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FLAME FLASHBACK IN HYDROGEN COMBUSTION WITH ACOUSTIC EXCITATION: SIMULTANEOUS PIV AND OH PLIF MEASUREMENTS AT HIGH REPETITION RATE

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PIV, OH PLIF, Flame flashback, Combustion, Hydrogen

Abstract

Flame flashback in acoustically excited premixed hydrogen combustion is investigated using simultaneous PIV and OH-PLIF. The PIV system and the OH PLIF setup allow for repetition rates up to 10 kHz and 20 kHz, respectively. The combination of both techniques was chosen to identify the interaction of flame and flow field in the presence of acoustic excitation. This is a key issue to understand the initiation of flashback in premixed gas turbine burners being prone to combustion instabilities.

Introduction

One approach to make use of fossil fuels without releasing carbon dioxide emissions into the atmosphere is Carbon Capture and Storage (CCS). A review on CCS is given by Haszeldine in [1]. Carbon dioxide is separated from the power generation process and stored underground in depleted oil and gas fields. In the pre-combustion capture route the fuel's carbon content is removed for example by natural gas reformation or coal gasification. This technique leads to hydrogen-rich fuels with hydrogen contents close to 100 %, which can be used for power generation in gas turbines.

Premixed combustion is commonly applied in gas turbines to control the flame temperature and to achieve low nitrogen oxide emissions. Here, fuel and air are mixed upstream of the combustion chamber. The flame is thus able to propagate from the combustor into the premixing zone if the flame speed exceeds the local flow velocity. This is especially critical in the wall boundary layer.

Boundary Layer Flashback (BLF) has already been investigated in two preceding projects at the Lehrstuhl für Thermodynamik, TU München [2–4]. It was found that the flashback limits depend on whether the flame is stabilized at the burner exit (unconfined flame) or whether it is already located in the burner duct (confined flame). The latter drastically increases the flashback susceptibility.

Finally, the safe and stable operation of gas turbines can be endangered by thermoacoustic instabilities. They arise when heat release fluctuations couple with the acoustic modes of the combustion chamber leading to pressure and velocity oscillations. Velocity oscillations induced at the burner exit might in turn influence the flashback behavior and eventually trigger the transition between the unconfined and the confined flame situation. A numerical study on the interaction of combustion instabilities and flashback was conducted by Thibaut and Candel [5]. They observed a periodic upstream propagation of the flame at the point of minimum velocity in the forcing cycle.

Boundary layer flashback and combustion instabilities are especially critical for hydrogen fuel due to its high reactivity and high flame speed. In order to investigate the influence of combustion instabilities on the flashback characteristics, an experimental project is conducted at the Lehrstuhl für Thermodynamik, Technische Universität München. This article presents a simultaneous application of high speed PIV (Particle Image Velocimetry) and high-speed OH PLIF (Planar Laser Induced Fluorescence) to characterize the interaction between the turbulent flow field and the flame in acoustically excited premixed hydrogen combustion at the onset of flame flashback. The combination of PIV and OH PLIF allows for detailed insight into the process of flashback initiation. The results are relevant for the design of safe and reliable gas turbine burners for highly reactive fuels.

Experiment

The test rig for boundary layer flashback consists of a rectangular model burner and a forcing section. Figure 1 shows a CAD model of the experimental facility. The hydrogen-air mixture enters the test rig at (1) and passes a flow conditioner (2) until it reaches the model burner (3). The flame is stabilized at the burner exit (4) representing an unconfined flame. Finally, the exhaust gas is removed at (5). Acoustic forcing is realized with six symmetrically installed

