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Flame Surface Density Measurements with PLIF in an SI Engine

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ABSTRACT

A technique to determine flame surface density in a spark-ignition engine from planar laser-induced fluorescence (PLIF) images of the flame front is presented. To resolve the flame surface density in a three-dimensional fully turbulent flow field from two-dimensional images, the direction cosine (angle of intersection between the PLIF laser sheet and the normal to the flame front) must be known. To determine the direction cosine, images from orthogonal planes in the engine have been used to resolve the mean orientation angle along the line of intersection of the planes. The effect of engine speed and fuel-air equivalence ratio on the flame surface density are investigated. The flame surface density (Σ) profiles and orientation angle are presented as a function of the progress variable. The direction cosines are almost identical in both orthogonal planes, indicating the isotropic nature of the flame front. As the engine speed is reduced, the direction cosine increases slightly. The Bray-Moss-Libby model coefficients obtained at maximum flame surface density in this work agree with previously reported experimental and DNS (direct numerical simulation) results and display an inverse correlation with the integral length scale when normalized by the laminar flame thickness.

INTRODUCTION

Development of spark ignition (SI) engines requires an advanced knowledge of the physico-chemical processes occurring within the cylinder during combustion. The structure of the turbulent premixed flame in SI engines controls all combustion events, and thus is of fundamental importance in understanding the combustion in internal combustion engines and in developing relevant combustion models. Numerous studies have attempted to relate the structure of the flame front in engines to the turbulence [1,2,3]. One of the promising approaches to modeling combustion in internal combustion engines is the laminar flamelet approximation [4,5,6], which suggests that in the turbulent propagation phase of a spark ignition engine the flame front can be treated as a sheet propagating

at a locally laminar velocity [7,8,9]. These thin flamelets are stretched and distorted by turbulence but they retain their laminar internal structure [8]. Thus, the major advantage of the laminar flamelets approach is that the chemical kinetics are decoupled from the formulation of the turbulent flow field. Within the laminar flamelets regime, the mean rate of conversion of reactants into products per unit volume, $\langle w \rangle$, can be expressed as [8]

$$\langle w \rangle = \rho_r S_L^0 l_0 \Sigma \quad (1)$$

where ρ_r is the density of reactants, S_L^0 is the normal laminar burning velocity, l_0 is a flamelet stretch and curvature correction term, Σ is the flamelet surface density defined as the mean flame surface area per unit volume, and $\langle \rangle$ indicates a mean value.

The objective of this work is to evaluate the flame surface density in an optically accessed engine. According to the flamelet assumption, the scalar field of a spark ignition engine can be expressed as a Boolean variable which is 0 in the reactants and 1 in the products. Thus the presence of burned gases is indicated when the instantaneous progress variable $c(x,y,z)$ is equal to 1. The step function 0→1 of c indicates the location where the reaction takes place, and thus the position of the instantaneous flame front. This step function represents a three-dimensional surface which is not easily described, and which is experimentally difficult to investigate.

Experimental measurements of Σ in atmospheric V-flames [10,11] and Bunsen flames [12,13] have been reported recently. In atmospheric flames, Σ can be determined by coupling one-point Rayleigh scattering measurements with the BML model [12], but this approach cannot be used for flames in spark-ignition engines. The structure of premixed turbulent flames has been investigated with planar visualization techniques [11], in which the step function 0→1 is observed as a curve in two dimensions. In a three-dimensional flow field, the orientation of the imaging plane to the flame front is not determined, and thus the measurement of Σ is underestimated as it is reduced to a length density. An innovative approach, one that is applicable to engine flames, consists of extracting Σ by data processing of flame front images from orthogonal planes in the combustion chamber, such that the flame front

orientation is determined from the mean crossing angle along the line of intersection of the planes.

In this study, the flame front visualization has been performed in orthogonal planes using laser-induced fluorescence of biacetyl, which is present in the unburned gases. Flame front statistics of the flames at different engine speeds and fuel/air equivalence ratios are compared and the implications are discussed. This intention of this study to provide experimental data under realistic conditions which links the turbulent flame structure to the laminar flamelet model, as required by the engine modelers.

Figure 1: Schematic of optically accessed single cylinder engine.

