Time-resolved PIV and flame front imaging of boundary layer flashback in a swirl combustor

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Abstract Boundary layer flashback of lean-premixed, confined swirling flames is investigated. Flashback characteristics of hydrogen-methane-air (H₂/CH₄-air) flames with 95% H₂ and 5% CH₄ by volume are compared to those of CH₄-air flames. Flashback is induced by first establishing a stable lean-premixed swirl flame in the combustion section and then increasing the equivalence ratio. Simultaneous chemiluminescence imaging and three-component particle image velocimetry are applied to study the flame-flow interaction inside the mixing tube. Regions of negative axial velocity upstream of the flame tip are observed in agreement with previous studies. In contrast, these regions of negative axial velocity are found to not correspond to regions of reverse-flow in the streamwise direction (separated flow). Instead, the current data suggest that flow separation only occurs upstream of small-scale convex shaped flame bulges, which appear to be similar to bulges observed in previous studies of flashback in non-swirling channel flows. However, these flame bulges are found to not drive flashback in swirling flows. Instead, one (sometimes a few) large-scale flame tongues swirling around the center body in the positive azimuthal direction are leading the overall flashback. Flashback of the high hydrogen content H₂/CH₄-air flame is found to behave similarly in terms of the flow field upstream of the leading flame tip despite a significantly more convoluted flame surface associated with many more small-scale bulges. An increase in flame speed is observed, which is in agreement with expected effects of thermo-diffusive instability on flame propagation.

1. Introduction

Combustion with high-hydrogen-content fuels is currently viewed as a potential method for reducing the output of greenhouse gases resulting from stationary power generation systems. However, swirl combustors used in gas-turbines, which are designed to operate on natural gas, exhibit different combustion characteristics owing to the fast kinetics, high diffusivity and low density of hydrogen fuel. High-hydrogen content fuels are particularly susceptible to flashback, which constitutes a potentially catastrophic failure of the combustor (Huang et al. 2009). The upstream flame propagation during a flashback event may occur in the core flow, or along a wall. The former is relevant for swirl combustors without a center body in the mixing tube, and resembles flame propagation along a vortex axis. Characteristics of flame propagation in a vortex core are summarized by Ishizuka (Ishizuka 2002). In swirl combustors, a mechanism described as combustion-induced-vortex-breakdown has been found to drive the upstream flame propagation in the non-trivial case of an axial core flow velocity exceeding the turbulent flame speed (Fritz et al. 2004; Kröner et al. 2007; Konle et al. 2008).

The latter, flashback along a wall, may occur in swirl combustors with center body. Boundary layer flashback in non-swirling flows has first been studied systematically by Lewis and von Elbe (Lewis et al. 1947), whose model based on a critical velocity gradient has been quite successful for an order-of-magnitude flashback prediction in various applications. However, the critical gradient model is not generally applicable owing to its key assumption that the flame has a negligible effect on the flow field. More recent studies on flashback in laminar (Kurdyumov et al. 2007; Eichler et al. 2011) and turbulent boundary layers (Eichler et al. 2011; Gruber et al. 2013) in channel flows have shown that this assumption is invalid, instead showing streamline divergence in both the spanwise and the transverse direction in the vicinity of the flame front. Regions of reverse-flow were observed upstream of the flame front in both the laminar case (Eichler et al. 2011), and upstream of local flame bulges in the turbulent case (Eichler et al. 2011; Gruber et al. 2013). Numerical simulations showed an increase in pressure in the streamwise direction across the laminar flame front (Eichler et al. 2011) and flame bulges (Gruber et al. 2013), respectively, with pressure peaking
immediately upstream of the flame front. The reverse-flow regions, which reach well above the quenching distance, were attributed to an interaction of low-momentum boundary layer flow and the increase in pressure. In the case of the turbulent boundary layer, a strong correspondence between reverse-flow and the upstream propagating leading edge of the convex flame bulges is shown. Pockets of negative axial velocity were also observed during flashback of an unconfined, swirling, lean-premixed CH4-air flame (Heeger et al. 2010).

The aim of the current study is to investigate boundary layer flashback of confined, lean-premixed swirl flames inside the mixing tube of a model swirl combustor with center body. High-hydrogen content H2/CH4-air flames are compared to the reference case of CH4-air flames. Recent work suggests that boundary layer flashback may become a key challenge for high-hydrogen content flames due to its high reactivity, small quenching distance and thus its capability to propagate closer to the wall in regions of lower velocity compared to hydrocarbon-air flames (Gruber et al. 2013; Mayer et al. 2012).

