Flow-flame interaction in turbulent boundary layer flashback of swirl flames

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ABSTRACT

Boundary layer flashback of lean-premixed swirling flames is investigated by focusing on the upstream flame propagation inside the mixing tube of a model combustor. High-speed stereoscopic and tomographic PIV synchronized with chemiluminescence imaging is applied to study the flow-flame interaction. The region of negative axial velocity upstream of the leading flame tip observed in previous studies is found to not correspond to reverse flow or flow separation. Instead, streamlines are merely deflected by the blockage induced by the flame. The velocity field in the burnt gas is analyzed in order to shed light on the mechanisms that govern the flow-flame interaction.

INTRODUCTION

The successful design of future lean-premixed and fuel-flexible gas turbine combustors requires an improved fundamental understanding of flashback. Currently employed combustors designed to run on natural gas are challenged by the desire to use high-hydrogen content fuels. Combustors operated with such fuels are particularly susceptible to flashback owing to the fast kinetics, high diffusivity and low density of hydrogen.

Since research on flashback began with the first systematic study by Lewis and von Elbe (1943), the focus has been on measuring flashback limits in (non-swirling) Bunsen-flame type burners for many years. It was not until high-speed imaging and laser diagnostics as well as more sophisticated numerical tools were established that the upstream flame propagation during a flashback event became the focus of studies.

Three configurations of interest can be distinguished: Flashback in the boundary layer of a (non-swirling) pipe or channel flow (Eichler et al., 2011; Gruber et al., 2012), flashback in the core of a swirling flow (Fritz et al., 2004; Kröner et al., 2007; Konle et al., 2008) and boundary layer flashback in a swirling flow (Heeger et al., 2010).

These studies revealed that there is a strong coupling between propagating flame front and approach flow which is in contrast to the originally proposed and still widely used critical gradient concept by Lewis and von Elbe. This concept assumes an isothermal flame and hence no effect of the heat release on the flow field.

Channel flashback was found to be facilitated by small scale flame bulges shaped convex towards the reactants, which intermittently form inside low-momentum streaks of the turbulent boundary layer (Eichler et al., 2011; Gruber et al., 2012). These bulges cause local pockets of reverse flow reaching above the quenching distance (about 20 wall units high) and hence enable the entire flame brush to propagate upstream.

Flashback in a swirling core flow may occur in combustors featuring a mixing tube without center body. In such configurations, a mechanism termed combustion-induced vortex-breakdown has been found to facilitate the upstream flame propagation where the heat release continuously shifts a vortex-breakdown bubble upstream causing flashback (Kiesewetter et al., 2007). The breakdown bubble is identified based on a region of negative axial velocity. A similar region of negative axial velocity has been observed during flashback in a wall boundary layer in a swirl combustor configuration with a center body (Heeger et al., 2010).

A recent study suggests that for the latter configuration where flashback occurs in the boundary layer of a swirling flow, regions of negative axial velocity upstream of the leading flame tip previously identified as separated flow or flow recirculation are instead merely regions of deflected streamlines with a negative axial component (Ebi and Clemens, 2014). This conclusion was based on the out-of-plane velocity component (azimuthal velocity), which was measured for the first time during a flashback event.

The first part of this paper presents more recent results concerning the kinematics of the upstream flame propagation confirming previous results by means of high-speed tomographic PIV. The second part of the paper then aims at providing some insights into the driving forces facilitating flashback in the boundary layer of swirl flows based on the flow field measurements not just upstream of the flame but also inside the burnt gas.

EXPERIMENTAL SETUP AND DIAGNOSTICS

Experiments are conducted with the model swirl combustor shown in Fig. 1. The combustor features a fused silica mixing tube and combustion tube to provide optical access for diagnostics. Swirl is generated with a single axial swirler consisting of eight curved vanes. Fully premixed mixtures of methane, hydrogen and air are investigated in this work. Flashback is triggered by starting with a stable flame in the combustion tube followed by a stepwise increase in equivalence ratio. The flashback duration, corresponding to the time it takes the flame to travel from the combustion tube to the swirler, is on the order of a few hundred milliseconds and hence requiring diagnostics with high temporal resolution.

