exit velocities v_{jet} from top to bottom in (m/s).

	T _{ph}	473	573	673	
v_{jet}					
90		(0.69) 0.68	(0.69) 0.64	(0.65) 0.63	
120		(0.73) 0.70	(0.67) 0.66	(0.65) 0.62	
150		(0.71) 0.70	(0.67) 0.65	(0.65) 0.62	

For hydrogen/air flames stability limits were not an issue. Here, they were investigated with nozzle exit velocities $v_{jet} = 90 - 150$ m/s at preheat temperatures $T_{ph} = 573$ K without flame flashbacks. The experiments with laser diagnostic measurements were carried out with preheat temperatures of 573 K, both for methane and hydrogen flames. In this work we will present results for two different flames; their operating conditions are shown in Tab. 2.

TABLE 2. Operating conditions.

	Fuel	p (bar)	T _{ph} (K)	v _{jet} (m/s)	φ	Q _{air} (g/s)	$Q_{\rm fuel}$ (g/s)
#1	CH_4	1	573	150	0.7	6.8	0.28
#2	H_2	1	573	150	0.7	5.1	0.12

LASER MEASRUEMENT TECHNIQUES

For the visualization of the flame structures OH* chemiluminescence imaging (OH*-CL) and planar laser-induced fluorescence measurements of the OH radical (OH-PLIF) were performed. These techniques allowed an analysis of the position and shape of the flame brush, the flame front and the flame stabilization. In addition, the OH-PLIF measurements yielded spatially resolved structures of the reaction zones. For quantitative results, laser Raman scattering was applied to these flames and evaluated on an average and single shot basis in order to simultaneously determine the major species concentrations, the mixture fraction and the temperature. The mixing of fuel (methane and hydrogen), air and recirculated exhaust gas, as well as the reaction progress could thus be spatially resolved. Planar velocity fields were measured using particle image velocimetry (PIV) at different section planes through the combustion chamber.

Particle Image Velocimetry

Velocity fields were measured using a commercial Particle Image Velocimetry (PIV) system (LaVision Flowmaster). Titanium dioxide particles ($d = 1 \mu m$) were added to the air flow 2 m upstream the combustion chamber. A dual-cavity flashlamppumped Nd:YAG laser (wavelength $\lambda = 532$ nm, pulse energy $E_{\rm p} = 2 \times 120$ mJ, pulse duration $\tau_{\rm p} = 5$ ns) was used for illuminating the particles as shown in Fig. 3. Through a combination of cylindrical and spherical lenses, the laser beam was formed into a sheet of 200 mm height and 1 mm thickness and then crossed the combustion chamber. Pairs of images of particle distributions (separation time $\tau_{sep} = 5 - 11 \ \mu s$) were recorded with a CCD camera (1376×1040 pixels) at a repetition rate of 5 Hz. The camera object lens (focal length f = 50 mm, f-number f/4) was equipped with a narrow band filter $(532 \pm 5 \text{ nm})$ and a mechanical shutter in order to suppress light emission of the flame. Due to contamination of windows with particles, the recording time was limited to ca. 200 sec corresponding to 1000 image pairs. After each series of recordings, the combustor was shut down and windows were cleaned.

repetition rate 5 Hz) was focused into the combustion chamber (Fig. 4). The Raman scattering emitted from the probe volume (length ≈ 0.6 mm, diameter ≈ 0.6 mm) was collected by an achromatic lens (diameter $\emptyset = 80$ mm, focal length f = 160 mm) and relayed to the entrance slit of a spectrograph (SPEX 1802, f = 1 m, slit width 2 mm, dispersion 0.5 nm/mm). The dispersed and spatially separated signals from the different species were detected by photomultiplier tubes at the exit plane of the spectrograph and sampled by boxcar integrators. The species number densities were calculated from the signal intensities using calibration measurements and the temperature was deduced from the total number density via the ideal gas law. The simultaneous detection of all major species with each laser pulse also enabled the determination of the instantaneous mixture fraction. At each measuring location 200 single-pulse measurements were performed within a scanning pattern of roughly 160 points.



FIGURE 4. Raman Setup.

