Experimental study of stratified lean premixed methane/air low-swirl turbulent flames – distribution and transport of formaldehyde

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ABSTRACT

Simultaneous high-repetition rate (3 kHz) CH\textsubscript{2}O planar laser-induced fluorescence (PLIF) and particle image velocimetry (PIV) measurements were performed in turbulent low swirl stratified premixed methane/air flames to investigate the large-scale spatial and temporal evolution of the flame and flow dynamics. In addition, PLIF of OH and CH\textsubscript{2}O at a low-repetition rate (10Hz) were carried to study the global effect of equivalence ratio, $\phi$, on the flame. A low swirler burner was used to stabilize a wide range of flames, from close-to-quenching lean flames to close to stoichiometric flame with $\phi = 0.9$. The flames exhibit a laminar flamelet structure in the leading front and thickened flame structure with local quenching at the trailing edge. Detailed statistical data are obtained, including the velocity field, the mean flame location; preheat layer thickness, flame brush thickness and the flame surface density. These data provide a useful database for comparison of combustion model simulations. The results reveal interesting flame behaviour; depending on the equivalence ratio the large scale interaction between the flame and the flow field takes different forms. In particular the shift in flame shape occurring when $\phi$ is increased from 0.6 to 0.7 is characteristic for the investigated flame sensitivity to a varying equivalence ratio. Whereas the leading edge of the flame, protected from the surrounding shear layers, maintains its form the trailing edge and post-flame region can drastically change with $\phi$. The flow field is also clearly modified by the combustion process. When $\phi$ is increased the flame volume and the thermal gas expansion is increased together with the mean flame position moving upstream - all these parameters influence the flow field. For $\phi > 0.7$ the thermal gas expansion from the flame is sufficient to counteract the flow stagnation along the centre axis encountered for the leaner cases. The flame surface density was investigated for $\phi = 0.6, 0.7, 0.8$ and 0.9. For $\phi > 0.7$ the peak in flame surface density was found at radial distance corresponding to the inner shear layer where the flame front is strongly wrinkled by the large scale vortices. At this location the fuel mixture is relatively unaffected by the dilution of the ambient air and the freely propagating flame can interact with the turbulent flow. With increasing HAB the ambient air dilution to the fuel becomes significant, which can lead to local flame quenching.
1. Introduction

Even with the growing activates in the field of turbulent combustion, it is evident that there are aspects of combustion physics that are still poorly understood. For example, premixed flame structures encountered in stratified flames and shear-layer regions and where diluted unburned gas is mixed with hot partly decomposed fuel and/or product gases. To explore these processes in both laboratory flames and in combustors of industrial relevance dedicated laser-diagnostic techniques are required. To assist in the designing of next-generation combustors the development of suitable simulation tools for assessing turbulent reactive flows has generated considerable interest, such as Large Eddy Simulations (LES), [1]. LES needs to be validated, however, with experimental results obtained in laboratory burners of increasing complexity to ensure adequate performance and to refine the combustion models. Such validation data should include flame series and both the initial and boundary conditions and the relevant physical properties of the flames that are investigated. Information concerning the mean flame front location and flame topology, as well as temperature and species concentrations, and the velocity field is required, [2, 3]. A sufficient amount of data, spatially covering the entire region of interest needs to be acquired with use of suitable measurement techniques.

In the field of premixed flames several groups have performed systematic experimental studies of low swirl flames. The low swirl concept was first developed at Lawrence Berkley National Laboratory (LBL) [4-6] where it was demonstrated that theses flame are stabilized, not in a recirculation zone typically existing in high swirl flames, but in a low speed zone in a core region downstream of the swirler where there is no recirculating flow. In addition, the flame is lifted and these features have led to the development of several low swirl flame rigs for studying turbulence-flame interactions in premixed flames. The resulting flame and flow offers a good compromise between simplicity and complexity for relevant LES validation and flame studies. Published results include Day et al. [7] who reported on a computational characterization of lean premixed turbulent low swirl methane/air flames. The simulations captured the overall dynamic behaviors of the low-swirl flame and the turbulent flow field. Results from simulations investigating the equivalence ratio effects in low-swirl flames are found in Ouali et al. [8]. With increasing equivalence ratio the flame/flow interaction was reported to become increasingly complicated leading to the risk of dynamic instabilities in the shear-layer region.
This work is a continuation of previous combined experimental and computational studies performed at Lund University on the low-swirl burner geometry [9-13]. Here, the objective is to investigate the equivalence ratio effect on the structures and dynamics, as well as several key flame properties. Analysis of the flame surface density, flame brush thickness and overall flame shape is performed using experimental data from planar Laser-induced Fluorescence (PLIF) of the distribution of formaldehyde (CH.O). The flow field is characterized using Particle Image Velocimetry (PIV). In particular, high-repetition rate laser-diagnostic techniques are applied to in detail study the distribution and transport of CH.O reflecting the properties of the flame preheat zone and its interaction with the turbulent flow field.