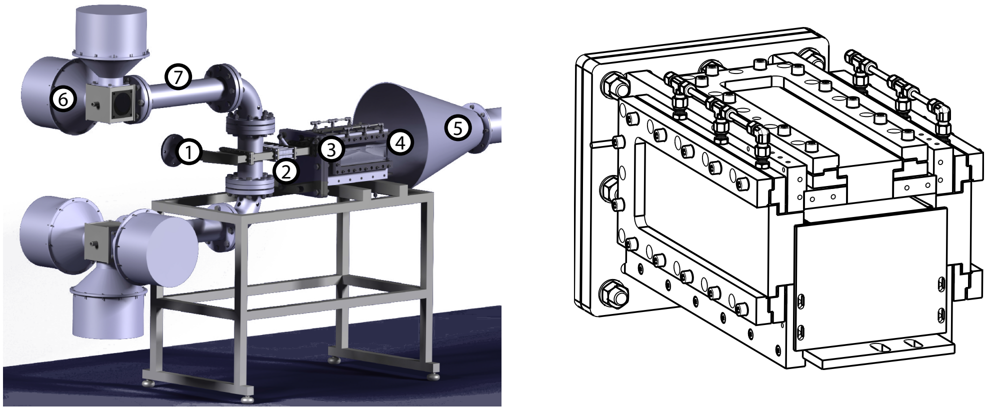

Fig. 1: Flashback test rig and rectangular model burner at the Lehrstuhl für Thermodynamik, Technische Universität München.

250 W speakers (6). The length of duct (7) can be varied to modulate the test rig's natural frequencies. At the natural frequency, velocity oscillations up to 100 % of the mean flow velocity can be obtained. The rectangular model burner is depicted on the right in Fig 1. The high aspect ratio geometry of 158 x 17.5 mm was chosen to perform quasi-2D measurements in the center plane. In order to enable optical measurement techniques, the flow channel is optically accessible from three sides. Two flames are established during operation with the help of pilot burners, namely one at the upper and one at the lower wall. The lower wall is extended 7 mm compared to the upper wall. The equivalence ratio of the main flow is increased until the flames are self-sustaining and the pilot burners can be switched off. Afterwards, the equivalence ratio is increased until flashback occurs. The temperature rise in the burner duct due to the flame flashback is detected by a type S thermocouple leading to an automatic shutdown of the fuel supply. During the experiment the system is excited by the speakers at a forcing frequency of 125 Hz. The amplitude of the forcing can be varied.

Measurement System

The measurement system consists of PIV, OH PLIF and OH* chemiluminescence. The three setups are introduced in the following sections.

PIV

For the PIV measurements TiO_2 seeding particles are injected into the main flow. They are illuminated by laser light at 527 nm from a New Wave Pegasus Nd:Ylf solid state laser. The laser has two cavities each allowing for repetition rates up to 10 kHz with pulse widths of 180 ns. In this way, the velocity field can be analyzed with a temporal resolution of 10 kHz. In this study a temporal resolution of 5 kHz was chosen to operate the high speed camera at maximum resolution.

The laser beam is guided from the laser to the test rig in a light arm and is then expanded with a cylindrical lens to form the light sheet. A high-speed camera Photron Fastcam SA5 775K-M2, which is combined with a 180 mm optics and a bandpass filter of 527 ± 10 nm, records the light scattered from the seeding particles.

OH PLIF

The OH PLIF system is composed of a frequency doubled Nd:YVO4 pump laser (Edgewave IS8II), which emits radiation at 532 nm and a tunable dye laser (Sirah Credo). The pump laser has two cavities each allowing for repetition rates up to 20 kHz at pulse width of 8 ns. In this study, for the desired temporal resolution of 20 kHz, only laser cavity 2 of the pump laser is used. The dye laser emits radiation of 283 nm, which is suitable for the excitation of the OH radical. The dye laser beam is guided by mirrors to the measurement section and is there expanded and focused to a parallel light sheet with an UV coated cylindrical lens and a spherical lens. The excited OH radicals emit radiation at 309 nm when returning to a lower energetic state. A high-speed camera Photron SA-X records the fluorescence signal and is for that purpose combined with an image intensifier (Hamamatsu C10880-03), a 105 mm UV optics and a 320±20 nm bandpass filter. A detailed description of the OH PLIF system is given in [6].

