Experimental investigation of a trapped vortex combustor featuring a 180°U-bend

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Abstract

Keywords: Hydrogen combustion, FlameSheet^{TM} technology, Turbulent premixed flames, Flame flashback

1. Introduction

2. Experimental setup

2.1. Combustor and flame conditions

Experiments were conducted at atmospheric pressure and room temperature on the trapped vortex combustor, with the relevant dimensions and nomenclature used in the present study shown in Figure 1. All parts of the combustor consist of ceramic glass, except for the U-bend which consists of a single piece of quartz glass. The burner has a main-flow and a co-flow inlet corresponding to the main reactants flow and the air co-flow. Both inlets have a height $h_1 = h_3 = 10\,\text{mm}$ and a span-wise width of 300 mm. Downstream of the U-bend, the flow confinement height is $h_2 = 30\,\text{mm}$. The burner features an inner liner with a blunt-shaped tip. Figure 1 also features dashed colored lines, which represent the locations where velocity statistics were extracted from the PIV data. All profile lines start at the inner liner (tip), with the the blue and orange profile lines oriented at 60°and 30°to the positive y-axis, respectively.

The hydrogen and air are premixed 2 m upstream of the liner tip to ensure that a fully premixed, homogeneous H_2-air mixture reaches the flame-stabilization location. In order to control the main flow (hydrogen and air) and co-flow (air only) three mass flow controllers (MFCs) are employed. The MFCs are controlled using a LabView control panel in which three parameters are specified, i.e. the Reynolds number (Re), the equivalence ratio (ϕ) and the volume percentage of hydrogen in the fuel (H_2%). The Reynolds number is based on the hydraulic diameter of the channel D_H and the bulk velocity in the main inlet (U_b). The bulk velocity is estimated using the volumetric flow rates from the MFC readings, which are corrected

Figure 1: Cross-sectional view of the FlameSheet^{TM} burner. The dimensions are in mm. The colored dashed lines represent the locations where velocity statistics from PIV data were extracted. All profile lines start at the inner liner (tip), with the the blue and orange profile lines oriented at 60°and 30°to the positive y-axis, respectively.

for standard pressure and standard temperature, and the cross-sectional area of the main inlet channel. The longitudinal extent of both inlet channels, main flow and co-flow, is 1 m in order to achieve a fully-developed turbulent flow.

Experiments were conducted for a lean H_2-air mixture at an equivalence ratio $\phi = 0.05$ for two Reynolds numbers $Re = 9677$ and $Re = 13\,548$. The co-flow is designed to match the Reynolds number of the main flow. If the Reynolds numbers were calculated using the inlet height h_1 instead of the hydraulic diameter D_H, the values would be $Re = 5000$ and $Re = 7000$, respectively. A preliminary flashback experiment was conducted to find the flashback limit of the investigated mixture. Flashback was subsequently induced by decreasing the Reynolds number (bulk velocity) incrementally, while keeping the mixture properties constant. From a total of 18 flashback experiments, the Reynolds number values at flashback Re were found to range from 8516 to 9483. The average Reynolds number at flashback was determined to be $Re_{fb} = 8978$. Consequently, the considered Reynolds numbers $Re = 9677$ and $Re = 13\,548$, are 7.8% and 51% above the average flash-

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Case	Re	U_b $[\mathrm{m\,s^{-1}}]$	ϕ	$H_2\%$	Condition
NR-1	9677	7.44	-	0	-
NR-2	13548	10.33	-	0	-
R-1	9677	8.57	0.35	100	near-flashback
R-2	13548	11.88	0.35	100	stable

Table 1: Specifications of the cases considered in this study.

back limit, respectively. The former is referred to as a near-flashback condition, whereas the latter represents a stable flame condition. More details of the cases considered in this study are given in Table 1.