The calibration of the Raman setup accounted for the dependence of the Raman scattering signal intensity on temperature and species concentration, as well as for the spectral signal overlap between species. The calibration coefficients were obtained from the Raman signals measured in reference gases and flames. The reference gases used were air, CO₂, CO, CH₄ and H₂ in a temperature range up to 800 K. Laminar methane/air and hydrogen/air flames varying in equivalence ratio between $\phi = 0.8 - 1.4$ and with temperatures ranging from 1200 - 2100 K provided the calibration coefficients for the higher temperature range. The accuracy for the species concentrations and temperature was better than 5 % in the calibration flames. The accuracy of the measurements in the combustion chamber was reduced due to reflections from the walls. To take into account day-to-day variations in signal intensity due to changes in window transmittance measurements in air were performed within the combustion chamber before and after actual flame measurement. In this way, a scaling factor was determined for each set of measurements.



FIGURE 3. PIV Setup.

From the image pairs, velocity fields were calculated using a multi-pass adaptive window cross-correlation algorithm with a final window size of 16×16 pixels (corresponding to spatial resolution of 2.2×2.2 mm²). Based on the 0.1 pixel uncertainty of the cross-correlation peak-finding algorithm, the uncertainty of the velocity measurements is estimated to be 2.3 m/s.

Laser Raman Spectroscopy

Laser Raman scattering was used for point wise quantitative measurement of the concentrations of major species (O₂, N₂, CH₄, H₂, CO, CO₂, H₂O) and temperature. The radiation of a flash lamp pumped dye laser (Candela LFDL 20, wavelength $\lambda = 489$ nm, pulse energy $E_p \approx 3$ J, pulse duration $\tau_p = 3$ µs,

OH* Chemiluminescence and Planar Laser-Induced Fluorescence

OH* chemiluminescence (OH*-CL) and OH planar laserinduced fluorescence (PLIF) were used to study the size and shape of the heat release zone and to identify high temperature zones, respectively. The schematic of the experimental facility used for the current studies is shown in Fig. 5.

OH radicals in the electronically excited state (OH*) are formed in the reaction zone. Previous research indicates that the key mechanism for OH* formation is the chemical reaction CH + $O_2 \leftrightarrow CO + OH*$ [20]. The chemiluminescence emission of OH* can be imaged directly (i.e. spontaneous emission of the electronically excited OH radical). The signals are line-ofsight integrated and thus the spatial resolution is compromised and they are not directly comparable to planar methods (PIV and PLIF). Nonetheless, OH* provides a good indication of the position and shape of the heat release zone.



THOME 5. LIF Setup.

For PLIF, the frequency-doubled output of an Nd:YAGpumped optical parametric oscillator (Spectra Physics GCR 290 and MOPO 730) was formed into a vertical light sheet with a height of h = 55 mm and a thickness of d = 0.5 mm. The light sheet was directed into the combustion chamber parallel to the larger burner window and intersecting the nozzle axis (see Fig. 1). The MOPO laser was tuned to excite the R1(8) transition of OH at 281.3 nm, with a bandwidth of $\Delta v \approx 0.5$ cm⁻¹, a pulse duration $\tau_{\rm p} = 50$ ns, and pulse energies $E_{\rm p}$ varying between 2 and 3 mJ. The fluorescence signal was imaged at 90° with respect to the sheet plane using an intensified CCD camera (Princeton Instruments PiMax, Gen II, 512×512 pixels, gate time $\tau_g = 40$ ns) equipped with an UV quartz glass objective (Halle Nachf., focal length f = 100 mm, f-number f/2) and an interference filter (312 ± 15 nm). A portion of the light sheet was deflected into a dye cell and the sheet profile was measured using a second CCD-camera/intensifier unit of the same model.

These images were used to correct for shot-to-shot variation in the laser profile and power. Furthermore, a reflexion of the laser beam was directed into a methane/air reference flame in order to monitor the wavelength position of the MOPO.

The same PLIF detection system along with the filter combination was used for the OH*-CL measurements. The exposure time for the image intensifier was set to 40 μ s to capture the integrated (along the line of sight) spontaneous emission from OH radical in the electronically excited state.

RESULTS

As stated in the previous section we focus upon two different flames in this work: results for a methane/air and a hydrogen/air flame operated at the conditions given in Tab. 2 are discussed. The images in Figs. 6, 7 and 8 cover marginally different sections of the combustion chamber (differences are due to restrictions of the applied measurement methods); they are at equal scale to make them comparable.

Flow fields

Figure 6 shows two streamline plots of the average flow field and two instantaneous flow fields for both flames. In addition, RMS values of velocity are shown for the methane flame. The absolute and instantaneous velocities are color-coded and scaled to a consistent maximum value of $\approx 1.4 v_{jet}$. The RMS values have been multiplied by a factor of 7 in order to cover the same color scale as the average and instantaneous velocities.

