Simultaneous PIV/OH-PLIF measurement in a gas turbine model combustor at 5 bar and 3kHz acquisition rate

James D. Gounder\textsuperscript{1,*}, Isaac Boxx\textsuperscript{1}, Peter Kutne\textsuperscript{1}, Stefan Wysocki\textsuperscript{2}, Fernando Biagioli\textsuperscript{2}

1: Institute of Combustion Technology, German Aerospace Center, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany
2: ALSTOM (Switzerland) Ltd, Brown Boveri Str. 7, 5400 Baden, Switzerland
* correspondent author: james.gounder@dlr.de

Abstract A scaled model of a gas turbine (GT) burner has been used to study the effect of fuel staging on turbulence-chemistry interaction in natural gas (NG) air flames at elevated pressure. The burner consists of two axially mounted swirlers. The stages are concentrically mounted with an area ratio of 0.54 (inner/outer). Laser and optical diagnostics techniques at kHz repetition rate were applied to gain a better insight into the flame behavior. Natural gas air flames operated at 5 bar pressure and preheated air of 733 K with constant bulk velocity of 30 m/s and three different staging ratios have been investigated using PIV, OH PLIF and OH* CL imaging at an acquisition rate of 3 kHz. Fuel staging has been defined as the percentage of fuel in the outer swirler (OS) to inner swirler (IS) i.e. 40/60 stands for “40% fuel in outer swirler stage / 60% fuel in inner swirler stage”. The global equivalence ratio was set to 0.57. Pressure in the combustion chamber was simultaneously monitored using a pressure transducer. In order to improve the signal to noise ratio of the PIV and PLIF measurements, the laser sheet height was kept constant at 23 mm and the imaged field of view from the PIV and OH PLIF camera covered only one half the combustion chamber width.

Mean Abel inverted OH* CL images show that the flame FLM\textsubscript{40}/60 has a broad reaction zone and as the staging is varied the reaction zone becomes thinner. The flame length also varies as the staging is varied. The acoustic spectra show strong peaks in all three flames. The first overtone in the acoustic spectra of flame FLM\textsubscript{40}/60 shows stronger pulsation intensity than at the fundamental frequency whereas in flame FLM\textsubscript{55}/45 and FLM\textsubscript{60}/40 the first overtone is weaker than the dominant thermo-acoustic frequency. The OH* CL spectra has peaks at the same frequency as the acoustics. The frequency and intensity of the pulsations change with staging. POD analysis of the kHz PIV data shows no PVC being present in the three flames. The spatial distribution of the power spectra of velocity shows high frequency regions corresponding to the first overtone close to the inner shear layer (ISL) and outer shear layer (OSL). It has been shown that the periodic shedding of vortices in this region is coupled with the heat release rate. Simultaneous PIV and OH PLIF measurements showed periodic occurrence of double OH zones in flame FLM\textsubscript{40}/60 resulting in a broad reaction zone. The OH PLIF images in flames FLM\textsubscript{55}/45 and FLM\textsubscript{60}/40 showed that increasing outer stage fuel results in a narrower OH zone, resulting in a thinner reaction zone.