2. Experimental Setup

2.1. Swirl Burner

The swirl burner consists of a plenum, a mixing tube and a combustion chamber, as shown in Figure 1. The plenum and the mixing tube have an inner diameter of 52 mm. The mixing tube is 150 mm long. The combustion tube measures 100 mm in diameter and 150 mm in length. Both, the mixing and the combustion tubes are made of quartz cylinders to allow optical access. Swirl is generated by a single axial swirler located at the upstream end of the mixing tube. The swirler consists of eight vanes and the vane trailing-edges are at an angle of 60° relative to the tube axis. The swirl number is approximately $S \approx 0.9$ based on a numerical simulation of the flow field and is calculated as the ratio of axial to circumferential momentum flux based on time and space averaged radial profiles in a plane 10 mm upstream of the mixing tube exit. The hub diameter of the swirler is 25.4 mm. A steel center body of equal diameter is attached to the swirler, ending flush with the end of the mixing tube.

![Figure 1: Model swirl combustor.](image)

Experiments were conducted at atmospheric pressure. Air and fuel were supplied to the combustor at room temperature. The swirl burner can either be operated in fully-premixed or in partially-premixed mode. In fully-premixed mode fuel and air are fully mixed far upstream of the combustor plenum. The fuel/air mixture is supplied through four symmetrically arranged air-supply tubes, whereas no fuel is injected through the ports in the swirler vanes (Figure 1). In partially-premixed mode only air is fed to the plenum through the four tubes, and fuel is injected through the ports in the swirler vanes. For this investigation, the swirl burner was operated in fully-premixed mode only. Methane and a hydrogen/methane mixture were used as a fuel. Two mass flow controllers (OMEGA FMA-2600), controlled with LabVIEW, regulate the fuel mass flow rate. Flashback experiments started with a stable flame in the combustion chamber. The sudden expansion at
the exit of the mixing tube causes vortex breakdown, which, together with the wake of the center body, leads to a region of low axial velocity in the core of the combustion chamber. This low velocity region holds the conically shaped flame in place downstream of the center body. The distance between center body and flame base under stable conditions is about 10 mm, depending on flow rate and equivalence ratio. Flashback was then initiated by a sudden increase in fuel mass flow to a pre-defined value. The change in fuel flow rate was fast enough that the flame propagated into constant equivalence ratio conditions in the mixing tube. The time from ignition to flashback was typically about 10 seconds. The center body is heated by both the incident laser sheet and the presence of the flame. The center-body temperature, measured after each run, was below 100°C for all runs. A center-body temperature of 100°C or less was found to have no effect on flashback limits within the measurement uncertainties, which is in agreement with previous studies (Eichler et al. 2012).

2.2. Flow Diagnostics

In order to investigate flashback, the location of the flame front and the velocity field in the vicinity of the flame front are of particular interest. High-speed planar Mie scattering of an aerosol seeded into the air stream and illuminated with a laser serves both purposes. First, the particle scattering is used for three-component planar particle image velocimetry (stereo-PIV). Second, the evaporation of the aerosol in the preheat region of the reaction zone provides an approximate marker of the flame front. Local flame extinction farther downstream of the flame base might not be captured when utilizing the evaporation of an aerosol as a flame front marker; however, since the location of the flame front at the flame base is the information of interest in this investigation, no additional diagnostic technique for determining the flame front is needed. In order to correctly interpret the flame propagation based on Mie scattering, information about the global position of the flame is important. This is achieved by simultaneously imaging the flame luminescence.

Time-resolved chemiluminescence of the flame during flashback is recorded with an intensified high-speed CMOS camera (FASTCAM-ultima APX-i2). The flame is imaged at 4 kHz, with a resolution of 512 x 512 pix². The camera was fitted with a Nikkor 105mm lens with an f/2.8 aperture. The shutter and gain gate is timed such that the luminescence is recorded between the two laser pulses for the Mie scattering images for best agreement between chemiluminescence images and velocity field data. The viewing direction is parallel to the laser sheet and so the field-of-view is perpendicular to the sheet as indicated in Figure 2.