2.2. Diagnostic setup

Particle Image Velocimetry (PIV) was used to obtain quantitative and qualitative data on the velocity fields. The air flow of the main inlet is seeded with aluminum-oxide particles (Al_2O_3) with a mean diameter of 1 µm. Particles of this size are sufficiently small so that they accurately follow the flow. A Nd:YLF dual-cavity laser (Quantronix Darwin-Duo Pro527-80-M) emitting a beam of green light (at 527 nm wavelength) was used to illuminate the particles. The laser beam is transformed into a laser sheet with a waist of approximately 1 mm using a system of plano-concave and convex lenses. The illuminated particles were imaged on the 12-bit CMOS sensor of a Photron Fastcam SA1.1 high-speed camera fitted with a Tokina 100 mm lens. The CMOS sensor, which has a resolution of 1024 × 1024 pixels each with a size of 20 µm × 20 µm, was cropped to 640 × 1024 pixels resulting in a field of view of 56 × 88 mm. The investigated flame was imaged using high-speed PIV recordings. The high-speed recordings were taken to obtain time-averaged statistics of the reacting flow field and to capture flame-flow interaction. For the recordings the frame rate was set to 4.5 kHz and a total of 5000 image pairs were collected. High-speed recordings were utilized, which provide statistical data comparable to low-speed recordings. The advantage of high-speed recordings lies in the flame front detection, due to the shorter measurement duration. This short duration minimizes the buildup of seeding particles on the glass walls, resulting in improved flame front detection.

A LaVision programmable timing unit was used to synchronize the laser pulses and the high-speed camera. The time interval, Δt, separating two consecutive pulses of the laser, is set to 40 µs in order to obtain an average particle displacement of around 8-15 pixels between two subsequent images within an image pair. Both the acquisition and processing of the PIV images are done with Davis 10.2 (LaVision). A multi-pass cross-correlation approach, one pass with an interrogation window of 64 × 64 pixels and three passes with an interrogation window of 32 × 32 pixels, was used. All interrogation windows have an overlap of 50%. Post-processing of the velocity vectors is done by means of a median filter with universal outlier detection to remove spurious vectors.

Figure 2: Top: The time-averaged (averaged over 300 images, imaged at 60 Hz) image of the flame ($\phi = 0.4$, $H_2\%$=80, $Re = 11613$) using a Nikon D5600 consumer camera. Bottom: three potential flame configurations.

2.3. Flame configuration

Figure 2 illustrates the flame configuration within the combustor. To address the challenge of visualizing a pure premixed hydrogen flame, a flame with $\phi = 0.4$, $H_2\%$=80 and $Re = 11613$ was used. The flame considered in this study has a similar flame location to that shown in Figure 2. Additionally, the figure highlights three potential flame configurations: flashback, actual and desired. In this study, the flame was positioned along the blue line, which represents the actual flame location, while the black line indicates the desired location of the flame front. This topic will be addressed in more detail later in the study.

3. Methodology

3.1. Favre-averaged quantities from PIV data

In standard PIV the mean of a velocity component u in a particular interrogation area is determined from the arithmetic mean of all instantaneous velocities $u(t_i) = u_i$ for that interrogation area as in

$$\overline{u} = \frac{1}{N}\sum_{i=1}^{N} u_i, \tag{1}$$

where N is the total number of instantaneous images in a PIV measurement. This results in a Reynolds-averaged velocity component. However, in combustion studies one is often interested in Favre-averaged (density-weighted)

quantities. In that case each instantaneous velocity u_i has to be weighted with the instantaneous gas density $\rho(t_i) = \rho_i$ as in

$$\widetilde{u} = \sum_{i=1}^{N} u_i \rho_i \Big/ \sum_{i=1}^{N} \rho_i. \tag{2}$$

Clearly, determining a Favre-averaged velocity component in a particular interrogation area requires information on both the instantaneous velocity and the instantaneous gas density in that interrogation area. The latter is not directly available from PIV, but there are procedures to estimate the instantaneous density from the PIV measurements. One procedure relies on an accurate determination of the flame front in each instantaneous PIV image, resulting in a bimodal density distribution, i.e. a clear distinction between the unburnt (reactants) and burnt (products) regions [1?]. However, due to the recirculation of hot products into the fresh reactants, this bimodal assumption may be violated, making it difficult to clearly distinguish the unburnt and burnt regions. Therefore, in this study another procedure is used, where it is assumed that the instantaneous number of seeding particles $n(t_i) = n_i$ in an interrogation area is (on average) proportional to the gas density ρ_i when the seeding particles do not burn or evaporate in the flame. In a further simplification it is assumed that n_i is proportional to the sum of the pixel intensities in an interrogation area $I(t_i) = I_i$. Thus, a Favre-averaged velocity component can be determined from Eq. (2) by replacing ρ_i with I_i.