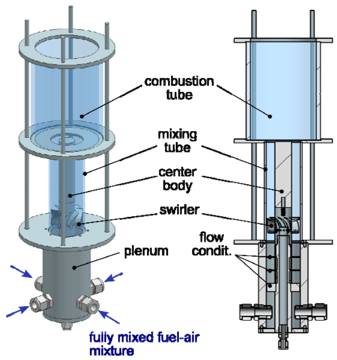

Figure 1. Model swirl combustor.

High-speed stereoscopic PIV is applied to study the flow-flame interaction inside the mixing tube. The laser sheet enters the mixing tube from the top and is positioned in a radial-axial slice (Fig 2). The field of view is about 30 x 11 mm². The top edge is at -45 mm meaning 45 mm upstream of the mixing tube exit. No velocity data is obtained in the outermost 2 mm due to severe distortion. Solid seeding particles (AlO_3) are used to obtain the velocity both in the unburnt and burnt region. The velocity field is measured at 4 kHz. The particle images are processed with a final interrogation window size of 0.85 x 0.85 mm² (~ spatial resolution) and a vector spacing of 0.21 mm. The uncertainty in the planar velocity measurement is computed based on the correlation statistics approach (Wieneke, 2014). For the higher Re-number case, the mean of the instantaneous uncertainties in the radial and axial component is 0.22 m/s with a standard deviation of 0.04 m/s. The out-of-plane (azimuthal) velocity component has an uncertainty of 0.45 m/s with a standard deviation of 0.08 m/s. These values correspond to about 3% uncertainty in the core-flow of the in-plane components and about 5% for the azimuthal component. The uncertainties are comparable in the lower Re-number case.

The drop in particle density is taken as an approximate marker for the preheat zone of the flame and subsequently referred to as the flame front. The precision in determining the flame front is about 0.25 mm, which is estimated based on the availability of four independent solutions at each time step (two cameras with two particle image frames each). The flame front is filtered to remove artificial small scale wrinkling due to individual particle images.

High-speed tomographic PIV is applied to study the three-dimensional flow field upstream of the flame front inside the mixing tube as the flame propagates upstream. A thick, retro-reflected laser sheet illuminates the seeded oil droplets for that purpose. The measurement domain is about 25 x 25 x 5 mm³ with the back-side of the domain being offset from the wall by about 0.8 mm as shown in Fig. 2 in order to prevent severe reflections off the center body. The velocity field is measured at 5 kHz. The final interrogation volume size is 1.44 x 1.44 x 1.44 mm³ with a vector spacing of 0.36 mm. The uncertainty of about 5% to 10 % is estimated from the divergence of the velocity field in the non-reacting flow following the approach by Elsinga et al. (2012).

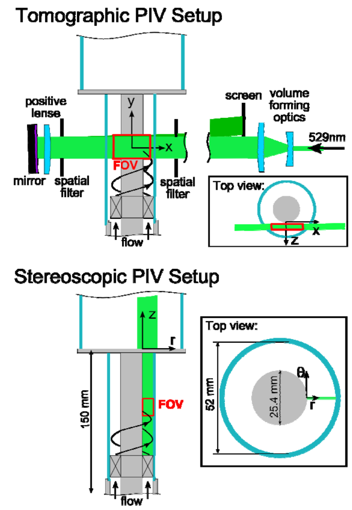

Figure 2. Diagnostic setups and fields of view for volumetric (top) and planar (bottom) PIV measurements.

The sharp interface in the Mie scattering images between oil droplets (cold reactants) and no droplets (hot products) due to vaporization of the oil in the preheat zone of the flame is frequently employed as an approximate marker for the flame front. This approach is now extended to allow the determination of the three-dimensional flame front. The strong temporal coherence in the propagation of the flame front as well as the good qualitative agreement with simultaneously recorded flame chemiluminescence (Fig. 5) are sufficient validation for any conclusion drawn in this work. A quantitative validation for the flame-front extraction approach is on-going.