![Figure 2: Swirl combustor schematic and diagnostics setup.](image-url)

For planar Mie scattering, the flow is seeded with olive oil droplets of approximately 1 μm in diameter using a six-jet atomizer (TSI Inc.). The oil droplets are illuminated with two high-repetition rate diode-pumped, frequency-double 527 nm Nd:YLF laser (Coherent Evolution-90) operated at a repetition rate of 4 kHz. A combination of a negative and a positive cylindrical lens is used to form a collimated 20 mm wide laser sheet. A long focal length spherical lens is used to focus the laser sheet to about 1.5 mm in thickness. The laser sheet enters the mixing tube from the top in the r-z plane. It is aligned with the mixing tube axis, as shown in Figure 2. Two high-speed CMOS cameras (FASTCAM-ultima APX) are operated in forward scattering mode at a framing rate of 8 kHz and a resolution of 256 x 512 pix². The cameras are fitted with
Scheimpflug adapters and Nikkor 105 mm lenses operated with an f/5.6 aperture. The angle between cameras and light-sheet normal is 30°. The field-of-view is 13.5 x 27 mm² with a pixel resolution of 50 µm. The top edge of the field-of-view is located at z = -42 mm, meaning 42 mm upstream of the mixing tube exit plane. In the current experimental setup, the center body can be removed for calibration purposes. A calibration target with a dot spacing of 0.64 mm and a dot diameter of 0.12 mm is traversed through the laser sheet in order to obtain the mapping function between pixel location and physical space. The Mie scattering images are dewarped based on this mapping function.

The light sheet setup and camera positioning allowed valid particle images all the way to the center body wall. The light sheet is brought in from the top, which significantly reduces reflections off the center body. The cameras are rotated into a stereoscopic setup in the z-θ-plane rather than the r-θ-plane such that the line-of-sight is parallel to the tangent on the center body wall. This camera orientation prevents bright spots on the wall to appear as particle images with zero velocity within the first few interrogation windows. These bright spots typically have a high intensity and frequently dominate the cross-correlation computation thus producing invalid vectors in a region that is of most interest for boundary layer flashback investigations. The issue of wall illumination deteriorating the Mie scattering images becomes more severe in flashback studies where the laser light is refracted toward the wall due to the density gradients associated with the presence of the flame. As a result, the intensity of these bright spots increases significantly. Thus, the camera positioning adopted in this study is crucial for near-wall stereoscopic PIV measurements.

The three-component planar velocity field is determined based on two subsequent Mie scattering images captured at 8 kHz using the LaVision software DaVis. The velocity field is consequently resolved at 4 kHz. The interrogation window size is 16x16 pix² corresponding to 0.8 x 0.8 mm² in physical space. A 75% overlap is chosen to minimize the distance between the flame front (based on vaporized droplets) and the first valid velocity vector. The distance between the wall and the first velocity vector in the radial direction is 4 pix, or 0.2 mm.

Accurate PIV measurements through curved glass surfaces (in this case a quartz tube) require a precise mapping function between image sensor and physical space to account for radial distortion (calibration). However, small-scale inhomogeneities in the glass surface leading to distortions on the order of a few pixels are not accounted for by the previously described calibration process. Standard quartz tubing, even with high optical homogeneity (e.g. standard MIL-G-174-B, grade A), has lengthwise striations due to its manufacturing process (electric fusion). As a result, particle images are stretched in the radial direction, which leads to broad correlation peaks in the same direction. A raw image and a representative correlation map using such a quartz tube are shown in Figure 3. For the current experiment, the standard quartz tube has been replaced by a custom made synthetic silica tube with highest optical homogeneity (i.e., no lengthwise striations) owing to a contact-less manufacturing process (flame hydrolysis). Figure 4 shows a significant improvement in both, raw particle image quality and correlation map. Additionally, since the particle image size in the radial direction is reduced to 1-2 pixels, this tube allows a higher seeding density and thus reliable velocity vectors down to an interrogation window size of 16x16 pix². For two-component PIV inaccurate particle displacements in the radial direction only affect the radial velocity component. In stereoscopic PIV, however, all three velocity components are obtained through triangulation of radial and axial particle displacements from two cameras, which makes an accurate radial displacement crucial for all velocity components. The uncertainty in the velocity measurement is estimated based on the stereoscopic residual error. The mean residual error is 0.09 pix in the interrogation window closest to the wall and 0.16 pix in the core flow. The time delay between two laser pulses is 90 µs, which corresponds to a particle displacement between 0 and 11 pixels. The uncertainty for the in-plane velocity components is consequently 1.5 % in the core flow (highest particle displacement) and 0.05 m/s at a stagnation point with zero velocity. The uncertainty in the out-of-plane component is larger by a factor of about 1.7 based on the camera angle.
The flame front is determined based on vaporized oil droplets for every other frame in the movie sequence in order to match the temporal resolution of the velocity field (4 kHz). The automated flame front extraction is based on a threshold intensity in 8x8 pix² probe windows with 75% overlap. A series of morphological operations is implemented to eliminate spurious patches both within and outside the area occupied by the flame. The resulting flame front is filtered to avoid artificial high-frequency wrinkles due to the discrete nature of the particle pattern. A sample particle image with flame and extracted flame front is shown in Figure 5. There is an ongoing discussion about the suitability of vaporized particles as a marker for the flame front. Vaporized particles are a consistent (from image to image) marker for the preheat zone, and as such suited for the current investigation where the velocity in the vicinity, but upstream, of the flame base is of interest (Pfadler et al. 2007; Kerl et al. 2013). In contrast, care has to be taken farther downstream along the flame front where inaccuracies may occur because evaporated particles do not re-form after evaporation (Heeger et al. 2010).
As an example, the flow field corresponding to the particle image in Figure 5 is shown in Figure 6. All subsequent data are presented in the same field of view. The center body is on the left, the mixing tube wall is on the right. The origin of the radial axis is shifted to the center body wall (nominally at 12.7 mm). Every second velocity vector is shown. Contours show the azimuthal velocity component. The red line marks the flame front obtained by mapping the pixel location shown in Figure 5 to physical space based on the calibration described previously. The thick white line is an isoline of 0 m/s axial velocity to indicate regions of flow with negative axial velocity. The two dashed white lines on each side are isolines of +/- 0.05 m/s to indicate the uncertainty in the location of the 0 m/s isoline based on the uncertainty in the velocity measurement as discussed above.