3.2. Flame front detection method

The histogram-based method described in Altenburg et al. [] is used to determine the instantaneous flame front in an instantaneous PIV image. In this method a flame front in an instantaneous PIV image was identified from the change of the local particle number density using a bilateral filter, i.e. utilizing both spatial and intensity information, of a raw Mie-scattering image. Due to the unavoidable presence of reflections, a preliminary step is conducted to improve the accuracy of the flame front detection. This pre-processing involves subtracting the minimum intensity observed over a time interval of 99 images, symmetrically centered around the reference image. Figure 3 shows the outcome of the flame front detected method to one of the premixed flames considered in this study. The parameter controlling the size of the bilateral filter was set such that it corresponds to the number of pixels covering a physical distance of 4 mm. By setting the size of the bilateral filter to this specific value, the larger structures of the flame front were captured. Setting the size too low results in the capture of small, artificial flame front details, while setting it too high leads to over-smoothing, and consequently to the loss of the larger flame structures.

The average flame front was determined by applying the for-mentioned method to the averaged image obtained from pre-processed images. In this case, the parameter

Figure 3: A pre-processed instantaneous image, i.e. subtracting the minimum intensity observed over a moving time interval with a width of 99 images, symmetrically centered around the reference raw Mie-scattering image. The red-dotted line indicates the detected flame front.

controlling the size of the bilateral filter was set such that it corresponds to the number of pixels covering a physical distance of 2 mm. Notice that the averaged picture is a smooth picture, so that $c_{\overline{\Omega}}$ (the average location of the flame front) is more accurately detected when the size of the bilateral filter is small.

4. Results

4.1. Non-reacting flow field

Figure 4a shows the Reynolds-averaged velocity vectors for the non-reacting flow with a Reynolds number $Re = 13\,548$ (case NR-2). The background color represents the dimensionless velocity magnitude $|\overline{V}|/U_b$. The flow field has a vortex adjacent to the inner liner and a region of low velocity near the U-bend wall. High velocities are observed near the wall at the U-bend extension. Figure 4b shows the dimensionless velocity profiles of the velocity component perpendicular (V_n) to the (colored) profile lines highlighted in Figure 1. The profile lines are given by $d(x, y)$ and are normalized with L, which is its corresponding length. These lines span from the inner liner (tip), where $d/L = 0$, to the U-bend (extension) wall, where $d/L = 1$.

To verify the inlet bulk velocity, the velocity profiles were integrated from d_0, the coordinate starting at the inner liner (tip), to d_1, the coordinate at the U-bend (extension) wall. These integrated profiles were then divided by the inlet height h_1 to obtain a bulk velocity from PIV data $U_{b,PIV}$. The calculated values for $U_{b,PIV}$ were compared to the bulk velocity U_b measured by the mass flow controllers, with an average deviation of approximately 9%.

The velocity profiles indicate non-zero velocities at the wall, which could be attributed to limitations of the PIV to measure velocities close to the walls, due to reflections and the finite size of the interrogation windows. Furthermore, the red, purple, brown and pink line display steep velocity gradients near the wall in the U-bend extension. The figure

(a) (b)

Figure 4: a) The Favre-averaged velocity vectors for the non-reacting flow with Reynolds number $Re = 13\,548$. The background colour corresponds to the dimensionless velocity magnitude $|\widetilde{V}|/U_b$. b) The extracted dimensionless velocity profiles of the velocity component perpendicular (V_n) to the profile lines highlighted in Figure 4a.

(a) (b)

Figure 5: a) The dimensionless Favre-averaged turbulent kinetic energy field $\widetilde{k}/U_b^2$ for the non-reacting flow with Reynolds number $Re = 13\,548$. b) The extracted profiles of $\widetilde{k}/U_b^2$ along the profile lines highlighted in Figure 5a.

also shows a long recirculation zone, which extends beyond the field of view, indicating that the observed scope does not capture the entire extent of the recirculation zone.