OH* Chemiluminescence

The OH* chemiluminescence technique is applied to monitor the initiation of flashback from the top view. A Photron APXI^2 camera is combined with a 45 mm UV optics to record the emissions of the chemically excited OH radicals. Originally, a 307±5 nm bandpass filter should have been used, but the remaining signal was too weak due to the short gating necessary to avoid interference with the PIV or OH PLIF system. Therefore, no filter was used, such that the entire emission spectrum was recorded. The additional information of the OH* chemiluminescence from the top view is necessary to detect if the flashback initiates in the laser plane.

Synchronization

In order to perform the simultaneous measurements, all components of the measurement system have to be synchronized. Figure 2 shows the synchronization of the lasers and cameras via three delay generators. Delay generator 1 creates the master signal of 20 kHz, which is used to trigger the LIF pump laser, the Photron SA-X camera and the Hamamatsu image intensifier. The time delays Δt1 and Δt2 account for the internal time delay of the high speed camera. A second delay generator converts the master signal to a 10 kHz signal, which triggers the high speed camera Photron SA5 for the PIV measurements. The third delay generator splits the 10 kHz signal into 5 kHz signals for the two PIV laser cavities and for the OH* Photron APXI^2 camera. A timeline of the measurement procedure is illustrated in Fig. 3. The LIF Laser pulse is delayed Δt1 = 3 μs plus its internal time delay. Around the laser pulse, the image intensifier is activated for 50 ns starting at 3.81 μs. Every fourth LIF laser pulse, the PIV laser pulses are emitted as the PIV system is working with half the LIF frequency. Thus the first pulse of PIV laser cavity 1 starts at Δt4 = 91.5 μs plus the laser's internal time delay. The pulse of cavity 2 is activated 20 μs afterwards. In this way, the PIV laser pulses do not interfere with the LIF image intensifier which could be overexposed if it caught the PIV signal. The shutter of the APXI^2 camera, which should not catch the LIF or PIV signals, opens for 40 μs at Δt6 = 5 μs.

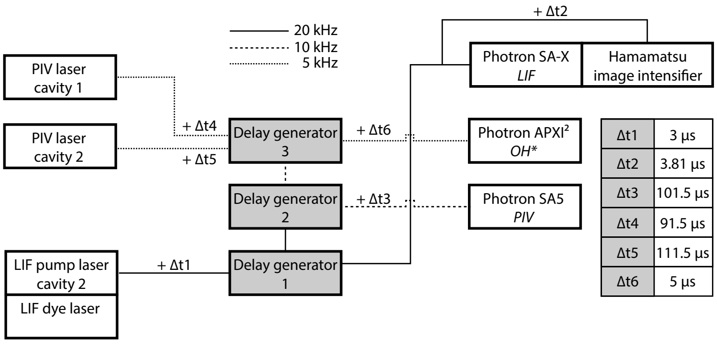

Fig. 2: Synchronization scheme of the simultaneous PIV, OH PLIF and OH* chemiluminescence measurements.

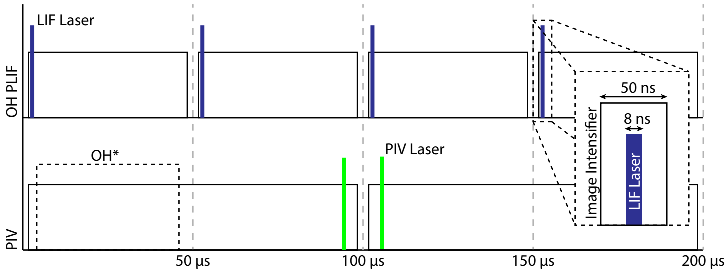

Fig. 3: Timeline of the simultaneous PIV, OH PLIF and OH* chemiluminescence measurements.