The flame luminescence is synchronously recorded with each PIV technique using a high-speed intensified camera. These line-of-sight images of the flame are particularly important in conjunction with stereo-PIV in order to unambiguously interpret the planar velocity field and its location relative to a flame tongue.

RESULTS

Non-reacting Swirl Flow in Annular Mixing Tube

Flashback experiments presented in this work are conducted at atmospheric pressure and Reynolds numbers of Re_h = 4,000 and 8,000, respectively, based on the streamwise centerline velocity in the mixing tube and the hydraulic diameter. The non-reacting radial velocity profiles for each Reynolds number are shown in Fig. 3. The left axis corresponds to the location of the center body wall, the right axis to the location of the mixing tube wall. As described previously, valid velocity data was only obtained up to about r = 11 mm. The swirl flow generated in this particular model combustor is characterized by axial velocities (black lines) that increase

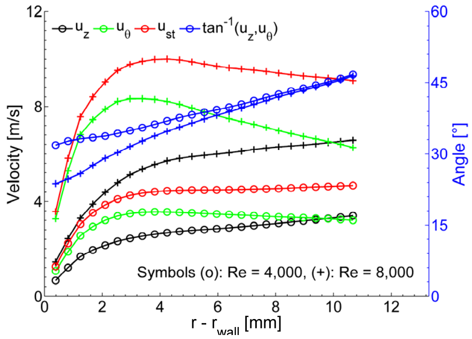

Figure 3. Mean non-reacting radial velocity profiles 50 mm upstream of mixing tube axis. Circels denote Re = 4,000 and pluses denote Re = 8,000 case. Shown in blue is the angle between the streamwise direction and the r-θ-plane.

towards the mixing tube wall before falling off in the outer boundary layer (not seen here). The azimuthal velocity (green) peaks at about r = 3 mm with the peak value and subsequent fall off being more prominent for the higher Re case. This is seen when plotting the out-of-plane velocity angle (angle between streamwise velocity vector and horizontal plane) shown in blue. The out-of-plane angle is lower close to the center body wall and continuously increases towards the mixing tube wall. Hence, the azimuthal momentum relative to the axial momentum decreases with increasing radial distance. This effect is stronger in the higher velocity case where the out-of-plane angle is about 25° at the inner wall and about 50° at the outer wall.

Kinematics of Upstream Flame Propagation

Two modes of flame propagation are observed in swirl flame boundary layer flashback. Under the investigated flow conditions and for both lean methane-air and lean hydrogen-methane-air flames (95% H_2, 5% CH_4 by vol.), flashback occurs in the form of 1 to 2 large scale flame tongues leading the flashback and swirling around the center body while propagating upstream as shown in Fig. 4. Additional large flame tongues may temporarily form on either side of the leading flame tongue as seen in Fig. 5. However, only one flame tongue prevails while others are washed downstream by the bulk flow such that the overall flame front preserves its asymmetry in the azimuthal direction during upstream propagation.

The second mode concerns small scale flame bulges observed along the approach flow side of the large scale flame tongues as highlighted in Fig. 4. The bulges are aligned with the streamwise direction of the mean swirling flow and convex towards the reactants side. The formation of such small bulges is frequently observed in hydrogen flames and rarely in methane flames which may be attributed to thermo-diffusive effects. The bulges intermittently form and counterpropagate into the approach flow, and thus may resist the bulk flow for short periods of time (~ 1 ms). The appearance and scale of

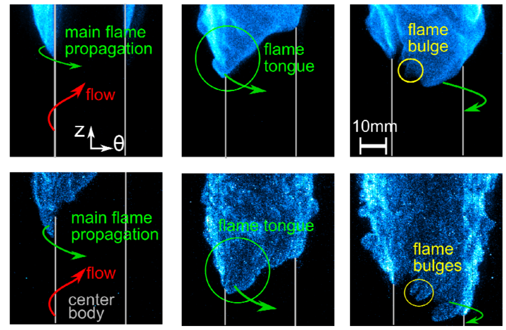

Figure 4. Chemiluminescence images taken from a movie sequence showing the flame inside the mixing tube during a methane-air (top row) and hydrogen-methane-air flashback (bottom row) at three instants in time .

