Laser optical investigation of turbulent transport of temperature ahead of the preheat zone in a premixed flame

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Abstract

This experimental study investigates temperature profiles upstream of localized thin reaction zones in a turbulent premixed flame stabilized on a low-swirl-burner. A simultaneous dual-sheet Rayleigh/OH-LIPF measurement technique was applied using two parallel laser light sheets to measure the temperature in the preheat zone for three lean ($\phi = 0.7$) turbulent methane/air flames. The ratio of the turbulence intensity to the laminar burning velocity $v' / s_L$ was varied from 3.5 to 9.2 and to 18.7. The first of these flames lies on the borderline between the “corrugated flamelets” regime and the “thin reaction zones” regime, while the other two are in the “thin reaction zones” regime. The results confirm the occurrence of strong temperature fluctuations ahead of the preheat zone for flames in the “thin reaction zones” regime. Single temperature images show a significant temperature increase ahead of the preheat zones of up to 700 K for flames at the highest turbulence intensity. For statistical analysis conditional mean temperature profiles and probability density functions conditioned on the distance from the flame contour were calculated from the experimental data. Only those portions of the flame front were included which were found to be approximately normal to the two laser sheets. The resulting probability density functions show that the effect of temperature rise ahead of the preheat zone becomes significant only for flames in the “thin reaction zones” regime. The mean temperature profiles show a much smaller temperature rise which, however, increases with increasing velocity ratios $v' / s_L$.

Keywords: Turbulent transport; Preheat zone; Flame structure

1. Introduction

Until recently theories in premixed turbulent combustion have focused on the flamelet regime which is valid only for conditions where the flame thickness $l_F$ is smaller than the smallest scale of turbulence, the Kolmogorov scale $\eta$. In that case the entire convective-reactive-diffusive structure of the flame can be assumed to be quasi-steady because it is not affected by turbulent eddies. If this criterion is not met, which is often the case in practical applications as well as in Direct Numerical Simulations, the nature of the interaction between turbulence and chemistry was less clear. The regime where $l_F > \eta$ was called the “thickened-wrinkled flame regime with possible extinctions” [1] or the “distributed reaction zones regime” [2].

A new interpretation of this regime was provided by Peters [3] who called it the “thin reaction zones” regime arguing that while the reaction zone remains thin and quasi-steady in this regime, small eddies can enter into the chemically inert preheat zone. The small eddies would cause turbulent fluctuations of the temperature and of the main species ahead of the preheat zone with the consequence that scalar transport in and out of the reaction zone would be enhanced.
Instantaneous temperature profiles from planar laser sheet Rayleigh scattering spectroscopy by Mansour et al. [4] show indeed such temperature fluctuations. Elevated temperatures ahead of the preheat zone of highly turbulent premixed flames have also been observed by Buschmann et al. [5] using a single-laser-sheet technique. However, errors in the interpretation of 2D-images cannot be excluded in cases where the convolution of the three-dimensional flame surface is such that the planar laser sheet just touches a part of the surface when it is bent into it from the third dimension. In order to circumvent this problem, in the current study a dual-sheet technique [6] is applied to turbulent premixed flames stabilized on a low-swirl-burner. This technique allows to measure the temperature fields from the Rayleigh scattering in two parallel imaging planes. For the determination of the flame front OH-laser-induced predissociative fluorescence (OH-LIPF) was measured simultaneously in combination with the Rayleigh measurements.

Since a turbulent eddy is a statistical concept rather than a physical entity it would be dangerous to base the hypothesis of turbulent transport ahead of the preheat zone on just a few laser sheet images. Also, since turbulence is intermittent the profiles in the preheat zone may not be affected in many of the measurements but in only a few events. Since those events are likely to attract the attention of the experimentalist they may preferably be reproduced for illustration purposes thereby overemphasizing their occurrence. In the current study we therefore not only present such single events but also mean profiles and probability density functions of the preheat zone temperature based on 200 single shot images for each flame conditioned on the distance from the flame contour.