2. Experimental set-up and applied laser diagnostics

2.1 Burner and flame operating conditions
A schematic overview of the burner used in this investigation is given in Figure 1a, details are found in [10, 12, 14]. The swirling flow is created by an outer annular swirler in combination with an inner perforated plate. The mass flow split between the outer swirler and the inner perforated plate is 60/40. After passing the swirler assembly, premixed methane/air discharges through a nozzle with diameter (D) of 50 mm into the ambient. The outflow from the nozzle can be characterized as an inner low speed, non-swirling, region and an outer region with higher axial and tangential (swirl) velocities [14]. Downstream, the flow diverges causing the axial velocity in the center region to gradually decrease to create a low-speed region, where lean premixed flames can be stabilized. Since the flame is lifted and unconfined, surrounding ambient air can be entrained into the outer region of the fuel stream causing a stratification of the mixture at the outer sections of the flame front. Methane/air flames with an equivalence ratio of 0.6, 0.7, 0.8 and 0.9 are used as the main conditions throughout this study. Two Reynolds numbers (Re), are investigated Re=20,000, and Re=30,000. The Reynolds numbers is based on the bulk flow velocity (6.2 and 9.3 m/s respectively), the diameter at the burner exit and a weighted viscosity for the air/methane mixture.
2. 2 Laser diagnostics

Combined high frame visualization of flow field (PIV) and CH\textsubscript{2}O distribution (PLIF) were performed to study the preheat layer characteristics and transport of CH\textsubscript{2}O in different regions of the flame in detail. An overview of the experimental setup is given in Figure 1b. In addition measurements of simultaneous imaging of OH and CH\textsubscript{2}O PLIF at 10 Hz were performed to capture the global and mean properties of the flame region.

A frequency-tripled diode pumped Nd:YAG (Edgewave) HD40I-OE laser at 355 nm and a repetition rate at 3 kHz was used to excite several rotational lines in the $A^1A_2 \leftarrow A^1A_1$, $4_0^1$ transition in CH\textsubscript{2}O. Each 12 ns laser pulse had an output laser energy of 8.3 mJ and was synchronized with the PIV laser system to be “fired” between every dual shots of the PIV-laser system. To separate the residual 532 nm beam from the 355 nm beam a Pellin Broca prism was used. The 355 nm beam then passed through two quartz lenses; one $f = 40$ mm cylindrical and one $f = 500$ mm spherical creating a 22x0.30 mm\textsuperscript{2} laser sheet positioned vertically above the burner. The laser sheet thickness was determined by translating a razor blade through the sheet-waist while observing the translation displacement (in µm) and laser power. A Gaussian fit was then applied to the derivative of the measured cumulative distribution function profile and the FWHM (full width half maximum) of the fitted Gaussian denoted the laser sheet thickness to be 300 µm. The fading wings of the laser sheet was not cut in the experimental setup, instead the PLIF images was cropped in the post processing routines, where also the images were corrected.
for the spatial variation of the laser sheet intensity (see further details below). The fluorescence signal from formaldehyde was recorded with a Photron Fastcam SA-X2 high-speed CMOS camera mounted on a Lambert high-speed 2 stage image intensifier with a gate width set to 200 ns, and a 50 mm Nikon Nikkor f. = 1.2 lens. To suppress reflections and Mie scattering from seeding particles a UVFS flat mirror, highly reflective (>99.5 % at AOI = 0°) for wavelengths at 351-361 nm was put in front of the lens. In addition, to remove laser interference below 385 nm further, a GG385 (longpass) filter was also used. Since a non-quartz lens was used part of the unwanted 355 nm stray light was naturally reduced. Despite these measures some seeding was still detected in the simultaneously PIV/PLIF images, hence complementary image post processing was performed. Firstly, background subtracted raw images were convoluted with a Gaussian filter with FWHM = 3.5 pixels. In order to correct the images for the non-uniform laser sheet profile, 5000 Rayleigh images were recorded with the high speed detector but with all filters removed. To suppress unwanted Mie scattering in the Rayleigh images from e.g. dust particles, all Rayleigh images was added to each other and the median in each pixel was calculated. The mean in horizontal direction provided a vertical average laser sheet profile which the convoluted images hence was normalized with. Finally, a 2D order-statistic minimum filter was applied to the images to suppress the remaining visible seeding particles further. The signal-to-noise ratios (SNR) achieved were then as high as 30 for the PLIF images with seeding present, and 46 for the PLIF images recorded with no seeding present. Image registration, i.e. pixel-to-pixel correspondence between the PLIF images and the PIV images were also conducted, providing final images with the size of 600x896 pixels. The spatial resolution achieved from a resolving target was established to 5.0 line pairs per mm.