Figure 5a shows the dimensionless Favre-averaged turbulent kinetic energy field $\widetilde{k}/U_b^2$, where $\widetilde{k} = \frac{1}{2}(\widetilde{u_x''^2} + \widetilde{u_y''^2})$, for the non-reacting flow with $Re = 13\,548$. The figure reveals a region with increased turbulent kinetic energy at the boundary of the recirculation zone, which could be attributed to the vortex shedding occurring in the strong shear layer. Another interesting observation is the region with high $\widetilde{k}/U_b^2$ close the the wall in the U-bend. This can be observed in more detail in Figure 5b, where the profiles of $\widetilde{k}$ in the U-bend (blue, orange and green line) show an increase when approaching the U-bend wall ($d/L \gtrapprox 0.7$).

The case NR-1 ($Re = 9677$) was excluded from the study, as the velocity statistics were similar to the highlighted case NR-2.

4.2. Reacting flow field

4.2.1. The average flame front location

Figure 6 illustrates the average location of the flame front, as determined by the method outlined in Section 3, for both Reynolds numbers. To examine the influence of the incoming flow on the flame front, profiles were selected 1.5 mm ahead of (but parallel to) the average flame front location. The distance corresponds to the grid spacing of the velocity vectors and was selected to be as close to the average flame front as possible, while still remaining within the averaged unburnt region. Due to the U-bend, the red (the average location of the flame front) and blue line (1.5 mm ahead, parallel to the average flame front location) were chosen as the reference axes throughout this study. For clarity, the average flame front location (red line) is denoted as c_1, and the parallel (blue) line as c_2 and their corresponding lengths as L_1 and L_2, respectively.

$Re = 9677$ $Re = 13\,548$

Figure 6: The averaged image obtained from pre-processed images for a) case R-1 and b) case R-2. The average flame front location (red line) was calculated using the method described in Section 3 . Additionally, a line was added located 1.5 mm ahead, parallel to the average flame front (blue line). These lines, represented by the curve $c(x, y)$, serve as reference axes throughout the rest of this study. For clarity, the red line is denoted as c_1, and the blue line as c_2.

The two cases show an almost identical average flame front location, with one distinction: in case R-1, the final section of the averaged flame front (represented by the red dotted line at the end of the U-bend extension) is concave towards the unburnt region, while in case R-2, it is convex towards the unburnt region.

4.2.2. The velocity field

Figure 7a and 8a show the velocity magnitude and vectors for case R-1 and R-2, respectively. It can be seen that both cases show similar recirculation zones of similar size, with the recirculation zone of R-1 being slightly more compact compared to R-2. By comparing the velocity profiles for R-1 and R-2 (Figure 7b and 8b), it can be seen that the profiles look similar throughout the U-bend (blue, orange and green line). However, further down downstream at the end of the U-bend extension, the velocity profiles for R-1 become higher compared to R-2. This observation can be attributed to the local orientation of the average flame front in this region. In R-1, the flame front is convex towards the unburnt region, whereas in R-2, it is concave. As a result, the angle formed by the flame front with the positive y-axis is smaller in R-1 compared to R-2. This leads to an increased velocity ratio across the flame front in R-1, resulting in a higher value of $|\widetilde{V}|/U_b$. This is consistent with the behavior observed in premixed unconfined jet flames [?].

4.2.3. Flame-generated turbulence

Figure 9a and 10a show the dimensionless Favre-averaged turbulent kinetic energy field $\widetilde{k}/U_b^2$ for case R-1 and R-2, respectively. Similar to the non-reacting flows, a region with high $\widetilde{k}/U_b^2$ close the the wall in the U-bend ($d/L \gtrapprox 0.7$) (from the blue, orange and green line) is observed. Which is slightly higher for R-1 compared to R-2. This can be observed in more detail in Figure 9b and 10b.

(a) (b)

Figure 7: a) The Favre-averaged velocity vectors for the non-reacting flow with Reynolds number $Re = 9677$ (case R-1). The background colour corresponds to the dimensionless velocity magnitude $|\widetilde{V}|/U_b$. b) The extracted dimensionless velocity profiles of the velocity component perpendicular (V_n) to the profile lines highlighted in Figure 7a.