1. Introduction

Gas turbine (GT) design has undergone significant changes and improvements in the last couple of decades. Strict emission regulations, as well as fuel flexibility requirements, demand continuous advancement, especially in the area of combustor design. Topics such as combustion and fluid mechanics play an important role towards the performance and stable operation of the combustor. The operation of a GT combustor with varying fuel composition would require a change to current burner designs. One promising design path is by splitting the combustion process into two or more stages. This requires the investigation of critical phenomena such as flame stabilization mechanisms, lean burn out limits, turbulence chemistry interactions and thermo-acoustics combustion instabilities in flames of GT burners with staging capability. A number of studies have already looked at staging effects on NOx emissions (Chockalingam et al. 2011; Hayashi et al. 2005; Johnson et al. 2005; Prathap et al. 2011; Zajadatz et al. 2007), while others have investigated the thermo-acoustic instabilities in different configurations (Barbosa et al. 2009b; Fritsche et al. 2007; Martin et al. 2006; Therkelsen et al. 2013).
The understanding of these processes requires experimental investigations but the physical constraints and lack of optical access to the GT combustor makes it difficult to perform sophisticated laser and optical diagnostic measurements while the GT is in operation. Therefore tailored experimental setups are being utilized to investigate these phenomena, as well as advancement in laser and optical diagnostic techniques. Studies performed with laboratory scale GT model combustors at atmospheric pressure have provided great insight into areas such aerodynamics (Meier et al. 2010; Sadanandan et al. 2009; Stöhr et al. 2012), turbulence-chemistry interaction (Barbosa et al. 2009a; Bayley et al. 2012; Boxx et al. 2012; Boxx et al. 2010; Meier et al. 2010; Sadanandan et al. 2008; Stöhr et al. 2012; Stöhr et al. 2011b), thermo-acoustic instabilities (Dawson et al. 2005; Fritsche et al. 2007; Giezendanner et al. 2003; Meier et al. 2007; Steinberg et al. 2010) and dynamics of lean blowout of swirl stabilized flames (Stöhr et al. 2011a). The success of the above studies is also due to improvement in the capabilities of Laser and camera systems. Measurements have been performed at a wide range of repetition rates (1 Hz – 10 KHz), which has resulted in a wealth of information and has led to advancement and improvement of numerical studies (Grinstein and Fureby 2005; Jones et al. 2012; Martin et al. 2006; Nogenmyr et al. 2009).

The benefits of the atmospheric measurements have been enormous, but it is still not possible to capture the behavior of GT combustion processes at realistic conditions of high pressure, preheated air, high turbulence levels and high thermal power. This is where the availability of high pressure test rigs with optical access has been a major contributor in advancing the GT combustion research. A number of studies have been performed with laser and optical diagnostic based measurements in high pressure test rigs at realistic GT operating conditions (Ax et al. 2009; Fleck et al. 2013; Geigle et al. 2006; Griebel et al. 2007; Meier et al. 2000; Stopper et al. 2009; Willert et al. 2006). A major challenge to perform laser diagnostics measurements at high pressure, as highlighted in previous studies, is window fouling due to high temperatures. This is further accelerated in case of particle image velocimetry (PIV) measurements due to addition of seed particles in the fluid stream. Planar laser induced fluorescence (PLIF) measurements of OH radical suffer from increased absorption at high pressure. One also has to take note that in these studies measurements were performed at relatively low repetition rates (Max ~ 10 Hz). Despite of all the challenges, these studies have provided insight into topics such as turbulence-chemistry interaction (Ax et al. 2009; Stopper et al. 2009), flame stabilization mechanism (Fleck et al. 2013; Griebel et al. 2007) and limits and effectiveness of measurement techniques such as PIV and PLIF (Meier et al. 2000; Willert et al. 2006; Willert and Jarius 2002) at elevated pressure.

In past few years kHz PIV and OH PLIF measurements at atmospheric pressure have resulted in explicitly resolving the dynamics of the flame and flow field (Boxx et al. 2012; Boxx et al. 2010; Steinberg et al. 2010; Stöhr et al. 2012). In this study, the use of kHz PIV and OH PLIF has been extended to measurements at elevated pressure. Kapadia et al. (2013) and Boxx et al. (2014) have shown first successful kHz PIV and OH PLIF measurements performed at 5 bars pressure. In this work, simultaneous kHz PIV, OH PLIF measurements have been used to study a conceptual design of an industrial GT burner at elevated pressure. The kHz measurements will be targeted at investigating the effects of fuel staging and conditions with enhanced thermo-acoustic pulsations. This work is part of a project looking into future development and improvement of GT combustors to provide better understanding of the physics behind the complex processes that are present in GT combustors. High speed (3 kHz) PIV, OH PLIF, OH* chemiluminescence (CL) and acoustic measurements are performed to investigate the effect of fuel staging on flame behavior.