Characterization of the reacting flow field was carried out by use of a 2D PIV system, enabling two velocity components to be assessed in a plane through the center of the flow/flame region. As light source a double cavity diode pumped kHz Nd:YLF laser (DualPower 30-1000) delivering around 30 mJ per pulse at 527 nm. Integrated light sheet optics was used to form a light sheet above the burner. As flow tracers ~1 μm-sized aluminum oxide particles were used. The PIV raw images were acquired using a SpeedSense 311 high-speed camera. To eliminate background light and flame emission a narrowband 532 nm (+/-10 nm) interference filter was mounted on the camera lens. For synchronization of the lasers and cameras, data acquisition and for evaluation of the velocity field the DynamicStudio software (v. 4.15) was used. For evaluation of the velocities an adaptive PIV algorithm was employed to optimize the analysis
with respect to seeding density (cold and hot region) and velocity gradients (low speed region and shear layer region). Erroneous vectors were removed using a scatter plot median filter.

Measurements of simultaneous imaging of OH and CHO PLIF at 10 Hz were also performed. Formaldehyde was excited by a frequency tripled Nd:YAG laser providing 355 nm laser pulses with a pulse duration of less than 10 ns. Hydroxyl radicals (OH) were excited by using an Nd:YAG pumped dye laser that was tuned to a wavelength around 283 nm. The laser beams were focused above the burner using a quartz cylinder lens and a spherical lens to create a light sheet. Two HiSense MkII CCD cameras with image intensifiers (Hamamatsu) were used to capturing the LIF signals. The CHO signal was imaged onto the camera by a 50 mm Nikon Nikkor $f_r = 1.2$ lens in combination with a double GG400 Schott filters to discriminate stray laser light. For the OH fluorescence a 100 mm B. Halle $f_r = 2.8$ UV camera lens was used in combination with an OH bandpass filter (313 nm ± 13 nm).

### 2.3 Flame structure & combustion regimes

Premixed combustion in technical devices often occurs in thin flame fronts. The propagation of these fronts, and hence also the heat release, is governed by the interaction of transport and chemistry within the front. In premixed combustion fuel and oxidizer are mixed, but at relative low temperature, in this paper the fuel/air mixture was at room temperature upstream the flame region.

A schematic example of the local laminar structure of a premixed methane air flame in the flamelet combustion regime is shown in figure 2. In the preheat zone (order of 1 mm thick) the fresh fuel is heated by the thin reaction layer - diffusion of heat and mass influences the constitution in this layer. The major heat is released in the reaction layer, this layer is thin 0.01-0.1mm. Formaldehyde, CHO is an intermediate species in hydrocarbon combustion which, in the flamelet regime, often is used as a marker of the initiation and progression of combustion i.e. of the flame preheat zone [15].
In the flames investigated here the flame base is characterized to be in the wrinkled flame regime $u_0 < S_L$, and along the flame edge in the corrugated flame regime, $u_0 > S_L$. Both regimes are based on a flamelet structure. Here, turbulence wrinkles and strains the flame but without modifying its flamelet structure since the smallest turbulent eddies are larger than the flame front thickness, the Karlovitz number $Ka < 1$. Only molecular transport increases the temperature of the reactants in the preheat zone above the inner-layer temperature (cross-over temperature), where self-sustained chemical reactions occur [16]. Towards the trailing edge of the flame for the leanest investigated conditions, the flame reaches the thin reaction zones regime ($Ka \sim 10$) due to the stratification. In this regime vortices are small enough to enter and mix and thus thicken the preheat zone but unable to modify the reaction-layer, which retains a thin laminar structure. The stratification can lower the local $\phi$ below the flammability limit and cause local quenching at the trailing edge for the leanest investigated cases.