The average velocity field of the methane/air flame (Fig. 6a) shows a straight jet flow above the nozzle which remains narrow and is only slightly bent towards the recirculation zone over a long distance. In the mean image the jet does not fan out up to a distance of $v \approx 12 d$ above the nozzle exit. To the right of the upward flow a large-scale lateral recirculation zone (LRZ) is located that vertically covers almost the full bottom segment. Through the LRZ hot reaction products ($T \approx 1500 - 1700$ K, see Fig. 8) are transported back to the nozzle and then mix with the incoming fresh gas. This enhances ignition and thereby leads to stabilization of the flame. At first sight the average flow field appears to indicate that the products are recirculated along a rather long path across the vertical extension of the LRZ. The amount of recirculated mass and temperature cannot be deduced from PIV measurements on its own. Considering the average position of the region with high heat release refering to the LRZ (see Fig. 7a and overlay in Fig. 9a), however, the average flow field would indicate that only a limited amount of flame reaction products could be added and mixed to the fresh gases prior to combustion.

The corresponding instantaneous flows fields from arbitrarily selected single shot frames shown in Figs. 6b and c, however, reveal the presence of small vortices that are primarily located in the shear layers surrounding the jet. These vortices change



FIGURE 6. PIV Results. (a) – (d) methane/air flame, (e) – (g) hydrogen/air flame. (a) and (e) streamline plots of the mean flow field. (d) RMS values. All others instantaneous flow fields.

their position with time and are therefore not represented in the average flow field. The instantaneous flow fields thus show that recirculation of products actually takes place on much shorter time- and length-scales (< 2 - 3 d) than suggested by the average flow field. It can further be seen that above y > 6 d, the jet is frayed out and wobbling to the left (Fig. 6b) and right (Fig. 6c). Although the average flow field does not exhibit a recirculation zone to the left of the jet flow, small-scale vortices form intermittently in the shear layer on the left side. This occurs primarily when the jet is deviated to the right as seen in Fig. 6c. The RMS values of velocity shown in Fig. 6d are highest in the two shear layers enclosing the jet (x = -0.5 d and x = 0.5 d). This is due to the unsteady dynamics of vortices in these layers. The width of the shear layers increases significantly in downstream direction as a result of the widening and the left-right movement of the jet.

The average flow field of the hydrogen flame can be seen in Fig. 6e. The main characteristics are qualitatively comparable with those of the methane flames: a strong upward jet flow and a widespread LRZ. However, the flame zone overlaps with the upward jet flow shortly above the nozzle exit (see average flame position in Fig. 7f). The expansion caused by heat release broadens the upward flow in lateral direction and leads to even higher absolute velocity values in this region. Again, two instantaneous flows fields are plotted in Figs. 6f and g. Similar to the methane flame, the flow field features small-scale vortices in the shear layer and the left-right wobbling of the jet at y > 6 d.

Position and shape of the flame zone

Although the effects of strain and fuel composition on the OH* concentrations are not exactly known, the OH* chemiluminescence signal can be taken as a marker for the regions of heat release in lean premixed flames [21, 22]. Therefore, OH* chemiluminescence provides a good indication of the position and shape of the flame zone. While OH* is only present in the flame front, OH in the electronic ground state is also found in regions with high temperatures.

For a given flame the OH equilibrium concentration increases exponentially with the temperature. The concentration is also influenced by mixture composition and collisional relaxation. Detectable OH concentrations exist above approximately 1400 K in fuel lean regions, and in fuel rich regions approximately above 1900 K [23]. In the reaction zone OH is formed in super-equilibrium concentrations which are up to 4-5 times higher than equilibrium concentrations. The relaxation of the OH concentration towards thermal equilibrium is dominated by three body collisions, with a relatively slow rate at atmospheric pressure. Thus, the typical relaxation time is about 3 ms [24]. It is important to note that the OH signal intensity is not directly correlated with the temperature. High OH concentrations may stem from super-equilibrium OH in or downstream of the flame front. Medium OH concentrations, however, are usually indicative of high temperature regions. Also, the PLIF intensities are not necessarily proportional to the OH species number density because no corrections have been performed for quenching effects, absorption of the excitation laser sheet, or fluorescence trapping. Here, no attempt is made to analyse the results quantitatively.