2. Experimental Setup

The measurements presented in this paper were performed at the High Pressure Optical Test (HIPOT) rig at DLR Stuttgart. The staged burner used for the high pressure testing has already been studied at atmospheric pressure (Gounder et al. 2013; Gounder et al. 2014). Detailed information and diagrams of the test rig layout has been provided by Kapadia et al. (2011) and only a brief description is presented in subsection 2.1.
Fig. 1 a) Experimental layout showing the optical module of the HIPOT rig and camera arrangement for kHz PIV and OH PLIF measurements. b) Effective imaged area of the 3 measurements conducted, OH* CL, simultaneous OH PLIF

2.1 HIPOT Rig

The HIPOT facility comprises of three main sections, supply module, optical module and exhaust module. In the supply module, the main air supply line is connected to a 192 kW electric heater which is followed by the supply module. This contains a plenum to homogenize the airflow before entering the burner. The supply module holds the burner and the combustion chamber and provides access ports for instrumentation (thermocouples and pressure probes) and fuel supply lines. The dynamic and static pressures in the test rig are monitored and measured using pressure transducers. Temperatures are monitored using thermocouples. The optical module provides access to the combustion chamber through large windows on all 4 sides. Figure 1 (a) shows the optical module and a cross-section of the supply module with the burner and combustion chamber.
assembly. The exhaust module contains the throttle and quenching zone to reduce the exhaust temperature to 170°C. The maximum thermal power of the test rig is 300 kW, which determines the maximum combustor air flow rate. The fuel mass flow rate to the test rig is controlled using electromechanical mass flow controllers (Bronkhorst). The fuel mass flow rate to each swirler stage is controlled using a split controller which has an accuracy of 99.8%. A second supply line, of up to 220 g/s of air is also available at the test rig for cooling purposes.

2.2 Burner and combustion chamber

Figure 1(b) shows the sketch of the staged burner assembled in the supply module with the optical combustion chamber. The burner consists of co-axially mounted swirlers with an area ratio of 0.54 (inner/outer). The outer to inner blade ratio is two to one. The outer stage has a fuel plenum with two fuel inlets. The inner swirler stage has a fuel tube acting as the plenum as shown in Fig. 1(b). The outer stage swirler is surrounded by a tube extending till the burner front plate. The inner stage swirler has a thin walled tube separating the flow that enters the inner and outer swirler. The inner tube is shorter than the outer tube which allows for further mixing of the air fuel mixtures from each stage before exiting the burner.

The burner housing is bolted to the supply module. The burner surface plate is cooled by impingement cooling for high thermal loads using a small percentage of main combustion air which is directed to the back face of the burner plate and re-introduced into the combustion chamber along the window. The combustion chamber has a square cross section of 85 x 85 mm². The length of the combustion chamber is 200 mm. The windows of the combustion chamber are double quartz glass with cooling air flowing in between the two glasses. All other metal parts of the combustion chamber are water-cooled. The exit of the combustion chamber has a diameter of 33 mm.

2.3 Initial Conditions

The effect of parameter variations on the flame shape and stability is used to map out the operability limits of the burner. Flames at 5 bars have been tested with the maximum bulk velocity of 30 m/s. In order to achieve the bulk velocity of 30 m/s the main supply air is preheated to 733 K. The fuel used is natural gas (NG). In this paper only the effect of varying staging on the flame behavior is investigated and hence the global equivalence ratio (Φc) is kept constant at 0.57. The fuel staging ratio in this study has been labelled as follows

Staging = % of fuel in outer swirler stage / % of fuel in inner swirler stage

For example staging 40/60 means 40% of fuel is injected in the outer stage and 60% of fuel in the inner. Flames with three different fuel staging ratios 40/60, 55/45, and 60/40 are presented in this paper. From this point forward the three flames would be labelled as FLM_40/60, FLM_55/45 and FLM_60/40 respectively. High speed laser and optical diagnostic techniques were applied to gain a better insight into the effect of fuel staging on the behavior of these flames.