3. Results

3.1. CH₄-air flame flashback

Flashback of a CH₄-air flame is investigated at Reₚ = 4,400 (based on the streamwise centerline velocity and the width of the annulus between center body and outer tube) and equivalence ratio φ = 0.8. The laminar flame speed under these conditions is sₐ = 0.26 m/s (Boushaki et al. 2012). The adiabatic flame temperature for the CH₄-air flame at φ = 0.8 is about 2000 K. Flashback was triggered by first igniting a stable flame in the combustion tube, and then commanding the flow controller to create a step increase in the fuel mass flow rate. The rise time for the step change is about 100 milliseconds. The case discussed here, with φ = 0.8 being constant during the upstream flame propagation, corresponds to a fuel mass flow rate of about 10% above the threshold value at which flashback occurs in the investigated model swirl combustor. A total of ten flashback events have been recorded under these conditions.

Flashback of swirl-flames is a highly three-dimensional phenomenon in terms of both the flow direction as well as the flame propagation. When working with planar measurement techniques, it is crucial to have information about the global flame propagation direction in order to interpret the planar velocity field and flame front data correctly. The flame luminescence integrated over the time interval between the two laser pulses for the PIV measurement provides this information in the current investigation. Figure 7 shows the synchronized flame luminescence (top row) and velocity field (bottom row) at four instants in time of a flashback sequence. Note that the elapsed time is indicated on each image. The upstream propagating CH₄-air flame consists of one (sometimes a few), fairly large, distinct flame tongues swirling around the center body in the direction of the bulk flow while propagating upstream. In the following discussion the most upstream portion of such a flame tongue is referred to as the flame tip. The counter-clockwise flame
propagation is indicated with blue arrows. The mean flow direction is indicated with a red arrow. The azimuthal-velocity component is on the same order as the axial-velocity component. The center body wall is indicated with grey lines. The vertical edges of the luminescence images coincide with the mixing tube wall. The green vertical line indicates the location of the field-of-view for the PIV measurement, which is perpendicular to the field-of-view of the luminescence images, as indicated in Figure 2. Contours show the azimuthal velocity component. The red line marks the flame front, and the white line indicates the location of 0 m/s axial velocity (see Section 2.2).)

The image sequence in Figure 7 highlights the importance of the chemiluminescence imaging. The PIV measurement by itself would suggest that flashback is characterized by an initial flame propagation away from the wall (Fig. 7(b)) followed by flame propagation along the wall without a region of negative axial velocity upstream of the flame base (Fig. 7(c)) and finally upstream flame propagation with a region of negative axial velocity (Fig. 7(d)). In contrast, the flame luminescence reveals that the apparent upstream propagation is instead a swirling motion. In the first image, the flame is on the back side of the center body. In the second image, a portion of the flame far downstream of the flame tip is convected into the laser sheet in a swirling motion. This portion of the flame is carried downstream by the flow. Similarly, the portion of the flame shown in Fig. 7(c) is merely advected azimuthally. At the instant in time corresponding to Fig. 7(d), the most upstream tip of the flame is in the planar field-of-view of the PIV measurement. This flame tip propagates in the negative axial direction.