Figure 7a shows the mean OH* chemiluminescence image of the methane flame; the corresponding RMS values are displayed in Fig. 7b. For the scale used here, blue/black represents low, and red high intensity and RMS values. A set of 5 mean images recorded at different heights above the jet nozzle was used to generate the segmented image. It is seen that the



FIGURE 7. OH*-CL and PLIF Results. (a) – (e) methane/air flame. (a) averaged OH*-CL image. (b) OH*-CL RMS values. (c) composition of PLIF single shot images. (d) and (e) randomly selected PLIF frames at 2 different measurement positions. (f) hydrogen/air flame, averaged OH*-CL image.

methane/air flame is lifted and not attached to the nozzle. The region of low signal intensity near the nozzle reflects the inlet flow of premixed gas. Further upwards the OH* chemiluminescence signal increases significantly due to the onset of combustion and a stable and asymmetric flame front in the shear layer between the fuel jet and the recirculation zone (see average flow field in Fig. 6a). Due to the high axial momentum of the jet flow, the average OH*-CL image suggests that the temperature of the methane/air mixture is preserved prior combustion: the combustion products may not be able to penetrate the fresh gas/burned gas interface. The main heat release zone is established further downstream between y = 14 d and y = 21 d. This region is also characterized by large RMS values indicating the turbulent nature of the flame.

Figure 7c shows a set of randomly selected single-shot OH distributions at different heights. These PLIF images depict the instantaneous flame structure featuring the turbulent transport and the mixing process within the flame.

In the instantaneous PLIF images taken near the jet nozzle (Fig. 7d) regions without OH as well as regions with broad OH distributions are seen. The OH-free regions represent relatively cold gas, like the cold jet flow. The regions with OH is interpreted as recirculated burnt gas which has not suffered a significant temperature loss by wall contact or admixtures of cold gas. Distinct layers of high OH concentrations at the periphery

of the jet which are indicative of reaction zones are not observed. This finding is in agreement with the chemiluminescence images which show no combustion in the start region of the jet. Further downstream, in the 4th segment, relatively high OH signal levels are found (Fig. 7e). These are indicative of OH superequilibrium concentrations, i.e., "young" OH which has just been formed in flame reactions. The boundary between the jet and these OH regions is strongly wrinkled and corrugated, typical of turbulent flame fronts, with separated OH layers and islands of different shapes and sizes. It is not clear whether the isolated OH regions are part of a larger three-dimensional flame front or whether they present auto-ignited flame kernels. The flame front seems to be convex towards the burned gas. The confinement of the jet sustains this structure till above y > 14 d where a cusp appears. At this height the flame front surface is extremely wrinkled and the cusp of the jet begins to oscillate without significant thermoacoustic oscillations. As a consequence, the jet breaks and more kernels that fulfil the entire combustion chamber appear behind the flame front.

Figure 7f presents a mean OH* chemiluminescence image of the confined hydrogen flame. Comparing the results with that of Fig. 7a, we observe that the flame shape and structure are changed substantially. Because of the higher reactivity of hydrogen this flame anchors directly at the nozzle exit. In the OH*-CL image, the recirculation zone seems to have no influence on



FIGURE 8. Raman Results for methane/air flame. (a) average fuel distribution $c(CH_4)$. (b) average oxygen distribution $c(O_2)$. (c) average temperature field *T*. (d) average water distribution $c(H_2O)$. (e) average carbon dioxide distribution $c(CO_2)$, (f) corresponding RMS values $\sigma_c(CO_2)$.

position and shape of the flame zone; the flame tip is slightly bent towards the center of the combustion chamber. The flame length is shorter while the chemiluminescence signal intensity is increased compared to the methane flame. The heat release zone is limited only up to a height of y < 10 d above the nozzle, maximum values appear at y = 2 - 4 d.

Major Species Concentrations and Temperatures

The results from the laser Raman scattering experiments allow for a more quantitative view into the flame. In Fig. 8 average values of species concentrations (fuel, oxygen, water and carbon dioxide) and the temperature field of the confined methane flame are shown as contour plots. Moreover, the corresponding RMS values for CO_2 are charted in Fig. 8f. The locations of the Raman measurements (equivalent to the nodes of the contour plots) are indicated by black crosses and small ticks at the borders. The color bars give the concentrations in percent (%).