2.4 High Repetition Rate (kHz) PIV Setup

The 2D PIV system consists of a dual cavity, diode pumped solid state Nd:YAG laser (Edgewave, IS-6IIDE) and a CMOS camera (Lavision HSS8). The laser outputs a 532 nm beam at repetition rates up to 10 kHz. The laser was operated at 3 kHz with laser energy of 2.6 mJ/pulse. The pulse duration is approximately 14 ns. Pulse timing separation is set to 3 μs with the OH PLIF excitation pulse triggered in between the PIV pulses. Three cylindrical lenses (f1 = -50 mm, f2 = 150 mm, f3 = 700 mm) are used to form a 20 mm high laser sheet. Mie scattering from titanium dioxide (TiO2) particles seeded into the flow is imaged at 90° to the laser sheet using the CMOS camera (Lavision HSS8). The CMOS camera is equipped with a Tokina 100 mm macro lens. A 532 nm interference filter is used in front of the camera lens to filter diffuse laser light reflections.
Velocity fields are calculated from the particle images using commercial PIV software Lavision Davis 8.1. An adaptive multi pass cross correlation algorithm was used with interrogation windows ranging from 64 pixels to 24 pixels. The final PIV window size was 24 x 24 pixels with a window overlap of 50%. The field of view imaged with the PIV system was 20 x 49 mm² (H x W) which resulted in a spatial resolution and vector spacing of 1.1 mm and 0.55 mm respectively.

2.5 High Repetition Rate (kHz) OH* CL and OH PLIF Setup

For the burner characterization phase, line of sight integrated imaging of OH* CL is performed using a CMOS camera (Lavision HSS5), with an external two stage, lens-coupled intensifier (Lavision HS-IRO) and a Cerco 45 mm, f/1.8 lens. The intensifier gate time is set to 25 μs. The OH* CL images are recorded at 3 kHz. The OH signal collected by the intensifier is filtered using a bandpass interference filter with center wavelength at 310 nm. The imaged field of view for OH* CL was 88 x 80 mm.

The OH PLIF system consisted of a frequency doubled dye laser and an intensified CMOS camera. The layout of the laser sheet and the camera are shown in Fig 1(a). A dye laser (Sirah Credo) using Rhodamine 6G dye dissolved in ethanol, was pumped with a frequency doubled, Q-switched, diode pumped solid state Nd:YAG laser (Edgewave IS-811E). At 10 kHz the pump laser delivered 3.8 mJ/pulse at 532 nm with an 8.5 ns pulse duration. The output of the dye laser was frequency doubled to excite the Q1(7) line of the A-X(1-0) transition of OH at 283.2 nm. The output energy of the dye laser beam was 330 μJ/pulse at 3 kHz. The dye laser beam was formed into a sheet of height 23 mm using three fused silica lenses (f1 = -50 mm, f2 = 150 mm, f3 = 750 mm). The laser sheet height is kept small in order to increase the signal to noise ratio of the OH PLIF signal which is strongly affected by absorption at high pressures. The 283 nm laser sheet was overlapped with the PIV laser sheet using a pair of dichroic mirrors.

For the OH PLIF measurement, the camera and intensifier is the same as for the OH*CL measurements, with one change. The collection lens is changed from a Cerco 45 mm to a Halle 64 mm lens. Background luminosity is reduced by using a 100 ns intensifier gate and elastic scattering from PIV particles at 283 nm is blocked using a high transmission bandpass interference filter with center wavelength at 310 nm and a 1 mm thick color glass filter (WG295 Schott glass). Figure 1 (b) shows the effective imaged area of the OH PLIF measurement which is 15 x 45 mm² (H x W).