3. Results and Discussion

3.1 Mean flow field and flame characteristics
As illustrated in Figure 3 the investigated flames are lifted and are propagating in an inner low-speed region created by the divergent flow field. The averaged flame is approximately bowl-shaped. The outer region of the flame interacts with large vortices in the inner shear layer and the flame base is wrinkled and convected by the flow exiting the nozzle. Methane/air flames are studied from $\phi = 0.6$ to $0.9$ and the corresponding laminar flame speed, $S_\text{L}$, increases from approximately $0.1 \text{ m/s}$ at $\phi = 0.6$ to $0.26 \text{ m/s}$ at $\phi = 0.9$. The $\phi = 0.6$ case is close to the LBO limit.
for this particular flame and is thus most sensitive to the effect of stratification, decreasing the local equivalence ratio along the flame edge. Due to the stratification and the low laminar flame speed, the flame edge is limited in height and aligned close to parallel with the axial direction. For the same reasons the radial flame propagation is limited resulting in a small flame volume. The global flame properties (flame angle, volume, length) and the thermal gas expansion are drastically changed when $\phi$ is increased. The flame move closer to the nozzle and also the flame interaction with the shear layer is influenced with increasing $\phi$. Since the flame is lifted and unconfined, surrounding air can be entrained into the outer part of the mixture ahead of the flame, causing a stratification of the mixture at the outer sections of the flame front [17]. The flame flow interaction and flame stabilization are discussed below using high-repetition rate sequences of the combined flow field and formaldehyde distribution.

By extracting data from Figure 3 (left) the development of the axial velocity along the center-line together with the mean flame position, from the progress variable $<c> = 0.5$ can be highlighted, Figure 3 (right). Here additional data from $\phi = 0.62$ and 0.65 is included to show the influence of the heat release at the leanest conditions. For $\phi<0.7$ the heat release is not compensating the velocity decay connected to the flow divergence and only a reduced decay rate of the axial velocity is seen. Furthermore, for $\phi<0.7$ the flow stagnation and negative axial velocities is clearly demonstrated at HAB>40 mm. The downstream (HAB>70 mm) increase in velocity, from a negative velocity, for the $\phi = 0.6$ an 0.62 case is due to a very small flame length and flame volume that makes it possible for the high-velocity shear-layer flow to “expand” towards the centerline and thus increasing the axial velocity over the investigated Field-of-View (FoV). With increasing $\phi$, the effect of the heat release (thermal gas expansion) becomes evident. The location where the axial flow accelerates due to the heat release is clearly seen for $\phi>0.7$ and the inserted mean flame location correlates well with this position. The flame series presented here are important for model validation for selecting relavant operation conditions depending on the aim and maturity of the model.
**Figure 3** $\text{Re}=20.00$. **Left** The mean flow field, streamlines represent the 2D flow and the color scale is the axial velocity magnitude. The solid line represents the mean flame location. **Right** The axial velocity development along the center axis and the mean flame position ($<c>=0.5$). Here data from $\phi=0.6$, 0.62 and 0.65 is included to show the influence of the flame heat release at the leanest conditions.

The mean progress variable, $<c>$, is shown in Figure 4 and was determined by creating a binary mask of every instantaneous OH PLIF images, indicating 0 in the unburned state and 1 in the burned state at locations within the turbulent flame brush. The ensemble average over the 760 instantaneous masks provided the mean reaction progress variable [18]. Mean flame position/lift-off height at the centerline depends mainly on the equivalence ratio and only marginally on the Reynolds number. At the flame base the $<c>=0.5$ contour is more or less horizontal in an interval of ±10 mm around center line (CL). Distinct positions around CL, which is used in the following analysis of the preheat zone thickness, are also marked in Figure 4.
3.2 Flame and flow dynamics - high-repetition rate laser diagnostics

Below a few short sequences of the flow field and the CH₂O distribution/flame are shown. In the first two sequences the fluctuating part of the flow field (the mean value of each velocity vector is subtracted) is shown to reveal vortices hidden by the convection. Several sequences of 3,000 combined images, at a sampling rate of 3 kHz, were collected for all of the operational conditions, making it possible to investigate in qualitative terms the interaction between the flow and the flame in different regions. An overview of the FoV used to investigate different regions of the flame is displayed in Figure 5.