Figures 8a and b reveal that the concentrations of CH₄ and O₂ change in the same way, as expected for a premixed jet flame. However, due to the lean nature of the flame, O₂ is also present in the burnt gas, in contrast to CH₄. Again, a straight and undisturbed jet flow is seen above the nozzle. The concentrations start to decrease considerably above y > 5 d due to either combustion or dilution of the jet with recirculated species. Moving in a horizontal direction from the jet axis at a height above y > 5 d, both concentrations drop quickly, until reaching the final exhaust gas concentrations in the LRZ. Along the jet center line, even at y > 15 d a significant amount of CH₄ is present, which indicates that the combustion has not finished yet. The temperature map in Fig. 8c even suggests that there is hardly any combustion occurring in the center of the jet within the measured height: starting at the preheat temperature of 573 K the mean temperature stays below 1000 K along the jet axis up to y < 11 - 12 d. Outside the jet, in the LRZ, the temperatures reached levels above 1600 K which indicates that the recirculating gas contains large amounts of burnt gas. It is noted that these temperatures are lower than the adiabatic flame temperature $T_{ad} = 2049$ K of this flame.

Figures 8d and e show the concentration maps for the combustion products H₂O and CO₂. Their distribution correspond to the concentrations of O₂ and CH₄: low amounts in the upward jet flow, and high values in the LRZ pointing to completed combustion reactions. The gradients within the temperature and species distributions suggest that combustion is only taking place in the shear layer in this part of the combustion chamber (temperature and H₂O/CO₂ gradient in horizontal direction). Within the reverse flow of the LRZ at the right side of the combustion chamber the temperature distribution exhibits a slightly larger vertical gradient than the concentrations of the combustion products, indicating that there is some temperature loss due to cooling effects at the wall. A comparison with the velocity field reveals that the highest RMS values of the carbon dioxide concentration (Fig. 8f) occur in the shear layer. This shows, as expected, that combustion is primarily taking place close to the shear layer where fresh fuel/air compositions mix with hot combustion products.

The scatter plot of CH_4 concentration and temperature, displayed in Fig. 9b, yields a more detailed view of the thermochemical state in the flame. Here, four groups of symbols are shown, representing four different measurement positions, which are marked in Fig. 8a by numbered circles. Each symbol represents the result from a single shot measurement at the corresponding location. The line represents the theoretical temperature of all possible mixtures of fresh gas with fully reacted burnt gas. The temperature results from a simple thermodynamic cal-



FIGURE 9. Raman results for methane/air flame. (a) position markers for scatter plots. (b) scatter plot of $c(CH_4)$ vs. temperature. (c) scatter plot of $c(H_2O)$ vs. $c(O_2)$

culation, where radiation and other cooling effects are not taken into account. Thus this temperature represents an upper limit for the expected temperatures in the flame. The burnt gas composition and temperature were calculated with the gaseq program [25]. Starting at the center line of the jet, the square symbols represent measurements at a height of y = 6 d. Although this is at the center of the jet, where the averaged images suggested an undisturbed flow, the plots show a significant scatter in CH₄ concentration and temperature. Because of the relatively low temperature between 600 K and 800 K, the decreased CH₄ concentration in some of the measurements must be interpreted as dilution of the fresh gas with flue gas, and not by combustion. This corresponds to the chemiluminescence images, which didn't show significant reactions in this area.

The second point (circles) was measured in the shear layer at a height of y = 10 d. The large scatter in temperature and CH₄ concentration reflects impressively the large variety of mixing states. All states of reaction progress from fresh gas to fully reacted gas are present at this position. A closer inspection of the data reveals that the samples containing CH₄ also contain O₂. The co-existence of fuel and air at elevated temperatures demonstrates the role of finite-rate chemistry effects in this flame. These samples either stem from local flame extinction or from mixtures of reaction products with unburnt fuel and air which have not reacted yet due to ignition delay. Similar effects have been observed in swirl flames within the shear layer between fresh gas and recirculing burnt gas [26, 27]. Following the flow further downstream, point three (triangles) is located in the outer recirculation. At this point the flame is dominated by the presence of hot fully reacted flue gas, with some sporadic appearance of partly reacted gas mixtures.

Two distinct features should be mentioned. Firstly, even the measurements in the outer recirculation zone show a methane concentration of slightly below 0.5 %. From the temperature and

the other concentrations measured at these positions, the presence of methane is very unlikely. The apparent signal in the methane detection channel steams from other effects, like stray light from the windows of the combustion chamber. Secondly, the temperatures of all measurements are clearly below the adiabatic value. This might partly be due to measurement uncertainties, e.g. caused by reflections of the laser beam from the windows of the combustion chamber. However, the major part of this temperature reduction can be assigned to cooling of the recirculating gas at the walls of the combustion chamber, particularly within the reverse flow part of the LRZ.