(a) (b)

Figure 8: a) The Favre-averaged velocity vectors for the non-reacting flow with Reynolds number $Re = 13\,548$ (case R-2). The background colour corresponds to the dimensionless velocity magnitude $|\widetilde{V}|/U_b$. b) The extracted dimensionless velocity profiles of the velocity component perpendicular (V_n) to the profile lines highlighted in Figure 8a.

(a) (b)

Figure 9: a) The dimensionless Favre-averaged turbulent kinetic energy field $\widetilde{k}/U_b^2$ for the reacting flow with Reynolds number $Re = 9677$ (case R-1). b) The extracted profiles of $\widetilde{k}/U_b^2$ along the profile lines highlighted in Figure 9a. The red curved line indicates the average location of the flame front. The average location of the flame front is situated at a position between regions with higher turbulent kinetic energy $\widetilde{k}$ (residing in a minimum of $\widetilde{k}$).

An interesting observation is the suppression of the turbulent kinetic energy at the boundary of the recirculation zone in the U-Bend.

Figures 9a and 10a present the dimensionless Favre-averaged turbulent kinetic energy field $\widetilde{k}/U_b^2$ for cases R-1 and R-2, respectively. Similar to non-reacting flows, a region of elevated $\widetilde{k}/U_b^2$ is observed near the wall in the U-bend ($d/L \gtrapprox 0.7$, indicated by the blue, orange, and green lines), with slightly higher values in R-1 compared to R-2. This difference is shown in more detail in Figures 9b and 10b. Another interesting observation is the clear reduction in turbulent kinetic energy at the boundary of the recirculation zone within the U-bend. Furthermore, as shown in Figures 9a and 10a, the average flame front (the red curved line) is located in a region where $\widetilde{k}/U_b^2$ has a minimum. In Figure 11 the dimensionless turbulence kinetic energy profile, $\widetilde{k}/U_b^2$, along the average location of the flame front, reveals a clear difference between the two cases. Case R-1, operating near flashback conditions, exhibits significantly higher values across the entire profile compared to case R-2, which corresponds to a stable flame.

This increase can be attributed to the slightly higher dimensionless shear layer, $\widetilde{S}^*_{tn}$, observed in case R-1 compared to R-2, as shown in Figure 12. The subscripts 't' and 'n' refer to the directions tangential and normal to the curves $c_{1/2}$. In regions of strong shear (case R-1), the steep velocity gradients result in elevated turbulent kinetic energy. This increased dimensionless shear leads to stronger dimensionless turbulence compared to regions with weaker dimensionless shear (case R-2). In this figure the components of the two-dimensional dimensionless strain rate tensor of the Favre-averaged flow $\widetilde{S}^*_{ij}$ were ex-

(a) (b)

Figure 10: a) The dimensionless Favre-averaged turbulent kinetic energy field $\widetilde{k}/U_b^2$ for the reacting flow with Reynolds number $Re = 13\,548$ (case R-2). b) The extracted profiles of $\widetilde{k}/U_b^2$ along the profile lines highlighted in Figure 10a. The red curved line indicates the average location of the flame front. The average location of the flame front is situated at a position between regions with higher turbulent kinetic energy $\widetilde{k}$ (residing in a minimum of $\widetilde{k}$).

Figure 11: The dimensionless Favre-averaged turbulent kinetic energy profiles extracted along the average location of the flame front (the red curved line in Figure 10a and highlighted in the top left of the current figure) for both Reynolds numbers. The lower Reynolds number shows higher values along the entire profile, attributed to the relative stronger shear layer.

tracted along the line, located 1.5 mm ahead, parallel to the average location of the flame front, as stated earlier, this distance corresponds to the grid spacing of the velocity vectors and was selected to be as close to the average flame front as possible, while still remaining within the averaged unburnt region. $\widetilde{S}^*_{ij}$ has been been made dimensionless by multiplying it with a fixed length scale (h_1, the height of the main-inlet) and divided by its corresponding bulk velocity U_b, so that $\widetilde{S}^*_{ij} = \widetilde{S}_{ij}(h_1/U_b)$, where the strain rate tensor of the Favre-averaged flow $\widetilde{S}_{ij}$ is defined as

$$\widetilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial \widetilde{u}_i}{\partial x_j} + \frac{\partial \widetilde{u}_j}{\partial x_i}\right), \tag{3}$$

