Experimental investigation of stability limits and upstream flame propagation in a lean premixed, swirled annular slot burner

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1 Introduction

Lean premixed combustion offers the potential for low NO_x-emissions. In practical realizations, swirling premixed flames are usually stabilized by internal recirculation zones induced by vortex breakdown occurring when a critical geometry-dependent swirl number is exceeded. The development of precessing vortex cores (PVC) often precedes the vortex breakdown. The interaction between the flame and the turbulent flow field can enable the flame to propagate upstream into the nozzle causing serious problems. This phenomenon is known as flashback and must be avoided. Occurring as different types flashback is a complex phenomenon not yet fully understood. Flashback by combustion induced vortex breakdown (CIVB), relevant for the flashback phenomenon observed in this study, is associated with a density jump due to combustion induced heat release [1]. Occasionally, negative axial velocities located ahead of the vortex breakdown region occur and push the flame upstream. The aim of the present investigation was to study turbulent premixed flames during flashback. For this purpose an unconfined, swirling, lean premixed methane/air flame was selected. The focus was on stability limits and upstream propagation of the flame to gain an improved understanding of the underlying mechanisms. Therefore, three cinematographic high speed measurement techniques up to $20kHz$ data rate were applied simultaneously inside the exit nozzle of the burner: planar laser-induced fluorescence of hydroxyl radicals (OH-PLIF), 2D particle image velocimetry (PIV) and chemiluminescence imaging (CL). These diagnostics give insights into the upstream propagation of the flame inside the burner's exit nozzle. The findings have led to the formulation of a 'propagation prototype' which is presented and discussed in this work.

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2 Experimental Procedure

Flame flashback was investigated in an unconfined, swirl-stabilized, lean premixed burner with central bluff body. A schematic of the burner is shown in Fig. 1. The burner is described in detail in [2]. Only the important features are given here. Inside the plenum, methane and air were mixed before entering the radial swirler and the subsequent exit nozzle. The outer tube ($D_{in} = 60mm$) and the central bluff-body ($D_{out} = 30mm$) were made from quartz to enable optical access and minimize laser reflections. The bluff body was protruding from the nozzle exit by $20mm$, resulting in an additional metastable combustion state. The movable block design allowed to vary the theoretical swirl number from 0 to 2 (with increments of 0.02) by rotating the movable block with a stepper motor. For an reciprocal equivalence ratio of $\lambda = 1/\Phi = 1.2$ and $S < 0.8$ the flame was burning stable at location (a)(see Fig. 1). At $S = 0.8$ the flame passed over into a metastable state. It started to spin around the bluff-body while the stabilization point moved from above the bluff-body to its top and further upstream along its side walls (b). Above $S = 1.0$ the flame suddenly propagated into the swirler (c), i.e., flashback occurred. The stability limits for swirl-induced flashback are already published in [3]. In the present study the flashbacks were additionally induced by gradually increasing λ by $0.01/s$ at a constant swirl number of $S = 1.035$ and Reynolds number Re. Starting from a stable state at $\lambda = 1.7$ the flame was going from a stable to a metastable state until it finally flashed back. The value for λ_{crit} when flashback occurred was recorded for multiple realizations of the same Reynolds number ($13-21$ flashbacks). This procedure was done for different Reynolds numbers ranging from 6000 to 10000.

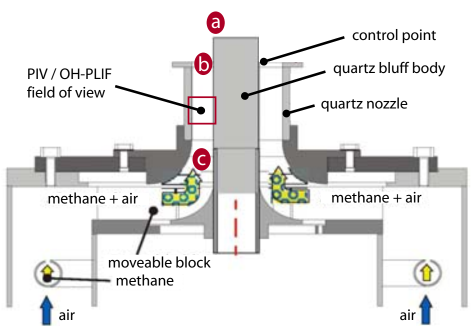

Figure 1: Scheme of the investigated swirl burner.