3. Results

3.1 Flame Characterization

Natural gas/air flames at 5 bars with varying staging ratios at fixed Φc (0.57) are investigated using the staged burner. Electronically excited OH (OH*), which is formed by the flame reactions in the regions of the highest heat release rates is used to determine the stabilization point and shape of the flame. The OH* CL is measured through line of sight method, thus it also provides information on flame symmetry over the central axis of the burner. Pressure signals from the combustion chamber are recorded simultaneously with the gate monitor signals of the image intensifier using a multichannel A/D converter with a sampling rate of 100 kHz. Figure 2 shows mean OH* CL images as well as the power spectra of the pressure fluctuations measured in the combustion chamber in the three flames. All the OH* images are approximately 1.55D x 1.49D mm (H x V), where D is the diameter of the burner. The pressure signal intensity in the power spectra has been normalized by the pressure intensity measured in flame FLM_55/45. All the frequencies presented in this paper have been normalized by the frequency of the first peak from the acoustic spectra measured in flame FLM_55/45.

The OH* CL intensity in Fig. 2 shows the changes in flame shape as the staging is varied. The flame length decreases as fuel injection in the inner stage is decreased. A more even distribution in OH* CL intensity is observed in flame FLM_40/60 compared to flames FLM_55/45 and
FLM_60/40. There is a reduction in intensity of OH signal close to the center axis (around $x/D = 0$) as the percentage of fuel in the outer stage is increased. The flame base in all the flames is upstream of the burner exit plane. The power spectra of the pressure fluctuations measured in the combustion chamber in the three flames show thermo-acoustic pulsations. The intensity of the acoustic pulsation decreases as the fuel is increased in the outer stage. The power spectra also show the first overtone in the spectra of the three flames. An interesting feature in the power spectra of flame FLM_40/60 is the intensity of the first overtone, which is significantly higher than the fundamental frequency. Flames FLM_55/45 and FLM_60/40 on the other hand show significantly lower energy in the first overtone.

![FLM_40/60](image1)

![FLM_55/45](image2)

![FLM_60/40](image3)

**Fig. 2** Mean OH* CL and power spectra of pressure pulsation measured in the combustion chamber for flames with three staging ratios.

Figure 3 shows the power spectra from the integrated OH signal for the three corresponding staging ratios. Power spectra are calculated from the time series of the integrated signal from half of the OH* CL image ($x/D = 0 - 0.8$). Only one half of the OH image is used in order to resolve any other periodic feature that may affect the global heat release. The OH intensities of all three flames have been normalized by the maximum intensity from flame FLM_55/45. The spectra shows that the heat release rate in flame FLM_40/60, FLM_55/45 and FLM_60/40 also pulsates at similar fundamental frequencies as shown in acoustic spectra including the first overtone frequencies. The second overtone in the OH* CL spectra has also been resolved. This coupling between heat release and pressure oscillation in the combustion chamber needs further analysis.
Fig. 3 Power spectra of integrated OH* CL measured in flames FLM_40/60, FLM_55/45 and FLM_60/40.

Fig. 4 (a) Mean Abel inverted OH* CL (b) Average velocity field and (c) RMS of velocity magnitude for flames FLM_40/60, FLM_55/45 and FLM_60/40.
3.2 Reaction Zone and Flow Field

Due to the rotational symmetry of the flames, as shown in Fig. 2, the images of the integrated OH* CL signal could be deconvoluted by a three point-Abel-inversion to derive a section of the symmetry plane through the center of the flame. It also gives a more accurate location of the reaction zone. Figure 4 (a) shows the Abel inverted OH* CL images of FLM_40/60, FLM_55/45 and FLM_60/40. Flame FLM_40/60 has a broad reaction zone and as more fuel is injected in the outer stage the reaction zone becomes narrower and shorter for flames FLM_55/45 and FLM_60/40. At the exit plane the radial position of the peak of OH intensity is around x/D = 0.33. The reaction zone seems to be influenced by both stages. The flame base in all the flames is upstream of the burner exit.