2. Experiments and diagnostics

2.1. Low-swirl-burner

For the generation of turbulent premixed flames the low-swirl-burner of Bédat and Cheng [7] was used. The main feature of this type of burner is, that it allows to stabilize freely propagating planar flames at very intense quasi-isotropic turbulence. Its design is presented in Fig. 1. The burner has been described in detail in Ref. [7] and will only be briefly reviewed here. It consists of a settling chamber, a turbulence generator (0.8 mm wide slit), and a 233 mm long tube section with a diameter of 50 mm. The tube section is connected to a swirl generator, which consists of 2.5 mm diameter tangential air jets inclined at 20°. The swirl generator generates a weak swirl, which stabilizes the turbulent flames on the top of the burner. The flow and turbulence properties of the burner were measured using laser Doppler anemometry (LDA) in [7,8] and using particle image velocimetry (PIV) in [9].

2.2. Experimental setup

The experimental setup of the simultaneous dual-sheet-Rayleigh/OH-LIPF measurements is presented in Fig. 2. For the generation of the two parallel laser sheets a Nd:YAG-laser (Spectra Physics GCR4) and a tunable KrF excimer laser (Lambda Physik EMG 150 TMSC) at \( \lambda = 248 \) nm were used. The wavelength of the Nd:YAG-laser was shifted with a harmonic generator to \( \lambda = 532 \) nm. To turn the polarization of the KrF excimer laser, a MgF2 plate was used in order to maximize the Rayleigh signal. Laser-induced predissociative fluorescence (LIPF) of the OH radical was excited by tuning the KrF excimer laser beam to the \( P_1(8) \) transition in the \([A^2\pi^+ ← X^2\pi(3,0)]\)-band system. It provides strong fluorescence of the OH radical due to the high spectral energy, although predissociation occurs [10]. The laser beam of the Nd:YAG laser was expanded with cylindrical lenses to the height of the beam of the excimer laser before passing the dichroic mirror. Both beams were focused by a cylindrical lens and formed two parallel imaging planes which were 0.4 mm apart for highly turbulent flames and 0.8 mm apart for flames of lower turbulence. The height of the laser sheets was about 25 mm. Their thickness was about 200 µm.

In order to avoid interference of the two light signals during the camera exposure the two lasers were triggered with a delay of 800 ns. This delay is longer than the time scales of fluorescence- and scattering effects, but it is shorter than the flame time and the shortest time scales of turbulence. The Rayleigh scattering at \( \lambda = 248 \) nm and the OH-fluorescence were collected to one side of the burner perpendicular to the incident laser sheets. The signals were separated with
Fig. 2. Optical arrangement for simultaneous dual-sheet-Rayleigh/OH-LIPF measurements.

a dichroic mirror. For the detection of the LIPF-signal an ICCD camera (La Vision Imager) was used in combination with an UG11 glass filter in order to discriminate between the OH signal around 298 nm and other wavelength signals. The Rayleigh-scattered light was isolated by an narrow-banded interference filter and detected by a second ICCD camera (La Vision Imager). A third ICCD camera (La Vision Dynamight) on the other side of the burner was used in combination with a narrow-banded interference filter for the detection of the Rayleigh signal at $\lambda = 532$ nm. The exposure time of all cameras was 300 ns in order to avoid background noise. The scaling of the images was 23.27 pixel/mm, thus a flame section of $22 \times 20$ mm could be visualized.

2.3. Image processing and determination of the flame front

Rayleigh and OH-LIPF images were matched and checked for distortion. Image smoothing based on convolution filtering has been applied twice to each instantaneous image to reduce the noise. The smoothing size was chosen to be significantly less than the smallest physical length scale (laminar flame thickness $\sim 0.3$ mm).

The gas temperature in the flame was calculated from the measured Rayleigh images as has been previously described by Dibble et al. [11]. The mean Rayleigh cross-section $\sigma_m$ was assumed to be constant over the flame front since changes of the cross-section for lean flames are no more than 3% between the unburned and burned gases.