EXPERIMENTAL METHODOLOGY

SPARK-IGNITED ENGINE - The GSM-IFP (Groupement Scientifique Moteur - Institut Français du Pétrole) optically accessed single cylinder engine, which has been well described elsewhere [14,15,16], was used for this study. An optical piston was bolted over the piston of a production engine and slid in an elongated cylinder. An upper set of rings made of graphite allowed oil-free operation and hence prevented fouling of the optical access ports. The combustion chamber provided optical access through four fused silica side windows and an extended piston with a fused silica top (Fig. 1). The extended piston allowed a fixed, 45° inclined mirror to be placed below the combustion chamber. This mirror permitted visualization of the combustion chamber from outside the engine through the piston top. The combustion chamber had a cylindrical shape. The spark was located in the

Table 1: Geometrical characteristics of the single cylinder engine

Displacement	476 cm ³
Bore	86 mm
Stroke	82 mm
Compression ratio	7.7
Rod/Half stroke ratio	3.341

center of the chamber by extended electrodes. See Table 1 for a summary of the geometrical characteristics of the engine.

Experiments were performed with propane at fuel/air equivalence ratios (Φ) of 0.75 and 0.9. The engine speed was kept constant and equal to 600 rpm or 1200 rpm, the volumetric efficiency for all conditions was 0.6, and the spark advance was 25° CA. Enhanced swirl was produced by modifying the single intake valve with a 90° shroud, which caused the intake flow to circulate around the cylinder axis (Fig. 2). In a previous study which included LDV measurements [16] it was shown that with the 90° shroud the center of rotation of the mean flow field is close to the center of the chamber and the velocity profile is stationary between 50° BTDC and 15° BTDC. It was also shown that the high frequency turbulence intensity was relatively homogeneous throughout the chamber. The 90° shroud configuration was chosen in order to minimize cycle-to-cycle variation of the flame barycenter. This maximized the probability of viewing the flame front at the chosen crank angle from both viewing directions, orthogonal (xz plane) and parallel (xy plane) to the cylinder axis. The turbulence intensities (measured at the same crank angles as the image acquisition) were about 0.4.

Figure 2: Schematic of the swirl motion in the combustion chamber. The semicircle on the intake valve (I) indicates the location of the 90° shroud. The exhaust valve is denoted by E.

Table 2: Summary of Experimental Conditions^a

Data Set	Equivalence Ratio (Φ)	Engine speed (rpm)	Image angle (after spark)	$\bar{u}$ (m/s)	u' (m/s)	S_L (m/s)	$u'S/L$
R90-600	0.9	600	7° CA	1	0.4	1.6	0.25
R90-1200	0.9	1200	14° CA	2	0.8	1.55	0.5
R75-600	0.75	600	6° CA	1	0.4	0.95	0.4
R75-1200	0.75	1200	12° CA	2	0.8	0.96	0.82

^a CA = crank angle; $\bar{u}$ = mean velocity; u' = rms velocity fluctuation; Φ = fuel/air equivalence ratio; S_L = laminar burning velocity.

and 0.8 m/s for engine speeds of 600 and 1200 rpm respectively, resulting in u'/S_L ranging from 0.25 to 0.82, as depicted in Table 2. The turbulence length scale (Λ) was evaluated to be ~ 1 mm in this engine [17]. Although the measurements of Λ were made under motoring conditions, it has been shown that there is no discernible difference in Λ between firing and motoring conditions [18].

PLANAR LASER-INDUCED FLUORESCENCE (PLIF) - For these experiments, the fresh mixture was seeded with a fluorescent tracer, biacetyl ($\text{CH}_3\text{COCOCH}_3$) which absorbs UV radiation over a broad range of wavelengths and fluoresces in the blue-green band (450-510 nm) of the visible spectrum. Biacetyl is a liquid with a boiling point of 88°C, making it an ideal marker for visualizing the fresh gas boundary. Its fluorescence decreases rapidly with the thermal gradient through the flame front and it is consumed in the reaction zone, so that there is no signal in the products.

To generate the required orthogonal images, two experiments were performed, one with a horizontal laser sheet and the other with a vertical laser sheet. A frequency tripler

Nd:YAG laser (355 nm) producing 0.1 J/pulse, synchronized with the engine at 10 Hz, was used as the excitation light source. A laser sheet is formed with cylindrical optics and is focused into the chamber with a spherical lens. In the combustion chamber the laser sheet has a width of 23 mm and its median thickness is about 0.5 mm (0.4 mm in the center and 0.7 mm at the quartz windows).

For the horizontal visualization, the laser sheet was introduced through a side window and the image was

Figure 3: Experimental setup for visualization in the horizontal direction. The image is viewed through the piston head via the in-piston mirror.