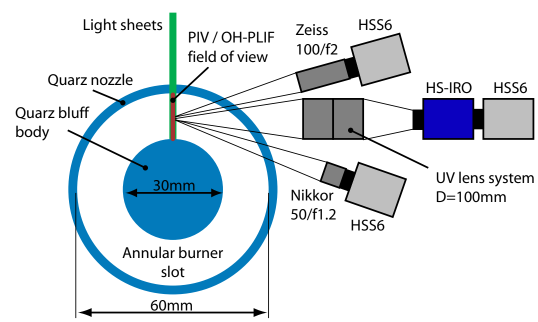

Figure 2: Layout of the experimental setup.

To gain insight into the mechanism of combustion induced vortex breakdown leading to flashback, three cinematographic measurement techniques were applied simultaneously. Figure 2 shows the experimental setup which was a further development of a setup by Heeger et al. [4]. In addition to PIV and OH-PLIF, information about the global flame position and structure was acquired by recording CL with a state-of-the-art high speed CMOS camera (HSS6), which allowed for $512 \times 512 pix^2$ at $20kHz$. The field of view was $70 \times 70mm$ covering the whole transparent nozzle. The FIFO (first-in-first-out) architecture of the on-board memory ($8GB$) allowed to record data continuously and held 20000 frames at $20kHz$. For post-processing a Fourier transformation of the time series of the luminescence intensity at a monitoring point was taken. It was located on the side wall of the bluff body to determine the precessing frequency of the LE around the central bluff body.

High speed PIV was conducted to obtain the 2-dimensional, 2-component velocity field in a vertical plane through the axis inside the nozzle (see Fig. 1). The field of view was $17 \times 17mm$ with a pixel resolution of $512 \times 512pix^2$. The acquisition rate of the system was $20kHz$ with an equidistant time separation ($dt = 50\mu s$). Due to the high out-of-plane velocity of the flow a $2mm$ thick and $25mm$ high light sheet was formed. The PIV data was processed with a modified open source code [6]. An interrogation area of $8 \times 8pix^2$ was used giving a physical resolution of $280\mu m$. Due to equidistant time steps all subsequent image pairs could be processed, thus yielding a temporal resolution of $20kHz$.

The data set is complemented by high speed planar OH-PLIF at $10kHz$ acquisition rate, which was taken in between every second PIV double shot. The OH radicals served as flame front marker and gave insight into the position and detailed structure of the flame's leading edge (LE). To excite the $Q_1(6)$ line of OH a frequency-doubled dye laser was pumped by a frequency-doubled Nd:YLF laser at $523nm$. At $10kHz$, the pump laser is capable of $8mJ/pulse$ ($80W$ quasi cw), but was limited to $5.3mJ/pulse$ to protect the system against thermal destruction. The pulse length was approximately $10ns$. For the dye laser two separate cuvettes (Rhodamine 6G) for oscillator and amplifier at brewster angle were used. This setup has advantages over previously used one-cuvette designs [5], making it much easier to align and increasing thermal stability. The $566nm$ radiation was frequency-doubled by a BBO crystal. At $10kHz$ the quasi cw power at $283nm$ was $2.5W$ ($250\mu J/pulse$). A $25mm$ high and $200\mu m$ thick laser light sheet was formed and combined with the PIV laser sheet to cover the same measurement volume. The emitted light was monitored by a state-of-the-art two-stage IRO (IRO: intensified relay optics) that was lens-coupled to yet another HSS6. At repetition rate of $10kHz$ an area of $768 \times 768pix^2$ was active, yielding a physical resolution of $24\mu m/pix$. PLIF signals were collected with a head-to-head UV lens system ($f285/2.8$ each). A threshold-based edge detection of the OH-PLIF signal supplemented the processed data set. During periods when the LE passed the measurement volume the detailed structure of the flame was obtained.

3 Results

Figure 3 shows λ_{crit} plotted versus thermal power at the moment of flashback. A total of 280 flashbacks were conducted to determine these stability limits. The open circles represent individual flashbacks whereas the red markers represent the mean values for constant Re. The dashed grey line represents the stability limit of the model of Konle and Sattelmayer [7]. Modeled by a scaled Damköhler criterion the predictions agree well with the experimental results.