these bulges agree with observations in previous studies which investigated flashback in turbulent boundary layers without curvature and radial pressure gradient (quasi-2D channel flows without swirl) (Eichler et al., 2011; Gruber et al., 2012). However, sustained upstream flame propagation in the mean negative streamwise direction in the form of these bulges has not been observed in the current study. These findings suggest that the mechanism facilitating flashback in a channel flow does not govern, but may contribute to, flashback in a swirling boundary layer in the form of a perturbation to the large scale flame tongues.

3D-Flow Field Upstream of Flame Front

High-speed tomographic PIV has been employed to measure the time-resolved volumetric velocity field inside the mixing tube during a flashback event. Figure 4 shows one instant in time of a methane-air flashback. The approximate location of the flame-front inferred from the reconstructed particle field is found to qualitatively agree well with the chemiluminescence images. Note that the luminescence imaging is a line-of-sight technique whereas the measurement volume for the tomographic PIV has a finite depth which is offset from the center body as shown in the top view schematic. The center part of the reconstructed flame front shown in Fig. 5 appears to miss the sharp tip of the center flame tongue, whereas in fact it is merely behind the measurement domain.

As summarized in the introduction, questions remain about the orientation of streamlines in the vicinity of the leading flame tongue and the three-dimensionality of the flow-flame interaction. The time instant shown in Fig. 5 is chosen to highlight a case where (based on the full movie sequence) a flame tongue is convected downstream by the flow as indicated by the green arrow. No region of negative axial velocity exists upstream of this flame tongue. If this case was imaged with a planar technique in a sheet in the radial-axial plane, the flame tongue would appear to propagate upstream as it swirls into the field of view suggesting upstream flame propagation without negative axial velocity. Instead, upstream flame

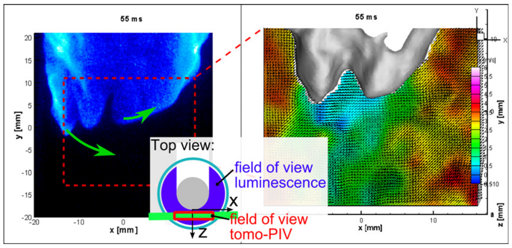

Figure 5. Simultaneous high-speed tomographic PIV (right, axial velocity field) with 3D-flame surface (grey) and chemiluminescence imaging (left) showing a methane-air flame flashback. Note the different depths in the field of view.

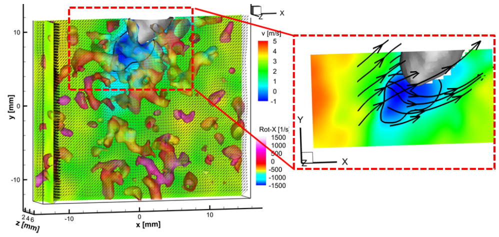

Figure 6. Flow field upstream of the flame front (grey surface) during a methane-air flashback. Flooded contour shows axial velocity. Black solid line marks 0 m/s axial velocity. Vortical structures are visualized by an iso-surface of λ_2 and colored by the x-component of vorticity. Black solid lines with arrows in zoomed view are streamlines.

propagation has been found to always be associated with a region of negative axial velocity upstream of the flame tip.

The axial velocity field in Fig. 7 shows the region of negative axial velocity in a radial-axial slice similar to how it has been observed in previous studies. This region has been identified as boundary layer separation or reverse flow pulling the flame tongue upstream (Heeger et al., 2010). The high-speed tomographic PIV measurements reveal quite the opposite as shown in Fig. 6. At this instant in time the leading flame tip truly propagates upstream as opposed to Fig. 5 and a region of negative axial velocity exists highlighted by the solid black line corresponding to an isoline of 0 m/s. Streamlines plotted in the zoomed view clearly reveal the deflection of streamlines as opposed to reverse flow or boundary layer separation hence confirming our recent findings based on three-component PIV in a plane.