Results

Non-Reacting Flow

In order to analyze the effectiveness of the acoustic forcing, the velocity field downstream of the burner exit of a non-reacting air flow (30 g/s) is recorded using the described PIV setup. Figure 4 shows one forcing period. The results are averaged over 50 forcing periods. The forcing cycle starts at t = 0 ms with the point of maximum velocity. The high velocity region is then transported downstream. The forcing amplitude in this case is about 45 % of the mean flow velocity. Thus, the induced excitations are comparable to those induced by Thibaut and Candel [5] and a periodic upstream propagation of the flame in the reacting case can be expected.

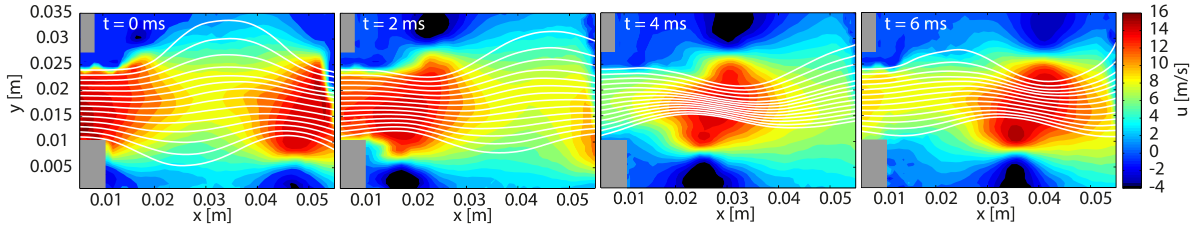

Fig. 4: Averaged velocity fields of non-reacting flow at forcing frequency of 125 Hz.

Stable Flame without Forcing

For the reacting case, the air mass flow rate of 30 g/s and the equivalence ratio of $\Phi = 0.36$ are chosen. Under these conditions and without acoustic forcing a stable flame can be established. The mean and instantaneous flame position and the velocity fields are depicted in Fig. 5. The combination of PIV and OH PLIF data clearly shows the gas expansion due to the combustion and the resulting outward deflection of the flow.

Stable Flame with Forcing

Starting from the stable flame without forcing, the forcing amplitude is slowly increased. Figure 6 shows instantaneous images of the flame and the velocity field during one cycle of moderate forcing. The first picture (t = 0 ms) again represents the point of maximum velocity

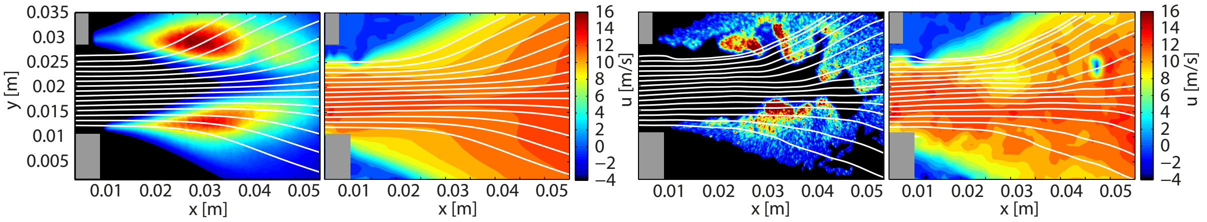

Fig. 5: Averaged stable flame and instantaneous image with corresponding velocity fields at air mass flow rate of 30 g/s and equivalence ratio Φ = 0.36 (left: OH PLIF with streamlines from PIV, right: PIV).

at the burner exit. The high flow velocities result in a slender and stretched flame as observed at t = 2 ms. Reaching the point of minimum velocity at t = 4 ms, the flame becomes broader and moves upstream. This observation is in good agreement with the streamlines which are deflected outward much earlier than at maximum velocity.