Figure 4 (b) presents the mean velocity field measured at axial locations from y/D = 0.00 till 0.72 for the three flames. In order to get a good signal to noise ratio, only half of the combustion chamber width was imaged. The PIV laser beam profile had a hot spot of width 0.27D and only the region illuminated by the hot spot resulted in first vector choice of 97%. Therefore the resulting PIV image height is equal to the laser beam hot spot height. In Fig. 4 (b) mean velocity field measured at three axial locations are overlaid together to show the overall flow structure. The flow field is typical of swirl flames and consists of a cone shaped stream of fresh gas (JET) entering the chamber from the burner, an inner recirculation zone (IRZ), and an outer recirculation zone (ORZ) as shown in Fig. 4 (b). The structure of the average flow field in Fig 4 (b) seems to be largely independent of fuel staging.

The RMS values of the velocity magnitude from the flow field measured close to the exit plane are shown in the Fig. 4 (c). Strong fluctuations in the areas of the flow field with large velocity gradients occur in the inner shear layer (ISL) between the inflow and the IRZ, and in the outer shear layer (OSL) between inflow and ORZ. The magnitude of the RMS velocity in the ISL is largest in flame FLM_60/40. The trend, shown in Fig. 4 (c), is that as fuel staging is varied from 40/60 to 60/40 the fluctuation in velocity increases. The magnitude of RMS velocity in the OSL is unaffected by the fuel staging.

![Fig. 5 Peak frequencies of velocity magnitude oscillations calculated at each pixel location in the three flames FLM_40/50, FLM_55/45 and FLM_60/40.](image)

The average and rms velocity field do not provide any information regarding oscillations shown in the acoustic and OH* CL spectra. Using 2000 instantaneous velocity images from the high speed data, the power spectrum of the velocity magnitude for each individual pixel in the PIV image was calculated. Figure 5 shows distribution of the normalised peak frequencies (normalised by frequency of first peak from the acoustic spectrum of flame FLM_55/45) of the velocity fluctuation in the flow field for flames FLM_40/60, FLM_55/45 and FLM_60/40. This
analysis was performed using measurement data collected at the burner exit plane. Figure 5 shows the oscillation of the velocity field at the fundamental frequency which are similar to frequencies shown in acoustic spectra in Fig. 2 and OH* CL spectra in Fig. 3 for flames FLM_40/60 (<1), FLM_55/45 (1) and FLM_60/40 respectively. A second frequency similar to the first overtone detected in the acoustic and OH* CL spectra are seen near the ISL and OSL in the three flames.

This indicates that a secondary periodic flow field phenomenon is occurring locally around the ISL and OSL. It is difficult to infer the nature of this flow structure as there are a wide range of fluid dynamic instabilities, which are known to affect shear layers in swirl stabilized flames. The corresponding frequencies detected in the acoustics, flow field and OH* CL suggest that the global heat release rate is coupled to the dominant thermo-acoustic frequency as well as the first overtone independent of the fuel staging ratio.

3.3 Proper Orthogonal Decomposition Analysis

Proper orthogonal decomposition (POD) analysis has been extensively used as a tool to extract and characterize coherent flow structures such as precessing vortex cores (PVC) in swirl flows. The POD analysis results in a set of orthogonal eigenmodes which represents the coherent flow structure, temporal coefficients and eigenvalues which represents the contribution of the modes to the total turbulent kinetic energy. The first overtone detected in the acoustic and flow field spectra suggests that there are fluid dynamic phenomena responsible for these frequencies in the three flames. The POD was calculated using the method of snapshots of 2000 instantaneous velocity fields.

![Fig. 6 First three spatial eigenmodes of flames with staging ratio 40/60, 55/45 and 60/40.](image)

Figure 6 shows the first three most dominant POD modes of flame FLM_40/60, FLM_55/45 and FLM_60/40. The contribution of energy from each mode to the total turbulent kinetic energy in the measurement domain is labelled on the top right hand corner of each image. Boxx et al. (2012) have shown that the PVC in the ISL can be resolved by the first two modes and it appears as a series of large scale vortices of opposite rotation aligned along the ISL. The spatial modes shown in Fig. 6 do not show such a structure. The spatial modes show vortical structures in all three modes but these are not conclusive enough to determine existence of PVC in the three flames investigated here.