![Figure 7: Simultaneous chemiluminescence (top row) and PIV measurement (bottom row) for correct interpretation of planar velocity field and flame front data. Contour: Azimuthal velocity. Red line: flame front. White line: isoline of 0 m/s axial velocity.](image)

Regions of negative axial velocity upstream of the flame tip have first been reported by Heeger et al. investigating flashback of unconfined swirling methane flames (Heeger et al. 2010). Similar regions of negative axial velocity, termed reverse-flow pockets, have been observed upstream of convex curved (toward reactants) flame bulges in non-swirling turbulent boundary layer flashback events (Eichler et al. 2011; Gruber et al. 2013). It was pointed out in (Heeger et al. 2010) that about half of the recorded sequences did not show reverse-flow upstream of the flame front, which was attributed to a convection-type upstream propagation, while the other half showed reverse-flow pockets indicating upstream propagation of the leading edge inside the measurement plane. In the current study, upstream propagation of the leading portion of the flame tongue is always associated with a region of negative axial flow upstream. The luminosity reveals that all instances where the flame appears to propagate upstream without a negative axial flow region correspond to a portion of the flame farther downstream that is advected azimuthally (following the swirl motion) through the laser sheet.
The axial velocity field in the vicinity of the flame tip is investigated in more detail in Figure 8. Every second image of the recorded data set is shown. In comparison to Figure 7, the PIV field-of-view is limited to 15 mm in the axial direction, while the radial field-of-view is preserved. The corresponding luminescence illustrates that in the first three images (Fig. 8(a)-8(c)) the portion of the flame front immediately downstream of the flame tip on the leading side of the flame tongue is in the plane of the laser sheet. In Fig. 8(d), the flame tip is in the plane of the laser sheet, whereas in Fig. 8(e) the flame tip has propagated out of the laser sheet. Figure 8(a)-(b) show a flame tip about 1.5 mm away from the wall and the flame front exhibits curvature that is convex toward the reactants side in agreement with (Heeger et al. 2010). The streamlines diverge toward the wall as well as toward the core flow due to the convex flame front. Those streamlines that diverge toward the wall are bent around the flame tip leading to a region of negative axial velocity. The most upstream tip of this negative axial velocity region is upstream of the flame tip away from the wall. Keep in mind that there is an out-of-plane velocity component whose magnitude is of the same order, which will be addressed below. As the most upstream flame tip starts to swirl into the field-of-view (Fig. 8(c)), the character of the negative axial flow region begins to change. Streamlines away from the wall are now reversed in the negative axial direction along the wall due to the presence of the flame tip in contrast to previously being bent around the flame tip. The region of negative axial velocity now reaches far upstream with its most upstream point being closest to the wall as opposed to away from the wall seen before in Fig. 8(a)-(b). The flame swirls out of the field-of-view in Fig. 8(e), while a region of negative axial velocity closest to the wall persists for several more time steps. The trailing side of the upstream propagating flame tongue seen in Fig. 8(e) is associated with a flame front whose shape is straight and subsequently concave in shape in the r-z-plane as opposed to the convex shape discussed in Fig. 8(a)-(d). It is interesting to note that for flashback to occur it would be sufficient that the flame speed locally exceeds the axial component of the incoming flow vector, and reverse-flow is not needed. And yet, flame tongues are found to propagate upstream with the aid of such regions of negative axial velocity, as indicated in (Heeger et al. 2010) and confirmed in this work.

![Figure 8: Flame luminescence (top row) and axial velocity field with streamlines (bottom row) in the vicinity of the flame tip. Red line: flame front. White line: isoline of 0 m/s axial velocity.](image)

One observation supporting the important role of these regions of negative axial velocity in the flashback process is that an increase in bulk flow velocity at constant laminar flame speed leads to a decrease in the duration of flashback. For example, the time it takes the flame to flashback a distance of about 80 mm decreases non-linearly from about 130 ms at 1 m/s average bulk flow velocity to about 80 ms at 4 m/s average bulk flow velocity. If a local balance between flow velocity and flame speed was dominating the flame propagation, flashback duration would decrease for an increase in flow velocity at constant flame speed. Note that the increase in Reynolds number, as expected, increases the (turbulent) flame speed despite holding the laminar flame speed constant. For example, the measured turbulent flame speeds of methane-air flames at $\phi = 0.8$ indicate a turbulent flame speed that is nearly the same as the laminar flame speed at 1 m/s.
bulk flow velocity, and three times the laminar flame speed at 4 m/s bulk flow velocity (Kobayashi et al. 1996). Since the increase in the bulk flow velocity exceeds the increase in the flame speed, this would suggest a decrease in flashback duration; however, the fact that the flashback duration decreases at higher flow velocity agrees with the findings that the presence of the flame strongly affects the flow (Kurdyumov et al. 2007; Eichler et al. 2011; Gruber et al. 2013; Heeger et al. 2010).