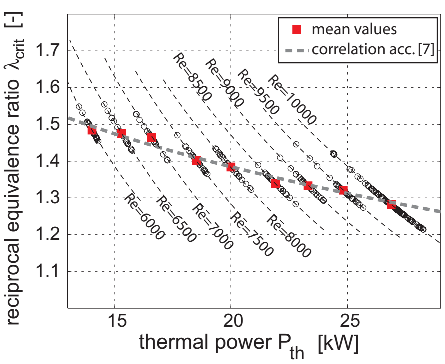

Figure 3: Stability limits of the investigated swirl burner for CH_4-air mixture.

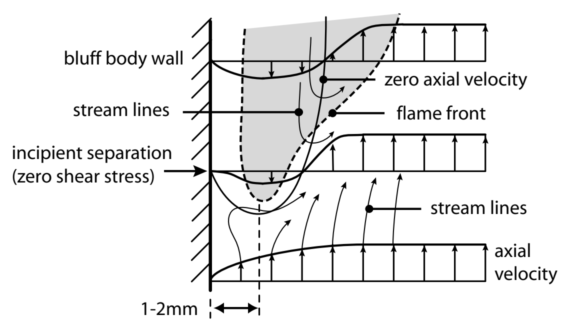

Figure 4: Concept of the 'propagation prototype' leading to flashback.

For the 14 flashbacks that were recorded by time-correlated techniques the precessing frequency of the flame around the bluff body was $57 \pm 5Hz$. The frequencies agree well with those reported by Schneider [2] for PVC inside an isothermal flow at swirl numbers of $S = 1.4$. Flow field and the structure of the flame resemble a typical temporal behaviour while propagating upstream. This will be presented in the following as 'flashback prototype' (sketched in Fig. 4) which is deduced from the sequence of images in Fig. 5. Each image shows a region $8.5mm$ wide and $10.5mm$ high with the left side coinciding with the inner wall of the annular slot. The dark region represents the hot products, while the colors represent the axial velocity. Very close to the wall the boundary layer flow decelerated and reversed its direction. It is seen that the v-shaped flame propagated in the backflow region that temporarily formed on the inner wall. Moving upstream the LE had a characteristic distance from the wall of about $1.5mm$ and propagated with a velocity of about $6m/s$ which is well above the laminar flame speed. The flame was quenched in a thin region ($\approx 1mm$) directly adjacent to the inner wall. Streamlines were no longer wall-parallel due to the large displacement of the separated boundary layer and further enhanced by thermal expansion.

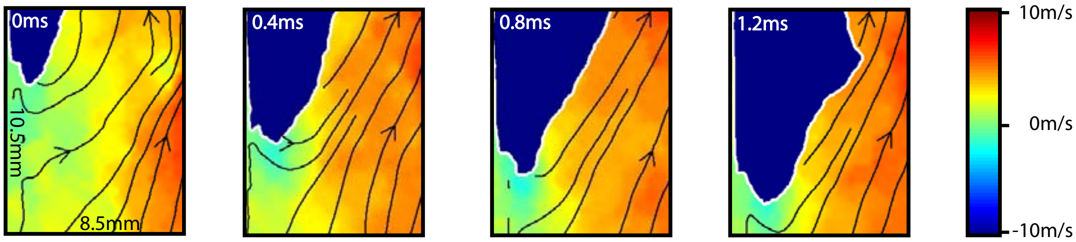

Figure 5: Sequence of leading edge upstream propagation from PIV data. Dark blue area: hot exhaust gas, background colours: axial velocity, lines: streamlines.

4 Discussion and Outlook

In this work we present stability limits of the investigated premixed swirl burner which show very good agreements with a new prediction model by Konle. Furthermore time-correlated simultaneously acquired PIV, OH-PLIF and CL data at kHz repetition rates is presented. To the best of the author's knowledge, OH-PLIF at $10kHz$ as well as the simultaneous application of PIV at $20kHz$ has not been reported so far. The results give insights into the mechanism of upstream propagation of the flame inside the annular slot of the burner. Based on these findings a 'propagation prototype' is presented, indicating that the flame tip propagates upstream following a recirculation zone which forms near the inner wall.

References

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