Figure 4: Experimental setup for visualization in the vertical direction. The image is viewed through a window in the cylinder wall.

Figure 5: Schematic showing relative positions of the two object planes and the electrode. Projection of the spark location is indicated on both the xy and xz planes. Shaded areas indicate approximate regions imaged by PLIF.

visualized through the piston top window via the inclined mirror (Fig. 3). For the vertical visualization, the laser sheet was introduced through one side window and the fluorescence observed through an orthogonal side window (Fig. 4). The fluorescence was collected at 8 bits (256 intensity levels) by an intensified CCD camera fitted with a conventional 80 mm Nikon camera lens. An optical interference filter was placed before the lens to block the scattered laser light while transmitting the fluorescence the 460-500 nm band.

The imaging planes were selected to maximize the probability of entire flame front being observed from both directions through the limited access windows. The horizontal laser sheet was located 2 mm below the electrodes and the vertical laser sheet 4 mm in front of them, as shown in Figure 5. The crank angles (Table 2) were selected so that for all conditions, the images were acquired at the same delay (1.9 ms) after the spark, where the flame front is turbulent, yet still within the field-of-view. The flame front is not in the kernel growth phase, but is turbulent and developed at 6-7° CA (600 rpm) and 12-14° CA (1200 rpm) after ignition [14].

The acquired images, were 29×23 mm for the horizontal orientation ($81 \mu\text{m}/\text{pixel}$) and 25.4×5.9 mm for the vertical orientation ($71.4 \mu\text{m}/\text{pixel}$). For each of the four engine conditions 700 images were acquired for each orientation. The images were corrected for variation in the incident laser power, background noise, local variation in laser intensity, and camera sensitivity. Additionally, the pressure histories for each cycle were recorded with the images. Unsatisfactory images due to poor synchronization between the engine, laser, and intensifier, and to higher intensity near the spark plug (due to deposits of biacetyl), were automatically eliminated. Visual inspection of images resulted in further rejections.

Examples of the uncorrected images, shown in Figs. 6-9 for both engine views and all four engine conditions, demonstrate the shot-to-shot variation in location and structure of the flames.

IMAGE ANALYSIS - The images were systematically binarized by setting a threshold of 125 after scaling the images from 0 to 255. The images required the application of an inverse operator to the binary images, since the high intensity areas represented unburned mixture. Pixel values of 1 indicate a progress variable equal to 1 (burnt gases)

and pixel values of 0 indicate a progress variable of 0 (fresh mixture). The resulting image represents the instantaneous map of the progress variable. By averaging over the number of images selected (typically 400) one determines the mean progress variable map. Individual flame contours (1 pixel wide) were detected from the instantaneous maps of the fresh/burnt gases. Averaging the flame contours provides a map of the probability of presence of the flame front.

Convolution of a Frei-Chen 3×3 matrix edge detection operator [19] with each pixel in the binary image provides both the magnitude of the spatial gradient relative to pixel size (length per unit area) and the orientation of the flame front boundary. The Frei-Chen edge detector is weighted such that the local edge orientation (horizontal, vertical, or diagonal) does not affect the magnitude of the gradient.

To evaluate Σ , the two-dimensional flame surface density, Σ'_{xy} , needs to be corrected by the orientation of the normal to the individual flame front, θ_{xz} , observed in the orthogonal plane. The need for this has been demonstrated in a comparison of experimental two-dimensional data with three-dimensional direct numerical simulations [20] in which there was a significant bias, in the order of 10%, in the purely planar results. Σ'_{xy} , which is the length of intersection between the flame front surface and plane xy , per unit area, was calculated from the product of the spatial gradient $|\nabla c|_{xy}$ with the individual contour map, $\delta_{xy}(c - c_f)$.

Ideally, the horizontal and vertical images would be acquired simultaneously so that the effect of the flame front orientation on surface density could be corrected on an image-by-image basis. However, this was not possible because the fluorescence from the laser sheet in the other direction would cause interference with the signal, especially in the region of interest, the line of intersection between the two planes. Slightly asynchronous laser sheets could solve this problem, although the biacetyl fluorescence lifetime would have to be much less than the shortest turbulence time scales. Thus, averaging of the components was selected as a compromise. This presents a significant advance in the measurement of flame surface density in practical flames. We assumed

$$\Sigma = \langle \Sigma' \rangle = \frac{\langle \Sigma'_{xy} \rangle}{\langle \cos \theta_{xz} \rangle} = \frac{\langle \Sigma'_{xy} \rangle}{\langle \cos \theta_{xz} \rangle} = \frac{\langle \Sigma'_{xy} \rangle}{\cos \theta_{xz}} \quad (2)$$

which should be valid for moderate turbulence intensities.