**Figure 4.** The $\langle c \rangle = 0.5$ contour for the different $\phi$ and Reynolds numbers. Indicated are also the analyzed distinct positions at the flame base. The different $\phi$ is represented in decreasing order with HAB, i.e. $\phi = 0.9$ closest to the burner and $\phi = 0.6$ furthest from the burner.
**Figure 5** Overview of the FoV for the investigated flame/flow regions with high-repetition rate (3 kHz) PIV & PLIF.

The nozzle exit flow and the ambient co-flow are both indicated in the figure.

### 3.3 Flame dynamics flame flow interaction

Combined high repetition rate PIV and PLIF of the CH$_2$O distribution were performed to study the transport of CH$_2$O at different regions of the flame as shown below.

**Flame base dynamics:**

In Figure 6 the flame base interaction with the turbulent flow field is shown. Here, the fluctuating part of the flow field, i.e. with the mean subtracted, is presented to visualize eddies convected by the mean flow. The wrinkling of the flame by eddies convected in the inner shear-layer and the inner low-speed region (fluctuating part of the flow field is show i.e. the mean is subtracted), $dt=1$ ms. At the flame base the CH$_2$O layer is thin and towards the flame edge a broadening of the CH$_2$O layer often occurs as an effect of the flame front interaction with shear layer vortices. The eddies in the in the inner shear layer are typically not strong enough to create flow reversal in absolute terms and the flame is not hold in position by the vortices at this position but the flame/flow are continuously interacting in a manner as shown here. This is creating the often noted W-shape of the flame base. Note also that the CH$_2$O layer is smooth, and not distorted, towards the burned side of the gas i.e. the reaction layer. This is in agreement with the reaction layer is not influence by the turbulence as expected in the flamelet regime.
Figure 6 The wrinkling of the flame base (preheat zone) by eddies convected in the inner shear-layer and the inner low-speed region (fluctuating part of the flow field is show i.e. the mean is subtracted), $dt=1$ ms.

Flame edge dynamics/ shear layer interaction:
In Figure 7 the roll-up of the preheat zone by a convected eddy in the inner shear layer region (fluctuating part of the flow field is show i.e. the mean is subtracted). Initially in the sequence, the preheat zone is well defined (no mixing distorting the layer) and flame is folded by the eddy interacting with the flame. Due to the flame folding the fronts meet locally and traps unburnt
gas. In these pockets the cooling by the ambient air is reduced. Towards the end of the sequence, as the eddy travels downstream its lower part “pulls” the flame outwards and seemingly also eroding the flame and transporting a part of the formed CH,O away from the flame front and thus cooling the flame. Once CH,O is formed it remains stable and can therefore be transported by convection and turbulent eddies in the unburnt cold fuel stream region. As the eddies not creates reverse flow in absolute terms (flow reversal in absolute terms is typically not seen in the in the inner shear layer) the flame is not hold in position by the vortices at this position but the flame/flow are continuously interacting in a manner as shown here. Note also that the CH,O layer is smooth, and not distorted, towards the burned side of the gas i.e. the reaction layer. This confirms that the reaction layer, as expected in the flamelet regime, is not influenced by the turbulence.
Figure 7 The roll-up of the preheat zone by a convected eddy in the inner shear layer region (fluctuating part of the flow field is show i.e. the mean is subtracted), dt= 1 ms.
Stagnation region:
Figure 8 captures the dominant flow characteristics encountered downstream of the main flame bowl for the leanest operating conditions. Due to the limited heat release and the short flame length the axial flow in the center is reaching stagnation and above this a reverse flow is often present in combination with large pairwise counter-rotating vortices (assumed to be a ring-vortex seen in 2D). In this region CH\(_2\)O is transported along the flame edge and entrained towards the product zone (center region). Also unburnt diluted fuel is entrained and can be decomposed into addition CH\(_2\)O in the hot product/stagnation region. As a result a region with distributed CH\(_2\)O is dominating this region of the leanest flames.
Figure 8 The CHO entrainment/transport in the stagnation region dominating the post-flame characteristics for $\phi$ <0.7 (absolute velocities).