Where $\widetilde{u}_i$ is the ith component of the Favre-averaged velocity, specifically $\widetilde{u}_t$ and $\widetilde{u}_n$, the tangential and normal velocity components along the reference axis (see Figure 6). As earlier stated, the figure reveals the presence of a strong shear layer, particularly within the U-bend, where $\widetilde{S}^*_{tn}$ is the dominant component of $\widetilde{S}^*_{ij}$. The flame's response to strain rates also impacts the strain rate at the flame front, particularly the tangential strain rate $\widetilde{S}^*_{tt}$ which affects the flame surface area and thus the flame speed [2]. Although the value of $\widetilde{S}^*_{tt}$ increases slightly along the line, the figure demonstrates that flame straining remains nearly negligible for both cases.

4.2.4. Alignment of the shear layer and the flame front

Figure 13 presents the probability density of the instantaneous flame fronts for case R-1 and R-2. In both cases, a concentrated distribution is observed in the U-bend, indicating a laminar-like flame front in this region. Further downstream, the distribution becomes more diffuse, indicating a more fluctuating flame front. This behaviour is more pronounced in case R-1 (near flashback), where the flame front exhibits greater fluctuations, compared to case R-2 (stable flame), where the flame front distribution remains more concentrated. For a qualitative understanding of the flame front, refer to Figure 3, which illustrates an instantaneous snapshot of the flame front for case R-2: a flat, laminar-like front inside the U-bend with a more wrinkled flame front structure downstream.

In relation to the laminar-like behavior of the flame front, an analysis was conducted similar to the study by Wang et al. [3], which quantitatively examined the alignment between the strain rate and the flame front in a high Karlovitz premixed turbulent jet flame. The two-dimensional strain rate tensor of the Favre-averaged flow $\widetilde{S}^*_{ij}$ can be characterised by its principal eigenvalues λ_1

Figure 12: a) The dimensionless strain rate profiles for a) case R-1) and b) case R-2, extracted along the blue line in Figure 6), which is located 1.5 mm ahead, parallel to the average flame front.

Figure 13: The probability density of the instantaneous flame fronts for case R-1 (left) and case R-2 (right).

and λ_2. The eigenvalues λ_1 and λ_2, where $\lambda_1 \geq \lambda_2$ are determined from

$$\det(\widetilde{S}^* - \lambda I) = 0, \tag{4}$$

where I is the two-dimensional identity matrix. λ_i and $\mathbf{e}_i$ are interpolated to the blue line in Figure 6, which is the line parallel and closest to the average flame front location inside the averaged unburnt region. The eigenvectors of λ_1 and λ_2 are $\mathbf{e}_1$ and $\mathbf{e}_2$, respectively. By convention, λ_1 corresponds to the most extensive strain rate, while λ_2 represents the most compressive strain rate of the Favre-averaged flow, with eigenvectors $\mathbf{e}_1$ and $\mathbf{e}_2$ indicating their respective directions. The orientation of the flame front and the principal strain rate directions is characterised by the absolute value of the cosine of the angle between the normal of the average flame front location $\mathbf{n}$ and each of the eigenvectors $\mathbf{e}_i$, i.e. $|\mathbf{n} \cdot \mathbf{e}_i|$. Figure 14 shows the alignment characteristics of the blue line of $\mathbf{n}$ and $\mathbf{e}_i$ as a function of the blue reference line for both cases. In the upstream region (up to $c_2/L \approx 0.6$), the angles between $\mathbf{n}$ and $\mathbf{e}_1/\mathbf{e}_2$ remain consistently close to 45°for both cases, in agreement with the findings of Wang et al. [3]. In this region, the influence of turbulence on the flame geometry is minimal, allowing the flame front to retain a laminar-like structure. Further downstream, however, the flame front normal increasingly aligns with the most extensive strain rate, while the flame front aligns with the most compressive strain rate. This observation contrasts with the findings of DNS/experimental results of turbulent jet flames [3, 4]. However, experimental results by Hartung et al. [5] and later studies by Chu et al. [6] support the present results, attributing this behavior to the fact that the dilatation ($\nabla \cdot \mathbf{u}$) induced by combustion strongly accelerates the flow in the flame normal direction resulting in extensive strain rates in this direction. These findings reinforce doubts about the validity of passive scalar turbulence models commonly used in premixed flame simulations.