In a swirling flow, the flame does not need to cause reversal of the approach flow in order to create a region of sufficiently small momentum to propagate upstream. In the swirling flow, a rather small deflection of streamlines is sufficient to produce even negative axial velocity. An increase in swirl leads to a decrease in deflection necessary for flashback to occur. In a channel flow the flame is restricted by geometry to flashback against the entire approach flow, but in the current swirling flow, the flame instead swirls with the bulk flow, but is able to propagate upstream by deflecting the streamlines ahead of itself. The question to answer then in order to understand the mechanism is how the flame exerts this force on the approach flow.

Flow-Flame interaction

The flow-flame interaction is investigated in more detail based on methane-air flashback events at $Re_h = 4{,}000$ ($\phi = 0.8$) and $Re_h = 8{,}000$ ($\phi = 1.0$), respectively. The three velocity components as well as the out-of-plane streamline angle and the in-plane dilatation are shown in Fig. 7 in a radial-axial slice. The lower and higher Re case are shown in the top and bottom row, respectively. The flame tip just swirled into the laser sheet in both cases. For the Re = 8,000 case this can be seen in Fig. 8 where the corresponding chemiluminescence image (time step 2) displays the flame in relation to the laser sheet. The black line in Fig. 7 marks the flame front. Comparing the top to the bottom row, the radial flame spread decreases with increasing bulk flow velocity. The wrinkling of the flame front increases with turbulence intensity as expected.

The region of negative axial velocity marked by the white solid line in Fig. 7 has been discussed before. The size of this region is variable but may reach upstream as much as 10 mm or more. The flow accelerates downstream of the flame front due to the drop in density. This acceleration is seen predominantly in the lower Re case. In the higher Re case, axial flow velocities in the burnt gases are similar in magnitude to those in the unburnt gases. However, farther downstream, the axial velocities do surpass those in the unburnt gases, which implies the acceleration is delayed at the higher Re. Regions of negative radial velocity are found to line up with the location of the flame front suggesting that the burnt gas is deflected towards smaller radii as it swirls out of the laser sheet.

When interpreting these images, it is important to keep in mind that the flow is swirling into and out of the plane with an angle shown in the fourth image pair. An angle of zero indicates pure swirling motion corresponding to zero axial velocity and an angle of 90° resembles purely axial flow. When analyzing the velocity field a fluid element cannot hypothetically be tracked, e.g. across the flame front, unless the angle is about 90° since otherwise the primary motion is out-of-plane. The green region corresponds to an angle of about 45° – 50°, which is the streamline angle in the non-reacting core flow. The yellow region in the burnt gas corresponds to 60° and above suggesting that the burnt gas is turned and accelerated in the axial direction in this region.

The gas expansion leads to a non-zero dilatation across a premixed flame. With planar PIV, only the in-plane gradients are available. Nonetheless, a significant level of non-zero in-plane dilatation is found, which lines up well with the flame front based on the drop in particle density as shown in the fifth image pair in Fig. 7.

In order to gain some insight into the coupling between the heat release in the flame and the velocity field it is instructive to examine the interaction over time. Figure 8 plots the relative axial and azimuthal velocity