The velocity field previously discussed in terms of streamlines can also be interpreted in terms of vorticity: The reverse-flow region in Fig. 8(a)-(c) is associated with positive out-of-plane vorticity in a small region immediately upstream of the flame tip and wall as seen in Fig. 9(a)-(c). This region of positive vorticity is coupled with the convex shape of the flame tip. In contrast, starting in Fig. 9(d) and even more so in Fig. 9(e), the region of negative axial velocity close to the wall is associated with a layer of strong negative out-of-plane vorticity reaching far upstream. This layer is indicated with a dashed, black line. In Fig. 9(e), the flame tip is in the plane of the laser sheet and it is seen that the presence of the flame is associated with a region of negative axial velocity; or equally, with a layer of strong negative vorticity close to, but not at the wall. The region of negative axial velocity reaches far upstream, not just in the axial direction, but in the streamwise direction, based on the subsequent frames of the movie sequence not shown here. The movies also show that starting far upstream, moving with the flow and approaching the flame tongue, the layer of high negative shear is then displaced radially outwards due to the presence of the flame (Fig. 9(d)). This gives rise to positive out-of-plane vorticity to form between the wall and the flame tip, which is coupled with a convex shape flame tip. Interpreting cause and effect in this sequence of events will require more work before conclusions can be drawn.

\[ \text{Figure 9: Vorticity field corresponding to velocity field and luminescence shown in Figure 8. The black dashed line highlights a layer of high negative shear that is coherently propagating with the flow based on the full movie sequence. Red line: flame front. White line: isoline of 0 m/s axial velocity.} \]

When studying flashback in swirling flows, a careful distinction between regions of negative velocity of individual velocity components and reverse-flow pockets is necessary. In this study, reverse-flow is considered a “complete” flow reversal in the opposite direction of the incoming streamlines. In case such reverse-flow pockets occur close to the wall (e.g. due to the presence of a flame), the flow is considered to be separated. In contrast, streamlines may just be deflected in the, say, negative axial direction, without being reversed in the streamwise direction. The image sequence shown in Figure 8 for instance revealed regions of negative axial velocity as discussed previously. Without the knowledge of the out-of-plane velocity component, it is unknown, however, whether these regions show separated flow or merely a deflection in the negative axial direction of the otherwise positive streamwise velocity vector.

Studies of flashback in the boundary layer of (non-swirling) channel flows revealed reverse-flow pockets that strongly correlate with upstream propagating convex flame bulges (Eichler et al. 2011; Gruber et al. 2013). In a previous study of flashback in swirling flows using two-component PIV, it was suggested that the flame propagates upstream if the boundary layer on the inner wall is separated or close to separation (Heeger et al. 2010). The current data suggest that boundary layer separation is not necessary for flashback to occur in swirling flows. With the out-of-plane velocity component known, the velocity vector in the streamwise direction can be computed based on the mean streamline angle of about 45° relative to the axial direction. Figure 10 shows a contour plot of the streamwise-velocity component corresponding to Fig. 8(a) and (e).
Despite the existence of a region of negative axial velocity upstream of the flame tip, the azimuthal velocity component is positive with a sufficiently high magnitude that the streamwise-velocity component direction is positive and the boundary layer is not separated.

\[ \text{Figure 10: Streamwise velocity fields at instants in time corresponding to Fig. 8(a) and (e) show no reverse upstream of flame tip. Red line: flame front.} \]