$\Sigma_{xy} = \langle \Sigma'_{xy} \rangle = \langle |\nabla c|_{xy} \cdot \delta_{xy}(c - c_f) \rangle$ and $\langle \theta_{xz} \rangle$ were then determined over the number of images. Although the flame contour is measured over its full extent within the field-of-view, the flame surface density is only determined along the line of intersection between the two laser sheets. The direction cosine ($\cos \theta_{xz}$) relates the length-per-unit-area data to area-per-unit-volume required for a 3D measurement. $\langle \theta_{xz} \rangle$ was resolved on the line of intersection between the xy and xz planes and $\Sigma = \langle |\nabla c|_{xy} \cdot \delta_{xy}(c - c_f) \rangle / \cos \theta_{xz}$. In the orthogonal plane, $\Sigma = \langle |\nabla c|_{xz} \cdot \delta_{xz}(c - c_f) \rangle / \cos \theta_{xz}$, where the length of intersection per unit area was calculated in plane xz , and the orientation angle was resolved in plane xy .

Figure 6: Flame images obtained by planar laser-induced fluorescence. The scale indicates intensity levels of the uncorrected images.

Top: Data set R90-600, $\Phi = 0.9$, 600 rpm, horizontal view
 Bottom: Data set R90-600, $\Phi = 0.9$, 600 rpm, vertical view

Figure 7: Flame images obtained by planar laser-induced fluorescence. The scale indicates intensity levels of the uncorrected images.

Top: Data set R90-1200, $\Phi = 0.9$, 1200 rpm, horizontal view
 Bottom: Data set R90-1200, $\Phi = 0.9$, 1200 rpm, vertical view

Figure 8: Flame images obtained by planar laser-induced fluorescence. The scale indicates intensity levels of the uncorrected images.

Top: Data set R75-600, $\Phi = 0.75$, 600 rpm, horizontal view

Bottom: Data set R75-600, $\Phi = 0.75$, 600 rpm, vertical view

Figure 9: Flame images obtained by planar laser-induced fluorescence. The scale indicates intensity levels of the uncorrected images.

Top: Data set R75-1200, $\Phi = 0.75$, 1200 rpm, horizontal view

Bottom: Data set R75-1200, $\Phi = 0.75$, 1200 rpm, vertical view

Table 3. Results^b

Data Set	Number of images (hor/ver)	Σ_{max} (mm ⁻¹)	$g/\sigma_y L_y$ (mm ⁻¹)	σ_y (hor/ver)	L (mm)	K	$\langle c \rangle_{max}$ (hor/ver)
R90-600	435 / 500	0.36	1.45	0.77 / 0.78	1	0.07	1 / 1
R90-1200	499 / 265	0.34	1.36	0.70 / 0.69	1	--	1 / 1
R75-600	338 / 559	0.38	1.50	0.75 / 0.81	1	0.11	0.5 / 1
R75-1200	381 / 495	0.38	1.51	-- / 0.68	1	0.08	0.8 / 1

^b Σ_{max} = maximum flame surface density; g = constant; σ_y = orientation factor; L_y = characteristic flame wrinkling length; hor = horizontal; ver = vertical; Λ = integral length scale; K = constant; $\langle c \rangle_{max}$ = largest value of progress variable in field of view.

RESULTS AND DISCUSSION

PROGRESS VARIABLE - The evolution of the progress variable along the intersection line of the two laser sheets in the engine is shown in Fig. 10. In the engine $\langle c \rangle_{max}$ (the maximum value of $\langle c \rangle$) does not always reach 1. For an equivalence ratio of 0.75 at 600 rpm, the flame diameter is so small compared to the fluctuations of the barycenter that $\langle c \rangle_{max}$ only reaches 0.5 in the horizontal plane.

As S_L or u' increases (Table 2) the flame becomes larger and the value of $\langle c \rangle_{max}$ (Fig. 10) increases until 1 is reached, where spatial fluctuations are smaller than the size of the flame. In the horizontal plane $\langle c \rangle_{max}$ is smaller than in the vertical plane (Table 3), indicating that the flame center is above or below the horizontal plane, or that the vertical fluctuations are dominant.

The probability of there being a flamelet surface in a given pixel, $P(c)$, was found to vary linearly with $\langle c \rangle(1 - \langle c \rangle)$.