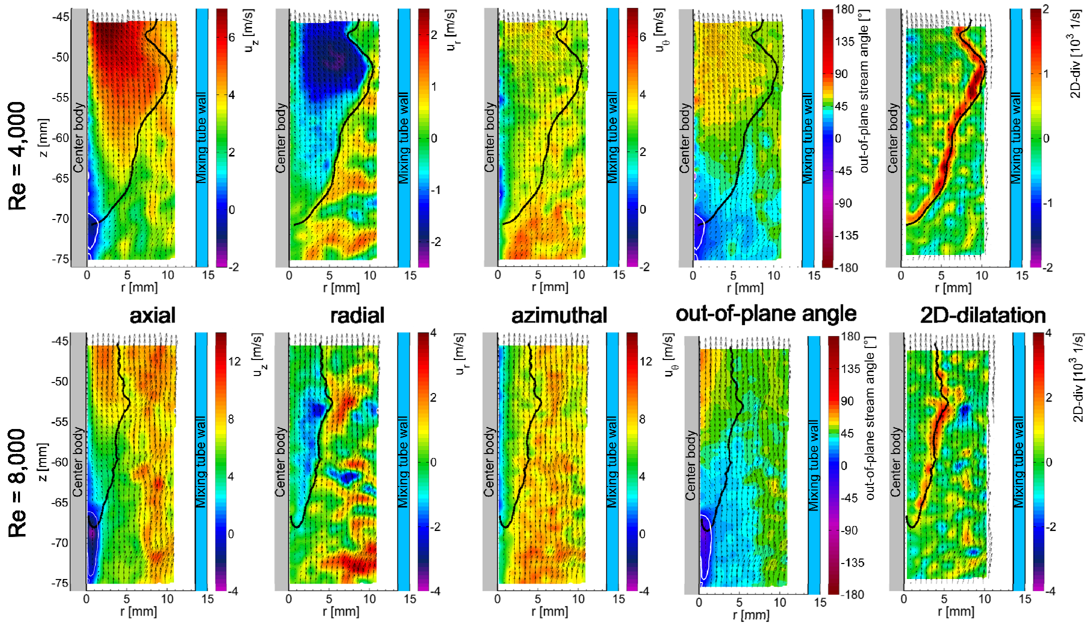

Figure 7. Radial-axial slices showing all three velocity components, the out-of-plane angle (angle between the streamwise direction and the horizontal plane) and the in-plane diliation. Top row: Re_h = 4,000. Bottom row: Re_h = 8,000. Black line: Flame front. Every third velocity vector is plotted.

(mean velocities subtracted) at two locations in the flow over time for the Re_h = 8,000 case. The first point located close to the center body wall at r = 1.7 mm is typically within the burnt gases as the flame swirls through the laser sheet whereas the point at r = 9.8 mm is outside the flame at all times in this case. The position of the flame tongue in relation to the axial position of the measurement point is shown in form of three chemiluminescence images. The red lines mark the corresponding time step in the plots.

At time instant 1 the flame tongue swirls above the laser sheet and yet the presence of the flame is already felt at the measurement location close to the wall in the form of a dip in axial velocity (top graph). Considering that a force can only be exerted on the flow through either viscous or pressure forces, the velocity trace suggests that the change in axial momentum in the form of a decrease in velocity can be associated with a pressure force originating from the heat release in the flame.

As the flame then swirls into the field of view, the velocity drops (region of negative axial velocity) and then rapidly increases due to the drop in density. At time instant 2 the point close to the wall is inside the flame. The flow velocity is high at this point as seen before in the Fig. 7. This pattern is observed every time the flame swirls into and out of the laser sheet. At the same time, the axial velocity trace at the location outside the flame (green dashed line) shows a steady increase as the flame swirls upstream. Thus no back-pressurization of the entire incoming bulk flow occurs but instead the flow outside the flame in the unburnt region accelerates as well to account for the volume creation due to the heat release.

Turning to the azimuthal velocity now (bottom graph), a rather counter-intuitive behavior is observed. The azimuthal momentum in the flow is conserved under the assumption of zero azimuthal pressure gradient. One might then expect a significant increase in azimuthal velocity across the flame front and in the burnt gas to account for the drop in density to preserve momentum. However, quite the opposite occurs in form of a dip in azimuthal velocity. To confirm this behavior the PDF of relative azimuthal velocity conditioned on the unburnt and burnt gas, respectively, is shown in Fig. 9. The hot products are associated with a lower azimuthal velocity than the cold reactants. It appears a rather strong increase in pressure in the azimuthal direction over a fairly large region exists in the burnt region (not just limited to the flame tip), which causes a change in the azimuthal momentum (the momentum must decrease because the azimuthal velocity and density decrease). Any pressure rise acts in all directions, including the upstream direction. It appears that the flame, through a sufficiently high heat release, overcomes the momentum of the approach flow to achieve the rather small streamline deflection sufficient to enable flashback.