3.4 Thickness of the preheat zone
The preheat layer thicknesses, $l_{CH_2O,\phi}$, was calculated and compared for the different running conditions and the trend can be seen in Figure 9. The thicknesses were obtained at the distinct radial positions marked in Figure 4 by analyzing signal intensity profiles of the preheat layer. A Gaussian profile was fitted to the perpendicular signal intensity profile towards the preheat layer and the FWHM was calculated, which then represents the thickness. Though, two constraints had to be introduced to increase the reliability of the statistics. First, the r-squared value of the fitted Gaussian was set to only be allowed for >0.97. Second, $l_{CH_2O,\phi}$ >2.3 mm was discarded from the statistics, since it is considered to be non-realistic thickness of the preheat layer. However, this only affected a limited number of outliers. With these two constraints, still more than 30 000 thickness values were obtained, represented in Figure 9. The trend shows a decrease in preheat layer thickness with increasing $\phi$, which indeed was expected as it was noted during the high speed recording of the PLIF images, seen in the sequential examples of figure SS-SS. The result can also be compared to results from Chemkin calculations giving $l_{CH_2O,0.6}$ = 1.2 mm and $l_{CH_2O,0.9}$ = 0.55 mm (see Fig. 9 left). The statistics of this experimental investigation coincide in good agreement to this, i.e. $l_{CH_2O,0.6}$ = 1.3 mm for Re = 20 000 and $l_{CH_2O,0.6}$ = 1.2 mm for Re = 30 000.

The validity, consistency and accuracy of the preheat layer thicknesses have to be considered. The major uncertainty in the length scale of $l_{CH_2O,\phi}$ is estimated to emerge from the finite spatial resolution in the PLIF images and the detection limit of the measurement technique. Besides, and independent from this, there are also the temperature-dependent quenching rates impinging the results. Another factor to have in consideration is the inherent temperature dependence originating from the temperature dependence of the Boltzmann factor, which will broaden the signal detected. Zhou et al [19] estimates the influence of the inherent temperature dependence for CHO and it is concluded that its effect in relation to the spatial detection limit of this investigation is negligible. Also to have in consideration is the turbulent induced strain rates which will influence the thicknesses of the preheat layer. However, as more than 13 000 thicknesses across the flame base is analyzed, and the mentioned constrain of discarding too thick thicknesses, the impact on the general trend is not considered to be much biased. These
sources of errors will always be present, but, as we believe that the general trend and its influence of the thicknesses are preserved and considered as minor, the trends in the overlapping thickness are deliberated as consistent and valid.

Figure 9. Left) Temperature profiles and flame thickness for $\phi = 0.6$ and 0.9 from Chemkin. Right) Trend of preheat zone thickness from CH$_2$O PLIF for the investigated flame conditions.

3.5 Gradient or counter-gradient transport

Counter-gradient diffusion (CGD) or gradient diffusion (GD) appears whether the burnt conditioned mean velocity is higher (CGD) or lower (GD) than the unburnt conditioned mean velocity [20]. The mean results presented in Figure 3 shows the axial velocity development along the center axis and the mean flame position ($<c>$=0.5) for the investigated cases. The limited influence of the flame heat release on the axial velocity at the leanest conditions is seen. First at $\phi > 0.7$ the axial flow acceleration due to the flame heat release is clearly observed in the data in Figure 3. Based on this first approximation it can be assumed that GD occur at for $\phi$=0.6 Re = 20 000 and 30 000 and for $\phi > 0.7$ CGD dominates at the mean flame location.

However, this can only be considered as a first approximation and a more correct analysis of the velocity conditions is if the burnt and the unburnt velocity vectors, $u_b$ and $u_{ub}$ could be collected with the movement of the flame base flame front. The simultaneous high-speed time resolved measurements of PIV and PLIF of CH$_2$O enables this with the method described below.