Figure 10: Mean progress variable, $\langle c \rangle$, location as measured from vertical images in the engine, on line of intersection with horizontal images, for four conditions. The distance from the projection of the spark location onto the xz plane is indicated by x .

The slope of this relationship is reported as $K = P(c)/[\langle c \rangle(1 - \langle c \rangle)]$ in Table 3.

FLAME SURFACE DENSITY - The Σ profile, including individual data points, for the engine condition at $\Phi = 0.9$ and 600 rpm is shown on Fig. 11 as a function of $\langle c \rangle$. The mean two-dimensional flame surface density, Σ_{xy} , and the mean orientation angles which produced the Σ profiles are also shown in Fig. 11. The Σ_{xy} profile is symmetric about $\langle c \rangle = 0.5$, while the orientation angles slowly increase with $\langle c \rangle$. This

Figure 11: Mean length of flame front per unit of area, Σ_{xy} , orientation angle, $\langle \theta \rangle$, and flame surface density, Σ , as a function of $\langle c \rangle$ for data represented in Fig. 6 in the vertical plane of the engine, along the line of intersection with the horizontal plane. Lines shown are Lowess smoothed fits to the data.

Figure 12: Spatial distribution across the flame brush of flame surface density (Σ) results for all data sets as a function of $\langle c \rangle$. Lowess smoothed fits to the data along the line of intersection are shown.

results in the Σ profile for the engine flame being skewed towards the burned gases zone. The orientation angle profiles for the engine flame are identical in both planes, indicating the isotropic behavior of the flame front. This has been observed for all four engine conditions. One can conclude that the second experimental set-up for the engine was not necessary,

Figure 13: Profiles of $\Sigma/[\langle c \rangle(1 - \langle c \rangle)]$ for all data sets as a function of $\langle c \rangle$. Lowess smoothed fits to the data along the line of intersection are shown.

and thus the method is not limited to the intersection line but can be extended, possibly to the full two-dimensional image. The mean direction cosines ($\cos\langle\theta\rangle$) of the flame front had a typical value of 0.69 for the engine flames at 1200 rpm, and higher values (~ 0.80) at an engine speed of 600 rpm. This is due to the shorter crank-angle delay between ignition and image acquisition at 600 rpm, where the ignition phase of combustion is not complete.

The profiles in Fig. 11 are typical of those found for the other flames, as shown on Fig. 12 (individual points are not shown for clarity). For the engine flames which do not reach $\langle c \rangle = 1$, the profiles are truncated. As one can observe, Σ_{max} (the maximum value of Σ) increases as $\langle c \rangle_{max}$ decreases. The shapes of the profiles are comparable to those found by Veynante et al. [11] in a two-dimensional V-flame and by Deschamps et al. [12] in a Bunsen flame but under different turbulence conditions. Comparison of maximum values of Σ will be discussed further.

The Bray-Moss-Libby model (BML) [21,22] for Σ is a simple algebraic closure model based on the spatial distribution of flame crossings along a contour of mean progress variable, $\langle c \rangle$, and is given by

$$\Sigma = \frac{g\langle c \rangle(1 - \langle c \rangle)}{\sigma_y L_y} \quad (3)$$

where g is a constant of the order unity, σ_y is a mean direction cosine, and L_y is a characteristic length related to flame wrinkling. The BML coefficient $g/(\sigma_y L_y) = \Sigma/[\langle c \rangle(1 - \langle c \rangle)]$ is shown in Fig. 13 to be relatively constant for the range from $\langle c \rangle = 0.2$ to 0.8 for the engine flames. Beyond this range, for $\langle c \rangle(1 - \langle c \rangle) < 0.16$, the probability of presence of the flame front is very low. This induced a large statistical error on the

Figure 14: Linear fits for all data sets of the flame surface density to $\langle c \rangle(1 - \langle c \rangle)$, along the line of intersection.

measurement of Σ_{xy} and mean direction cosine. However, one should not conclude that the BML model is not applicable to these regions. Analysis of a much larger number of images is required to deduce meaningful results in these regions of the flame brush. Assuming Σ_{max} is near $\langle c \rangle = 0.5$, one can estimate the BML coefficient as being equal to $4\Sigma_{max}$. The profiles of Σ as a function of $\langle c \rangle(1-\langle c \rangle)$ are linear, as shown in Fig. 14, and the slopes are reported as $g/(\sigma_y L_y)$ in Table 3.