CONCLUSION

Boundary layer flashback in swirl flows of lean methane-air and hydrogen-methane-air flames is studied at moderate Reynolds numbers. The upstream flame propagation inside the mixing tube is investigated experimentally by means of high-speed planar and volumetric PIV as well as simultaneous chemiluminescence imaging.

Flashback occurs in form of rather large scale flame tongues swirling upstream. The region of negative axial velocity upstream of the leading flame tip is found to not correspond to reverse flow or flow separation. Instead, the

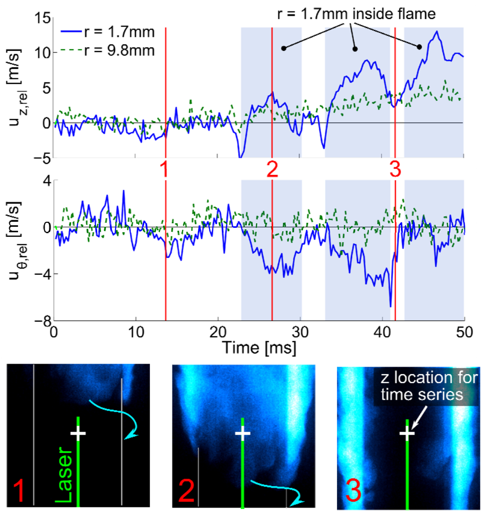

Figure 8. Relative axial (top) and azimuthal (bottom) velocity traces over time at axial location z = -49.2 mm and two radial locations r = 1.7 mm (close to center body wall) and r = 9.8 mm (core flow). Chemiluminescence images show flame at time instants 1, 2 and 3. Re_h = 8,000.

flame merely deflects the streamlines around its tip and hence provides itself with a region of negative axial momentum which "carries" it upstream.

Measurements of the velocity field in the burnt gas show acceleration in the axial velocity and a drop in azimuthal velocity. Considering the drop in density across the flame front, it may be concluded that a rather strong pressure force has to act on the azimuthal flow. In turn, any pressure rise in the burnt region exerts a force in all directions, which may lead to the observed deflection of streamlines in the negative axial direction to facilitate flashback.

These findings suggest that the mechanism governing flashback in the boundary layer of a swirling flow differs from flashback in the core of a swirling flow where the upstream flame propagation has been found to be associated with vortex-breakdown and an upstream propagating recirculation bubble. It also differs from flashback in the boundary layer of a channel flow in terms of scale as a result of differences in geometric constraints. In a channel flashback, small scale bulges cause reverse flow inside the low momentum streaks of the boundary layer. Hence, flashback is facilitated by the flow-flame interaction on a scale which is an order-of-magnitude smaller than what has been observed in this work.

For the cases investigated here, the presented data suggest that the flow-flame interaction facilitating flashback occurs on a scale on the order of the annular gap width. The blockage effect that the flame has on the approach flow appears to be a result of the momentum exchange over a rather large region inside the burnt gas. The approach flow "feels" the presence of the upstream propagating flame at a distance upstream comparable to the order of the annular gap width.

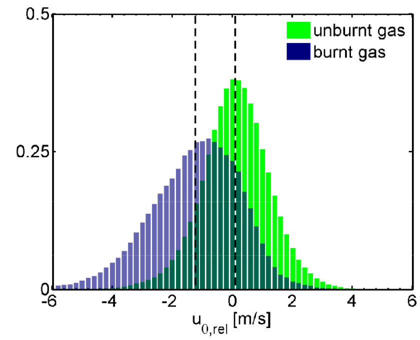

Figure 9. PDF of relative azimuthal velocity conditioned on regions inside the cold reactants (green) and hot products (blue), respectively. Re_h = 8,000.

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