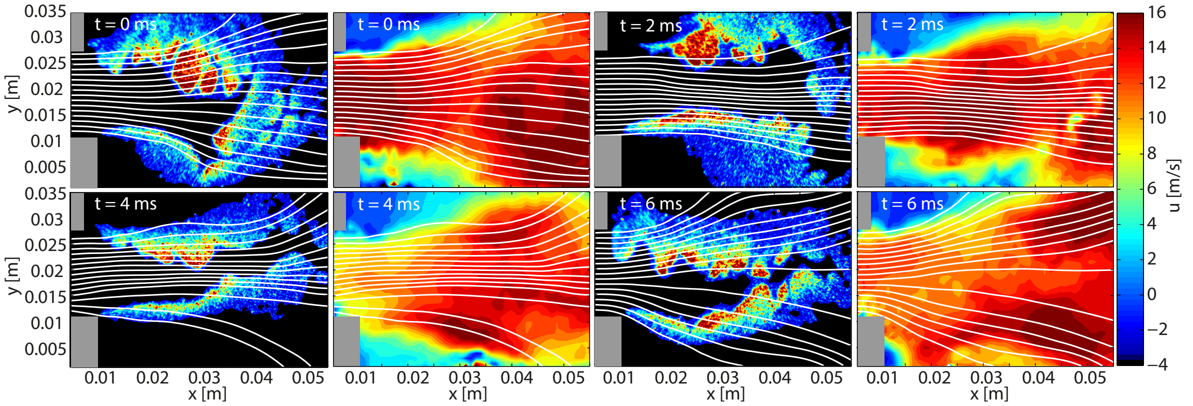

Fig. 6: Instantaneous images of stable flame and velocity fields at air mass flow rate of 30 g/s and equivalence ratio Φ = 0.36 during one forcing cycle (left: OH PLIF with streamlines from PIV, right: PIV).

Flashback

By further increasing the forcing amplitude, the flame periodically enters the channel. This can be seen in Fig. 7 where the images t = 144 ms till t = 150 ms represent one entire forcing cycle still in the stable regime. At this state, the flame is still periodically washed out of the channel. A little increase of the forcing amplitude finally causes the flame to enter the channel at the upper wall and propagate against the flow. This leads to an increase of the axial velocity at the burner exit as depicted on the lower right side of Fig. 7. The velocity increase is caused by blockage of the burner duct by the flame and gas expansion due to combustion now being located inside the duct. The beginning of the increase in axial velocity indicates the starting point of an unstable regime and can be defined as the initial onset of flashback. The propagation of the flame into the burner duct can also be seen in the flame luminescence results shown in Fig. 8. Contrary to boundary layer flashback (BLF) without acoustic forcing (see [2–4]), the observed process of acoustically induced flashback in this study appears to be rather gradual. It will have to be investigated if this applies generally or if it is specific to the configuration shown here.