The power spectra of the corresponding temporal coefficients of the first three POD modes from flames FLM_40/60, FLM_55/45 and FLM_60/40 are presented in Fig. 7. The spectra from the first mode show strong oscillations at similar frequencies to the fundamental acoustic frequencies shown in Fig 2. In the spectra of the second mode all three flames have fluctuations at the fundamental acoustic frequencies but flame FLM_55/45 and FLM_60/40 have a second peak at...
twice the fundamental frequency corresponding to the first overtone. Mode 3 spectra of the three flames do not show any dominant peaks. The analysis of the temporal mode suggests that there are no PVC’s in the three flames investigated here.

The large vortical structures, which are shown in the spatial modes; and the frequency spectra of the velocity field in Fig. 5 suggest that the first overtone is due to periodic vortex shedding in the ISL and OSL. The power spectra from the acoustic (Fig. 2), OH* CL (Fig. 3) and velocity field (Fig. 5) confirm the coupling between the heat release rate and the dominant longitudinal mode as well as the first overtone. The effect of staging seems to be that at 40/60 where more fuel is in the inner stage the first overtone is more energetic than the fundamental mode. As staging is varied to 55/45 and 60/40 the fundamental thermo-acoustic frequency becomes dominant.

![Fig. 7 Power spectra of the first three temporal mode coefficients of flames with staging ratio 40/60, 55/45 and 60/40.](image)

### 3.4 Simultaneously Measured Instantaneous PIV/OH PLIF

Simultaneous PIV and OH PLIF measurements were performed at 3 kHz in flames with three staging ratios to look at the interaction between the flow field and the reaction zones. Figures 8, 9 and 10 show instantaneous PIV and OH PLIF images from flames FLM_40/60, FLM_55/45 and FLM_60/40 for one acoustic cycle, where the first image at time (T) = 0 ms is randomly chosen, followed by consecutive images at delta T of 0.333 ms. The instantaneous images show an offset at the y-axis of the PIV and PLIF images. The flow field image starts at y = 0.13D and the OH PLIF at y = 0.08D. This offset at the y-axis was due to the sheet profiles. The PIV laser sheet had an asymmetric beam profile with a hot spot on the top part of the laser sheet. Even though the PIV and the OH PLIF sheets were overlapped in the vertical plane, the maximum intensity of the profiles from the two sheets had an offset. This resulted in the existing y-axis positions in the images shown in Fig. 8 to 10.

The OH PLIF images have been corrected for background noise and normalized by mean image of the laser beam profile. The OH PLIF images have not been corrected for laser absorption at high pressure. The OH PLIF images show regions without OH (black) representing unburned gas that exits the burner. The high intensity areas represented by orange to white regions are the super-equilibrium concentrations of OH formed in the reaction zones which decay towards equilibrium levels over several milliseconds. Medium and low levels of OH (blue to red) represent burned gas whose OH concentration has decayed towards equilibrium, while it was transported away from the reaction zone. The PIV images have been reconstructed from the first ten POD modes which represents over 40% of the turbulent kinetic energy in the measurement volume.

The images in Fig. 8 to 10 have been plotted for one acoustic cycle. Figure 8 shows the interaction of flow field and reaction zone in flame FLM_40/60. The flow field vectors show the existence of vortical structures in the regions close to the OSL and in some instances close to the ISL. The OH PLIF images show super equilibrium OH formed at two radial locations as marked in
Fig. 8. This results in double OH zones at the beginning of the cycle and later merging into one. The occurrence of the super equilibrium OH has been seen in the double OH zones as well as the single OH zone. The whole image series (2000 images) has shown that this behavior is periodic. At t = 1 ms (3rd row 1st two columns) where the first high intensity OH zone is seen around x/D = 0.47 and a second low intensity zone close to x/D = 0 till t = 2.667 ms where the next peak in OH intensity is detected in the single OH field represents approximately half the acoustic cycle. This would result in the frequency being similar to the 1st overtone observed earlier in the velocity and OH* Cl spectra. The switch between double and single OH zones could be due to uneven mixing of fuel air mixtures from the two swirler stages resulting in periodic shift in the flame being stabilized by either outer stage (resulting in double OH zones) or inner (single OH zone).