The contour of the flame front was extracted from the temperature images. First, a temperature of $T = 800$ K was defined as the threshold temperature between the burned and unburned gases. At this temperature the maximum temperature gradient is found for flames with $\phi = 0.7$. Binary images were generated by setting all regions with $T \geq 800$ K to one and all regions with $T < 800$ K to zero. In the next step the binary image was scanned in order to mark all transitions from one to zero (and from zero to one). All other positions were set to zero. As a result all pixels belonging to the flame contour have a different value from zero. The contour was further conditioned on
the presence of an OH-LIPF signal, in order to distinguish between a reacting and a non-reacting front at the temperature threshold.

The dual-sheet technique [6,12] which is illustrated in Fig. 3 allows to measure quasi three-dimensional temperature gradients. The angle $\alpha$ denotes the inclination of the flame front with respect to the direction normal to the laser sheets. It can be calculated from the shift $A$, which measures the distance between the intersections with the two light sheet planes as $\alpha = \arctan(A/\delta z(y))$. Here $\delta z(y)$ is the distance between the parallel laser sheets. We will measure temperature profiles in the vicinity of the flame contour. Here we want to exclude cases where the flame surface is bent into the laser sheet from the third dimension. This limits the statistics to those parts of the flame contour where the angle $\alpha$ is smaller than a maximum value $\alpha_{\text{max}}$. By setting $\alpha_{\text{max}} = 18^\circ$ we allow for a 5% error in the measured distance.

3. Results and discussion

3.1. Operating conditions

Measurements were performed for lean ($\varphi = 0.7$) premixed methane/air flames. The ratio $v'/s_L$ was 3.5, 9.2, and 18.7. Here $v'$ is the turbulence intensity in main flow direction and $s_L$ the laminar burning velocity. $v'$ was measured using particle image velocimetry (PIV) as described in [9]. The three cases correspond to turbulent Karlovitz numbers $Ka$ varied of 0.98, 4.3, and 12.30 [13]. Since the thin reaction zones regime starts at $Ka = 1$ and ends at approximately $Ka = 100$ [14] the flame with the lowest intensity is on the borderline to the “corrugated flamelets” regime while the two others fall into the thin “reaction zones” regime.

3.2. Two-dimensional temperature- and OH-LIPF field

Examples of two-dimensional images of the two temperature fields, the OH image and the difference between the two temperature fields are shown in Fig. 4. Each row represents one flame realization of the highest turbulence case of $v'/s_L = 18.7$. The last column in this figure shows the difference between the first two temperature fields and thereby the shift of the flame front between the two images. The value $-1$ means, that the front has a negative inclination angle $\alpha$ to the normal direction, while the value $+1$ means, that the inclination angle $\alpha$ is positive. Sections with a broad red or blue color indicate a shift between the two flame fronts, resulting from a large inclination angle $\alpha$. These sections are therefore discarded. Selected sections of the flame front with an angle smaller than $\alpha_{\text{max}}$ are those where the difference between the temperature fields show up as a thin line.

The horizontal stripes in the temperature images in Fig. 4 are believed to result from slight shot to shot variations of the laser profile and from beam steering due to refraction index gradients in the flame. For an error estimate two vertical temperature profiles in the unburned mixture ($T = 290$ $K = \text{const}$.) are shown in Fig. 5. Obviously the signal to noise ratio in plane 1 with a maximum relative error of 15% is better than in plane 2, where the maximum relative error is found to be 22%. From the temperature profile in plane 2 a standard deviation of $s = 27$ $K$ was calculated including all single temperature measurements along the profile in Fig. 5. Since the mean temperature was 290 $K$, this results in a relative error for the single measurement of about 9%. Taking into account 1000 single temperature measurements the average error $s/\sqrt{1000}$ of the mean temperature is less than 1 $K$.

For temperatures at around 800 $K$ the standard deviation can be estimated to be $s = 72$ $K$ assuming a similar relative error of 9%. In this temperature range the average error of the mean temperature is then less than 3 $K$.