As the fuel/air mixture was seeded with particles, unwanted Mie scattering were interfering with the CH$_2$O signal detection aggravating the determination of the CH$_2$O position. However, working with time resolved PLIF imaging is beneficial while detecting the correct position of the
CHO signal, and not some induced Mie scattering from the added seeding particles. By focusing at distinct radial coordinates, the CHO signal \((i)\) can be followed and recorded for every frame \((i)\), giving the position of maximum CHO signal, \(I_{\text{max},i}(x, y)\), where \(x\) represents the radial direction and \(y\) the vertical direction. The mentioned benefit of working with time resolved data is that the position of \(I_{\text{max},i+1}(x, y)\) can be based on the position of \(I_{\text{max},i}(x, y)\). Furthermore, since the position of the maximum CHO signal \((I_{\text{max},i}(x, y))\) now is determined, an additional 30 positions of \(I_{\text{max},i}\) in the direct vicinity of \(I_{\text{max},i}(x, y)\) can be determined. A linear fit to these points provides the angle, \(\theta\), between the fitted line and the \(x\)-axis which is calculated for every frame. This makes it possible to, first; collect \(u_\theta\) and \(u_s\) from each side of \(I_{\text{max},i}(x, y)\), and secondly; calculate the perpendicular vectors of \(u_\theta\) and \(u_s\) to \(I_{\text{max},i}(x, y)\). Further, as the CHO signal represents the preheat zone [21] and the grid of the PIV field is set to a spacing of 16 pixels which is approximately two times the spatial distance from the preheat zone to the post flame zone [22], it is relevant to argue that; in this investigation it is determined whether CGD or GD occur at the position of the flame front.

The subtraction between \(u_\theta\) and \(u_s\) collected at the preheat zone position provides scatter plots of the velocity difference versus HAB. This scatter plot is then analyzed by segmenting the different HABs into bins whose positions is determined from the distinct vertical positions of \(u_\theta\) and \(u_s\) at the CL. The mean value of every bin is represented in Figure 10. Also, as the HAB can be represented by \(<C>\) Figure 10 shows the difference between \(u_\theta\) and \(u_s\) over \(<C>\).

Obviously, the presence of \(u_\theta\) and \(u_s\) at \(<C>=0.1\) or \(<C>=0.9\) is less likely, hence less samples are evaluated at the flanks of Figure 10. Also, keep in mind that the mentioned flow stagnation and backflow, caused by the limited heat release at the very lean flame conditions of \(\phi=0.6\), will influence the conditional velocities at \(<C>=0.9\) as the stagnation zone is close to the position of \(<C>=0.9\). The largest source of error is of course the lack of the third velocity component for \(u_\theta\) and \(u_s\). Though, only the radial position at the CL is here investigated, where the lack of the third velocity component is least affected.

The trends observed in Figure 10 confirm what the first approximation indicated, but it is now with a more robust statistics over the flame brush for both \(\text{Re} = 20\,000\) and \(30\,000\). The limited flame heat release for \(\phi=0.6\) results in GD and for higher \(\phi\) CGD starts to dominate. The change from GD to CGD is noted when \(\phi > 0.7\), only a marginal influence on the Reynolds number is noted. Thus CGD associated with thermal expansion and the acceleration of fluid passing the
flame front dominates in cases above $\phi > 0.7$. In addition, with the statistics at hand, no clear change is observed over the flame brush.

![Flame front dominance](image)

**Figure 10** The difference between the burnt and the unburnt velocity vectors at CL for the investigated flame conditions.

### 3.6 Flame wrinkling and Flame surface density

The flame flow interaction is previously investigated both experimentally and by LES [12]. Characteristic flow features that were identified for the investigated cases include the large-scale vortex structures that were convected within the inner shear layer. Only few of these vortices are strong enough to create flow reversal but do, on the other hand, frequently create local regions with low axial velocity that allows the flame (depending on $\phi$) to propagate upstream and in the radial direction. It has been discussed, [10], if the shear layer is important for the stabilization of the investigated flames. Vortices of lower strength that often appeared in the shear layer as
vortex-pairs wrinkled the flame locally. In the inner, low-speed region, the freely propagating flames responded to local fluctuations in the flow field.