4.2.5. (Un)desired flame position

Figure 15 shows the tangential and normal velocity components extracted along the average flame front location (red line in Figure 6) for both case R-1 and R-2. It is clear that the normal velocity component is nearly zero within the U-bend ($c_1/L \leq 0.5$), indicating the velocity is primarily tangential to the average flame front. This lack

(a) (b)

Figure 14: The absolute value of the cosine of the angle between the normal of the average flame front location $\mathbf{n}$ and each of the eigenvectors $\mathbf{e}_i$, i.e. $|\mathbf{n}\cdot\mathbf{e}_i|$ for a) case R-1) and b) case R-2, interpolated to the blue line in Figure 6. The black dashed line represents an angle of 45°and is used as a reference.

Figure 15: The tangential and normal velocity components extracted along the average flame front location (red line in Figure 6 for case R-1 and R-2. Since the normal velocity component is zero within the U-bend ($c_1/L \leq 0.5$) and the velocity is purely tangential to the average flame front, it indicates no expansion across the flame front. As a result, this region is dominated by diffusion effects.

Figure 16: The time-averaged (averaged over 300 images, imaged at 60 Hz) images of a hydrogen-air flame (top) and a natural gas-air flame (bottom). The hydrogen-air flame is characterised by $\phi = 0.4$, H_2%=80, $Re = 11613$, while the natural gas-air flame is characterised by $\phi = 1.0$, H_2%=0, $Re = 3871$. The red arrow highlights the presence of a reaction zone (indicated by the chemiluminescence of the flame) in the U-bend for the hydrogen-air flame, which is attributed to the nonunity Lewis number effect and the preferential diffusion effect, that occurs in lean-premixed hydrogen flames due to the high mass diffusivity of hydrogen. In contrast, there is no reaction within this region for the natural gas-air flame.

of expansion across the flame front in this region suggests a dominance of diffusion effects. Therefore, the laminar-like flame front in the U-bend can be seen as a large bulge, convex-shaped towards the reactants. This particular shape combined with the non-unity Lewis number and preferential diffusion of hydrogen causes local enrichment, thereby increasing the extinction strain rate and allowing combustion to persist in this region. This phenomenon is absent in the natural gas-air flame, where the reaction zone doesn't survive the high shear within the U-bend. Figure 16 provides visual support. The time-averaged images compare a hydrogen-air flame (top, $\phi = 0.4$, H_2%=80, $Re = 11613$) and a natural gas-air flame (bottom, $\phi = 1.0$, H_2%=0, $Re = 3871$). The red arrow in the top image highlights the presence of a reaction zone (indicated by chemiluminescence) within the U-bend of the hydrogen-air flame. In contrast, the natural gas-air flame shows no reaction in this region.

Returning to the topic addressed in Section 2.3, the natural gas-air flame is situated in the desired position (see Figure 2). This position is advantageous because it keeps the flame away from walls, which are regions prone to flashback and potential material failure due to high flame temperatures. However, this particular flow geometry (the U-bend) presents a challenge with lean hydrogen-air flames. Due to the aforementioned preferential diffusion and nonunity Lewis number effects, a lean hydrogen-air flame will

Figure 17: A sequence of a flashback event, captured at 286 µs intervals.

potentially burn within this U-bend region, which poses a risk of flashback and severe material damage.

4.2.6. Routes to flashback

Given the complex geometry and unpredictable flashback behavior, an effort was made to understand the flame's route during flashback. Prior research by Gruber et al. [7] found that with a blunt liner tip, the flame propagates along the inner liner, whereas with a sharp-shaped liner tip, it tends to propagate along the U-bend wall. Although definitive conclusions are challenging due to the inherent difficulties in capturing flashback events precisely in-plane using PIV measurements, the current observations suggest that even with the blunt liner tip employed in this study, flame propagation along the U-bend wall may be the predominant route for flashback. While the in-plane occurrence of the flashback event cannot be confirmed, Figure 17 offers evidence in support of this observation. This is plausible since a flame bulge reaching the low-velocity zone at the U-bend wall, could potentially propagate along the U-bend wall.

5. Conclusion

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