In order to illustrate the concept of iso-distance contours in evaluating temperature profiles an example of a single shot two-dimensional temperature image from plane 1 is shown in Fig. 6 for $v'/s_L = 18.7$. The instantaneous flame contour was determined from the temperature image and the corresponding OH image as described above. The thin black lines in front of the flame contour are iso-distance lines ($G = \text{const}$.) with respect to the contour ($G = 0$). Figure 7 presents two different temperature profiles evaluated along lines normal to the iso-distance lines. They show the preheat zones in front
Fig. 4. Selected temperature and OH-LIPF images ($\nu'_{\kappa_1} = 18.7$).
Fig. 5. Vertical temperature profiles in the unburned mixture \((T = 290 \text{ K} = \text{const.})\) for imaging planes 1 and 2 \((v'/s_L = 18.7)\).

Fig. 6. Temperature image with iso-distance contours \((v'/s_L = 18.7)\).

Fig. 7. Single temperature profiles \((v'/s_L = 18.7)\).

Fig. 8. Conditional averages of the temperature ahead of the preheat zone for different turbulence intensities.

of the reaction zones. The profiles called A and B correspond to the lines shown in Fig. 6. The temperature along line B shows a profile that is similar to that of a non-disturbed laminar premixed flame with only slight temperature variations upstream of the preheat zone and a steep temperature rise in the vicinity of the reaction zone. In contrast to that, profile A shows a significant temperature hump in front of the preheat zone. The maximum difference between the two temperature profiles is as large as 300 K at \(G = -1.5 \text{ mm}\) and therefore significantly larger than the maximum deviation of 65 K for plane 1 shown in Fig. 5. This suggests, that the observed temperature increase is physical, it may be attributed to a turbulent eddy that transports heat from other parts of the reaction zone to regions ahead of the preheat zone (cf. [14, Fig. 2.11]).

In order to calculate conditional mean temperatures averages were taken from flame realizations of 200 images and conditioned on the distance from the flame contour with the origin \(G = 0\) being fixed at \(T = 800 \text{ K}\). In addition to the requirement that the angle between the fronts in the two planes must be less than \(\alpha_{\text{max}}\) regions are excluded that belong to an opposite flame front or to an island in front of the main flame front. Such Islands could originate from a three-dimensional bending of the flame surface into the laser sheet. Temperature profiles from the preheat zones around these islands were also used, if the respective flame front was found to be approximately normal to the laser sheet. Using on the average more than 5 profiles per image the average number of data
probability density function of the temperature ahead of the preheat zone at $G = -1.5$ mm. At each distance from the flame front corresponds to at least 1000 single temperature measurements.

Figure 8 shows averaged temperature profiles in the preheat zone for three different flames. It is seen from Fig. 8 that at a distance of 1.5 mm from the flame contour the increase of the average temperature with respect to 290 K is larger for the high intensity flame of $v'/s_L = 18.7$, where it is approximately 20 K, than in the intermediate intensity flame of $v'/s_L = 9.2$, where it is half that value at the same distance. For the case of $v'/s_L = 3.5$, corresponding with $Ka = 0.92$ to the flame at the borderline between the “corrugated flamelets” and the “thin reaction zones” regime the increase is only 5 K and therefore less significant. For larger distances from the flame contour fluctuations of 3 K around the mean temperature profile are observed. This is of the order of the error estimated above. Maximum local temperatures in the preheat zone for $v'/s_L = 18.7$ were as high as 700 K, but upon averaging the mean temperature profiles are increased in this region by only 20 K.

Probability density functions $P(T)$ of temperature at $G = -1.5$ mm are shown for $v'/s_L = 18.7$ and $v'/s_L = 3.5$ in Fig. 9. For the low turbulence intensity flame the pdf is nearly symmetric around the value of $T = 290$ K with a rms of 30 K which roughly corresponds to the standard deviation of 27 K quoted above. For the high intensity case, however, the pdf is strongly skewed towards higher temperatures extending up to temperatures of 700 K.

4. Conclusions

Temperatures of up to 700 K were measured upstream of the preheat zone in a premixed turbulent flame. This confirms the hypothesis of turbulent transport ahead of the preheat zone for flames that lie in the “thin reaction zones” regime. Such fluctuations are less prominent in a flame at the borderline to the “corrugated flamelets” regime. Conditional averages with respect to the distance from the flame contour were calculated. The resulting mean temperature profiles show a much smaller temperature rise since only relatively few high temperature events are observed.

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