However, reverse-flow pockets (regions of negative streamwise velocity) are observed upstream of small-scale flame bulges forming on the trailing side of the main (large-scale) flame tongue. A flashback event where such a bulge forms immediately downstream of the PIV field-of-view, is shown in Figure 11. Note that this is a different flashback event compared to the previously discussed one. In Fig. 11(a) the main flame tongue swirls around center body in the positive azimuthal direction in the same way as seen in the flashback event discussed previously. In Fig. 11(b), however, a bulge aligned in the streamwise direction forms on the trailing side of the main flame tongue. The main flame tongue continues to swirl upstream in the positive azimuthal direction as indicated by the blue arrow, whereas the small-scale bulge is convected downstream as indicated with a yellow arrow. The flame bulge continues to separate from the main flame tongue in Fig. 11(c). The corresponding streamwise velocity field is shown in the bottom row. Fig. 11(a) shows the same behavior as seen in the flashback event discussed previously. Despite the presence of a region of negative axial velocity (not shown here), no reverse-flow exists. In contrast, Fig. 11(b) now reveals a small region of reverse-flow upstream of the convex shaped flame bulge, in agreement with studies of flashbacks in non-swirling channel flows (Eichler et al. 2011; Gruber et al. 2013). However, the flame bulge does not manage to propagate upstream, possibly because the reverse-flow pocket does not reach above the quenching distance, and instead is convected downstream. At the same time, the main flame tongue continues to swirl upstream and flashback persists, which suggests that flashback may occur in a swirling flow under conditions (flow field in the streamwise direction and flame properties) at which flashback would be prevented in a non-swirling channel flow.

\[ \text{Figure 11: Streamwise velocity field of a different flashback event compared to Figure 8 through Figure 10, where flow separation occurs upstream of a small-scale flame bulge. Red line: flame front. White line: isoline of} \]
3.2. Effect of H₂ addition on flashback

The effect of hydrogen on flashback is investigated by comparing the upstream flame propagation of a lean H₂/CH₄-air mixture to the previously discussed flashback of a pure methane flame. The approach taken in this study is to match the laminar flame speed of the H₂/CH₄-air flame to the laminar flame speed of CH₄-air flame. A H₂/CH₄-mixture of 95% H₂ and 5% CH₄ by volume was used, which has a laminar flame speed of 0.26 m/s at an equivalence ratio of about $\phi_{H₂/CH₄} = 0.4$ (Vagelopoulos et al. 1994; Bouvet et al. 2013). The adiabatic flame temperatures $T_{ad}$ are about 2000 K and 1400 K for the CH₄-air and the H₂/CH₄-air flames, respectively. The density ratios $\rho_u/\rho_b$ of the unburnt mixtures to the burnt mixtures based on the adiabatic flame temperatures are therefore 6.7 and 4.7, respectively. The CH₄-air flame has a Lewis number Le of about unity (Lafay et al. 2008), and the flame is diffusive-thermally stable (Bansal et al. 2012). In contrast, the Lewis number of the hydrogen-enriched case is much smaller than unity and is thermo-diffusively unstable (Law et al. 2000).

The flame surfaces of the CH₄-air and H₂/CH₄-air mixtures are compared in Figure 12 and show a fairly smooth surface for CH₄-air and a much more convoluted surface for H₂/CH₄-air. Since hydrodynamic instabilities are due to the density jump across the flame front, and this density ratio is higher for the CH₄-air flame investigated here, thermo-diffusive effects seem to be the cause for the observed flame wrinkling. The incoming flow field is unaltered for the two cases shown. The CH₄-air flame is characterized by a smooth flame surface, and the occurrence of only few, large flame tongues are consistently observed for various equivalence ratios and various flow rates up to $Re_b = 9,000$. In contrast, for hydrogen addition above about 70% by volume, the flame surface is consistently found to be more convoluted. The upstream propagating flame is similar to the CH₄-air flame in a sense that there are one to a few main (large-scale) flame tongues swirling around the center body. However, in contrast to the CH₄-air flame, small scale, convex shaped flame bulges form and break up constantly. These bulges, aligned in the streamwise direction, are smaller in size compared to the few bulges observed in CH₄-air flashbacks. Their shape and dynamic behavior appears to be very similar to what has been observed in turbulent boundary layer flashback of hydrogen flames in (non-swirling) channel flows (Eichler et al. 2011; Gruber et al. 2013). It is important to emphasize, however, that for high enough flow rates it is not these small-scale flame bulges propagating against the incoming flow in the streamwise direction that are leading the flashback. Instead, the flame tip of a large-scale (swirling) flame tongue again drives the flashback, similar to what is observed in the case of a CH₄-air flame.