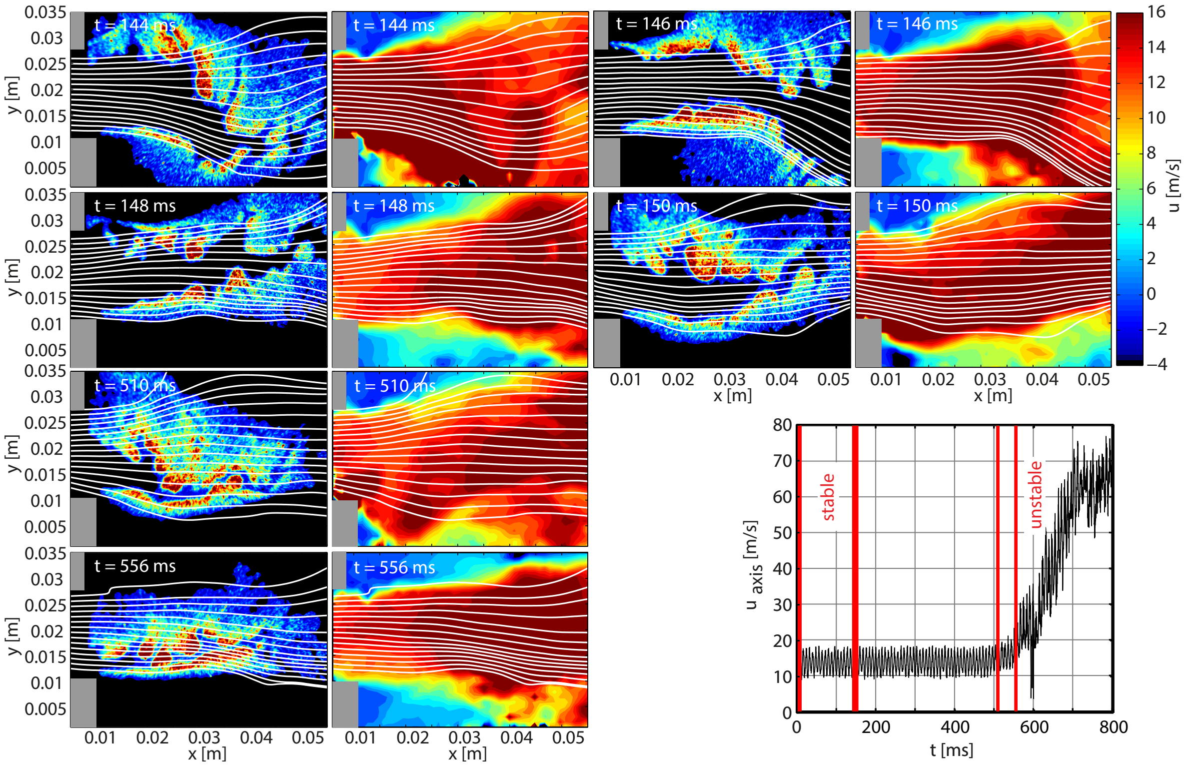

Fig. 7: Instantaneous images of flame and velocity field at the onset of flashback (air mass flow rate: 30 g/s, $\Phi = 0.36$, left: OH PLIF with streamlines from PIV, right: PIV).

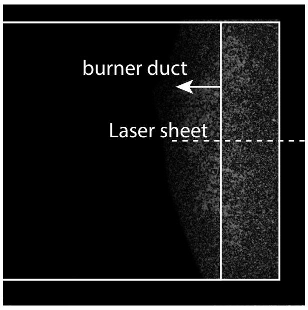

Fig. 8: Flame luminescence from the top view at the onset of flashback (air mass flow rate: 30 g/s, $\Phi = 0.36$).

Conclusions

It was experimentally demonstrated in this paper that acoustic oscillations can lead to flame flashback in premixed hydrogen-air combustion. A rectangular model burner allowed for a quasi-2D analysis. The authors investigated the phenomenon by means of highly time-resolved optical measurement techniques, namely high-speed PIV and high-speed OH PLIF. Two laser systems were synchronized and combined with two high-speed cameras. A third camera recording flame luminescence was added to the system to monitor the lateral position of the leading flame tip entering the burner channel. By characterizing the isothermal flow field with excitation and the time-averaged flame position and flow field without forcing, the experimental boundary conditions and reference conditions were shown.

Instantaneous image sequences shortly before and during flashback reveal that the flame can periodically enter the burner channel and be washed out without final flashback occurring. This phenomenon is the starting point of an unstable combustion regime, where the flame located in the burner duct leads to an increase in axial velocity at the burner exit.

The next steps in the analysis of flashback induced by acoustic excitation will be the reconstruction of the flame propagation path and its dependence on the flow field. Therefore, PIV and OH PLIF measurements will be performed on small scale to resolve the wall boundary layer. Critical conditions for flashback will be defined as a function of mean flow velocity, equivalence ratio as well as forcing amplitude and frequency.

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