Flames FLM_55/45 and FLM_60/40 have very similar flow field and OH distribution as shown in Fig 9 and 10 respectively. The sharp gradients in the OH PLIF intensity show that the reaction is taking place between the jet and ISL. For flame FLM_55/45 the IRZ shows almost even distribution of equilibrium OH in the center. This is due to recirculated burned gases. Flame FLM_60/40 on the other hand shows images with very low intensity OH close to the central axis x/D = 0. As shown earlier in Fig 4(a) the reaction zone became narrow and shorter as the fuel staging ratio was varied from 40/60 to 60/40. The OH PLIF images in Fig. 9 and 10 show that the increase in fuel in the outer swirler stage results in a narrow zone between the two stages where the flame can be stabilized. The other interesting feature that has been observed in the full image series is that the large vortical structures in the ISL and OSL as well as the occurrence of super equilibrium OH has similar frequencies to the first overtone.
Fig. 9 Simultaneously measured instantaneous PIV and OH PLIF image sequence of flame FLM_55/45. The first image (T = 0 ms) is randomly chosen followed by 12 consecutive images with delta T of 0.333 ms.

Fig. 10 Simultaneously measured instantaneous PIV and OH PLIF image sequence of flame FLM_60/40. The first image (T = 0 ms) is randomly chosen followed by 12 consecutive images with delta T of 0.333 ms.
4. Conclusions

Natural gas air flames from a gas turbine model burner operated at 5 bar pressure and air preheat of 733 K has been investigated using PIV, OH PLIF and OH* CL imaging at an acquisition rate of 3 kHz. The model burner used in this study consists of two coaxially mounted swirlers stages which allow for fuel staging by varying the percentage of fuel injected in each swirler stage. The effect of fuel staging on flame behavior with enhanced thermo-acoustic pulsations has been investigated in three flames with staging ratio 40/60, 55/45 and 60/40. Successful application of the kHz Laser based measurement techniques have also been demonstrated in investigating flames at gas turbine relevant initial conditions.

The flame shape and length changed as the percentage of fuel in the inner swirler stage is decreases from 60% to 40% (percentage of fuel in the outer swirler is increased from 40% to 60 %). The reaction zone narrows as staging is varied from 40/60 to 60/40 and acoustic spectra show the intensity of the fundamental thermo-acoustic frequencies reduces too. The OH* CL spectra has peaks at the same frequencies as the acoustics spectra. All flames show 1st overtone in the acoustic as well as the OH* CL. POD analysis of the kHz PIV data shows no PVC being present in the three flames. The spatial distribution of the power spectra of velocity shows high frequency regions corresponding to the 1st overtone close to the ISL and OSL. It has been shown that the periodic shedding of vortices in this region is coupled with the heat release rate.

Simultaneous PIV and OH PLIF measurements showed for flame with 40/60 staging ratio, periodic occurrence of double OH zones. The switch between double and single OH zones could be due to uneven mixing of fuel air mixtures from the two swirler stages resulting in periodic shift in the flame being stabilized by either outer swirler or inner and hence resulting in a broad reaction zone. The OH PLIF images in flames with staging ratio 55/45 and 60/40 showed that increasing fuel in the outer swirler stage is resulting in a narrower zone between the two stages where the flame can be stabilized and hence a thinner reaction zone. The successful application of the kHz PIV and OH PLIF measurements at high pressure in this experiment opens a large number of possibilities in using the high speed technique to investigate gas turbine combustors at actual gas turbine operating conditions.

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Reference