![Figure 12: Comparison of fairly smooth flame surface of CH₄-air flame ($\phi = 0.8$) with convoluted flame surface of H₂/CH₄-air flame ($\phi = 0.4$) with 95% H₂ and 5% CH₄ by volume.](image)

The simultaneous flame luminescence and axial velocity field in the vicinity of the flame front is shown in Figure 13. Fig. 13(a) is an instant in time with a portion of the flame immediately downstream of the flame tip in the planar field-of-view of the PIV measurement. This situation corresponds to Fig. 8(a)-(b) in case of the CH₄-air flashback. The observed flow divergence and region of negative axial velocity is comparable to the CH₄-air flame. The similarity also holds for Fig. 13(b) showing the most upstream flame tip in the PIV field-of-view. As seen previously in Fig. 8(d)-(e), streamlines turn toward the wall and are reversed in the negative axial direction to form a region of negative axial velocity close to the wall. This level of agreement suggests that the underlying mechanism driving flashback is the same between the investigated CH₄-air and H₂/CH₄-air flame.

In contrast to the CH₄-air flashback, the flame surface during the H₂/CH₄-air flashback does not extend as far
into the core flow. This may be due to the lower temperature and 30% smaller density decrease across the flame front. Despite the lower density ratio, an estimate for the global flame propagation speed in a lab-frame-of-reference suggests that the H₂/CH₄-air flame propagates faster. This estimate is based on the time it takes the most upstream flame tip to travel an axial distance of 40 mm upstream. The mean global propagation speed over ten runs is 0.58 m/s for the CH₄-air flame, and 0.94 m/s for the H₂/CH₄-air flame. As described previously, the laminar flame speed is matched between the two mixtures, and the Reynolds number agrees to within 5% (the difference stems from the lower density of hydrogen compared to methane). The higher lab-frame-of-reference propagation speed of the H₂/CH₄-air flame may then be attributed to a higher turbulent flame speed due to thermo-diffusive effects in combination with positively stretched flame tips. Additionally, the H₂/CH₄-air flame can propagate closer to the wall due to a lower quenching distance which possibly also contributes to the higher global propagation speed.

![Figure 13: Flame luminescence and axial velocity field of H₂/CH₄-air flame flashback. Red line: flame front. White line: isoline of 0 m/s axial velocity.](image)

4. Conclusion

Boundary layer flashback of swirling flames was studied in a model swirl combustor at atmospheric pressure by investigating the upstream flame propagation inside the mixing tube along the center body wall. Challenges and uncertainties associated with stereoscopic PIV measurements inside quartz tubes close to the wall are discussed. High quality Mie scattering images were made possible by bringing in the laser sheet from the top, positioning the cameras in forward scattering mode with a line-of-sight parallel to the tangent at the wall where the laser sheet is located, and using a synthetic-silica tube with good optical homogeneity.

The flame propagation was first investigated for a CH₄-air flame at an equivalence ratio of $\phi = 0.8$. Flashback consists of one (in some instances a few) large-scale flame tongue propagating upstream in a swirling motion in the positive azimuthal direction. A region of negative axial velocity is always found in the vicinity of the leading flame tip of such a flame tongue, and apparent upstream propagation without negative axial flow regions is in fact corresponding to a portion of the flame farther downstream, which is simply advecting azimuthally (out of the plane of the laser sheet). The shape of the flame tip associated with upstream propagation is concave toward the reactants side, while the transition to a straight flame shape indicates the edge of the upstream propagating flame tongue. It is found that the regions of negative axial velocity in the vicinity of the flame tip in general do not correspond to separated flow. Separated flow is considered to be a region of reverse-flow in the streamwise direction as opposed to, say, a negative axial velocity component. Instead, separated flow is observed upstream of small-scale flame bulges occasionally
forming on the trailing side of the large-scale flame tongue. In the investigated swirling flow, however, these bulges are not leading the flashback; they are convected downstream. Instead, flashback is associated with large-scale flame tongues, which propagate upstream inside a region of negative axial velocity independently of the formation of small-scale flame bulges.

The effect of hydrogen addition on the flashback process is studied by investigating flashback of a H₂/CH₄-air flame with 95% H₂ and 5% CH₄ by volume. An equivalence ratio of φ = 0.4 is chosen in order to match the laminar flame speed to the previously investigated CH₄-air flame. It was found that upstream flame propagation is again associated with a region of negative axial velocity suggesting a similar mechanism compared to the CH₄-air flame case. In contrast, the flame surface of a H₂/CH₄-air flame during flashback is more convoluted due to the constant formation and break-up of small-scale flame bulges. These bulges are smaller in size compared to the occasionally forming bulges in the CH₄-air, and appear to be very similar to bulges observed in previous studies of hydrogen flashbacks in non-swirling channel flows. An increase in flame speed is observed, which is in agreement with the theory of thermo-diffusive effects on flame propagation.

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References