This significant cooling of the recirculating flue gas in the LRZ is seen in the measurements at the fourth position (diamonds). The methane concentration shows that this is fully reacted exhaust gas, but the temperature is significantly lower than at position 3. The presumption, that this is fully reacted flue gas is also proven by the scatter plot shown in Fig. 9c. It presents a correlation between the H₂O concentration as a product and the O₂ concentration as an educt. The line represents again the calculated correlation for mixing fresh gas with flue gas without any reaction. Experimental and theoretical correlations are in good agreement within the measurement uncertainty. The figure shows further that at point three and four the same O₂ and H₂O concentration are present reflecting fully reacted gas. The strong cooling by more than 300 K can hardly be explained solely by heat transfer to the walls of the combustion chamber. Another possible region of heat loss is the lower part of the combustion chamber. The PIV results indicate a separated recirculation bubble in this part of the combustion chamber. Here, the residence time of the fluid is relatively long leading to significant heat transfer to the confinement.

SUMMARY AND CONCLUSIONS

A generic combustor was constructed for the investigation of confined jet flames with the goal to support the design process of novel GT combustors based on the FLOX®-principle. Turbulent, lean, premixed, preheated methane/air and hydrogen/air flames with high jet velocities were stabilized in a rectangular combustion chamber. The selected geometry with an off-center positioning of the jet caused the formation of a strong, widespread, lateral recirculation zone (LRZ). The basic shape and dimensions of the LRZ were not affected by variations of the equivalence ratio or jet velocity. The recirculation and entrainment of hot combustion products play a key role for the stabilization of the flames. From previous investigations it is known that also the degree of premixing of fuel and air has an important influence on the combustion behaviour of enhanced FLOX®-combustors [2]. In order to concentrate on the influence of recirculation perfect fuel/air premixing was applied in the present study.

Different laser diagnostic techniques were applied. Average and instantaneous flow fields were measured using particle image velocimetry. Position and shape of the flame zone were investigated by OH* chemiluminescence imaging and planar laserinduced fluorescence of OH. Laser Raman spectroscopy was used for the quantitative, simultaneous determination of species concentrations and temperature.

The methane and hydrogen flames showed basically different flame shapes. While the hydrogen flame was attached to the nozzle, the methane flame was lifted. The average flow fields featured the same global characteristics with comparable recirculation lengths. A discernible difference was seen in the upward jet flow: the hydrogen flame exhibited a larger broadening of the jet due to the thermal expansion in the heat release region. The OH* chemiluminescence images revealed that the hydrogen flame was anchored at the nozzle despite of the high jet velocity and that its shape resembled the one from unconfined jet flames. The flame stabilization was hardly influenced or supported by the LRZ. Considering the high reactivity of H₂ and the preheating to 573 K, this behaviour appears plausible.

The methane flames were lifted and detached considerably from the nozzle. Mixing of fresh fuel/air with combustion products in highly turbulent shear layers surrounding the jet induced by the LRZ caused a stable and asymmetric flame shape. The OH PLIF and Raman measurements revealed that the LRZ contained hot combustion products without any methane. Compared to adiabatic conditions, the measured temperatures were significantly reduced. This was explained by heat loss to the combustor side wall and bottom plate. The correlations deduced from the single-shot Raman results showed a large variation of the thermo-chemical states occurring in the flame. Besides nonreacted and completely reacted mixtures, a lot of samples from the shear layer contained partially reacted gas at elevated temperatures with fuel, air and reaction products. Similar effects of finite-rate chemistry have previously been observed in swirl flames and seem to be characteristic of turbulent flames with recirculation of hot combustion products. The partially reacted mixtures are explained by mixing of hot gas from the LRZ with fresh gas. Their final burn-out by spontaneous ignition (autoignition) or the propagation of a flame front is delayed long enough to contribute significantly to the measured distribution of flame states. It can thus be concluded that the combustion in the confined methane jet flame is strongly influenced by the mixing process and that it takes, at least partly, place via a variety of intermediate mixing states. The Raman results and the fragmented nature of some of the OH PLIF single shot distributions further suggest that auto-ignition contributes to the combustion process.

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