The lifted unconfined flames are freely propagating in the generated swirling flow field. With the characteristics of the flow along the flame front combined with the fuel stratification, increasing with HAB, the local flame properties changes accordingly. The leading flame edge is propagating in the inner region without swirl and mainly interacting with weak large flow structures. The interaction with counter rotating vortex pairs convected from then nozzle is responsible for the large scale smooth wrinkling of the flame front. In between the counter rotating vortices the incident velocity has a local minimum or maximum, so that the flame propagates upstream or downstream accordingly. This leads to the relatively large fluctuation of the flame base location at the centerline, see Figure 11. The flame base wrinkling process is relatively insensitive to increasing equivalence ratio as demonstrated by the similar values for flame surface density at the flame base for each case in Figure 11. This is attributed to the fact the flame base is for all cases located in the same region, i.e. in the inner region close to the nozzle, and that the local equivalence ratio in this region is not influenced by entrained air. At the trailing edge, the flame is propagating in the much more turbulent shear layer which wrinkles and folds the flame. With increasing HAB the fuel stream, slipping outside of the flame base region, is diluted by turbulent mixing with the coflow of air. For the leanest cases this leads to local quenching due to additional air entrainment into an already lean mixture. With increasing \( \phi \) this stratification becomes a less limiting factor, the flame moves closer to the nozzle and the flame volume increases as the flame can expand radially out in the shear-layer region and also extends its length, see Figures 11 and 3.

In both regions, flame base and trailing edge, the fluctuating velocity field wrinkles the flame and increase, to a different degree, the flame surface area. In the flamelet theory, this effect is described by the flame surface density [23]. To characterize the mean flame position the flame surface density (\( \Sigma \)) was calculated for \( \phi=0.6, 0.7 \) and \( 0.8 \), the corresponding 2D distributions are presented in Figure 3a. To identify the flame fronts from the OH PLIF images the Canny edge detection method was applied. Since \( \Sigma \) is defined as the average flame surface area per unit volume a 2D approximation [24] [25] [26] was applied on the extracted flame fronts. The size of the interrogation box (\( \Delta x \)) was investigated to ensure correct calculations of \( \Sigma \) by comparing \( \Sigma \) profiles for different \( \Delta x \) spanning from 0.4 mm to 5.5 mm at a constant HAB=44.8 mm. No significant difference could be seen in the resulting \( \Sigma \) between \( \Delta x=0.4 \) to \( \Delta x=2.1 \) mm hence an
interrogation box of 1.7x1.7 mm was chosen, which indeed is smaller than the turbulent flame brush thickness [26].

![Flame surface density for \( \phi = 0.6, 0.7, 0.8 \) and 0.9.](image)

**Figure 11** Flame surface density for \( \phi = 0.6, 0.7, 0.8 \) and 0.9.

### 4 Conclusions

Simultaneous high-repetition rate (3 kHz) CH\(_2\)O planar laser-induced fluorescence (PLIF) and particle image velocimetry (PIV) measurements were performed in lean premixed methane/air turbulent flames stabilized in a low swirler burner to investigate the flame/flow interaction in detail. In addition, PLIF of OH and CH\(_2\)O at a low-repetition rate (10Hz) were carried to study the global effect of equivalence ratio on the flame. The flames exhibit a laminar flamelet structure in
the leading front and thickened flame structure with local quenching at the trailing edge. The experimental conditions are varied to cover a wide range of flames, from close-to-quenching lean flame to close to stoichiometric flame with equivalence ratio of 0.9. Detailed statistical data are obtained, including the mean and rms (not shown) of the velocity field, the mean flame location and flame brush thickness, thickness of the preheat layer and the flame surface density. These data provide a useful database for comparison of combustion model simulations. The results reveal interesting flame behaviour. Depending on the equivalence ratio the large scale interaction between the flame and the flow field takes different forms. In particular the shift in flame shape occurring when $\phi$ is increased from 0.6 to 0.7 is characteristic for the investigated flame and its sensitivity to a varying equivalence ratio. Whereas the leading edge of the flame, protected from the surrounding shear layers, maintains its form the trailing edge and post-flame region can drastically change with $\phi$. The flow field is also clearly influenced by the combustion process. When $\phi$ is increased the flame volume and the thermal gas expansion is increased together with the mean flame position moving upstream - all these parameters influence the flow field. For $\phi > 0.7$ the thermal gas expansion from the flame is sufficient to counteract the flow stagnation along the centre axis encountered for the leaner cases. The flame surface density was investigated for $\phi = 0.6, 0.7, 0.8$ and 0.9. For $\phi > 0.7$ the peak in flame surface density was found at radial distance corresponding to the inner shear layer where the flame front is strongly wrinkled by the large scale vortices. At this location the fuel mixture is relatively unaffected by the dilution of the ambient air and the freely propagating flame can interact with the turbulent flow. With increasing HAB the ambient air dilution to the fuel becomes significant, which can lead to local flame quenching.

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**References**