It is interesting to note that Σ_{max} has little variation over the range of u'/S_L (0.25 to 0.82) investigated here. This is consistent with Deschamps et al. [12], who found Σ_{max} was constant with u'/S_L over the range 0.3 to 3.0. Deschamps et al. [12] also found that Σ_{max} decreased by a factor of 1.6 as Λ was increased from 3.1 to 4.7 mm while Φ was kept constant. The integral length scale appears to be a key parameter in determining the maximum flame surface density.

Figure 15 shows values of $g/(\sigma_y L_y)$ at Σ_{max} available from the literature [10,11,12,13] plotted along with our results as a function of Λ . There is a clear trend of $g/(\sigma_y L_y)$ decreasing as Λ increases. The effect of another parameter, the bulk strain rate, has been studied in a counterflow premixed flame [23]. At high strain rates $g/(\sigma_y L_y)$ was much greater than one would expect from the trend with Λ and thus the strain rate may be a more dominant parameter than Λ .

As can be observed from Fig. 15, two groups of flames are evident. There may be another key parameter related to the BML coefficient. At similar Λ , propane/air flames [11,13, this work] produce larger values for $g/(\sigma_y L_y)$ than ethylene/air [10] or methane/air [12] flames. The flame surface density for

Figure 15: Variation of $g/(\sigma_y L_y)$ with the integral length scale (Λ) at the location of maximum flame surface density. The line of Trounev and Poinso is from DNS modeling.

a propane/air flame at $\Phi = 0.7$ [11] is twice as large as that measured in a methane/air flame at $\Phi = 0.8$ [12]. Direct numerical simulation (DNS) results [24] are also shown in Fig. 15, for $Le = 1$, where Le is the Lewis number. For this simulation, Σ and Λ were made nondimensional by the laminar flame thickness, δ_L . The datum for Σ_{max} relating $g/(\sigma_y L_y)$ to Λ thus appears as a curve (Fig. 15) which showed the same trend as the experimental results [25]. The results for the range $Le = 0.8$ to 1.2 were very close to the curve represented in the graph. The DNS study found that the predominant effect of Le was on δ_T , not on Σ_{max} . Also, the values of the orientation factors found in DNS (0.7-0.8) [24] and in a Bunsen burner (0.7) [13] are the same as found in the engine for $0.1 < \langle c \rangle < 0.9$, where the results are statistically significant. The orientation factor is primarily determined by the small scales of turbulence, which are those most relevant for DNS.

For the experimental data, $g/(\sigma_y L_y)$ and Λ were made nondimensional by δ_L , as shown in Fig. 16. The best fit to the experimental data is represented by

$$g/(\delta_y L_y) = 7 \Lambda^{-1.29} \delta_L^{0.29} \quad (4)$$

The accuracy of the fitted terms in this relation is constrained by the limited number of flame surface density results, and the relation is valid only for the range of data presented. Nonetheless, observation of the plot in Fig. 16

Figure 16: Variation of $g/(\sigma_y L_y)$ with the integral length scale (Λ) at the location of maximum flame surface density, made nondimensional by the laminar flame thickness $\delta_L = \alpha/S_L$ (where α is the thermal diffusivity of the unburned gas), for the experimental data from Fig. 15. The solid line is a best fit to the experimental data.

emphatically confirms the influence of Λ on the BML coefficient, as the two groups of flames noted in Fig. 15 now coincide.

SUMMARY AND CONCLUSIONS

Surface densities of turbulent three-dimensional premixed flames in a spark-ignition engine determined from planar laser-induced fluorescence images of the flame front are reported. Due to the three-dimensional nature of these flowfields, the orientation of the flame front in the plane orthogonal to the visualization plane was necessary to determine the flame surface density. Thus in the engine, a second experiment was required to measure the mean orientation factor. Then, a three-dimensional flame surface density could be obtained along the line of intersection of the planes in the engine, passing 2 mm under and 4 mm in front of the spark location. Profiles of the mean progress variable, mean gradient and the mean orientation of the flame fronts have been used to determine the flame surface density as a function of the mean progress variable for the engine flames. Our results conclude that:

- A typical direction cosine value of 0.7 has been found for the engine flames at 1200 rpm. Slightly higher values have been obtained at the lower engine speed. The similar values of the direction cosines for the flame fronts in both orthogonal planes show the isotropic behavior for the engine flames investigated.
- Due to typical cyclic variations of the barycenter, the progress variable does not always reach unity, and thus it is comparable to the probability of presence of the burned gas. The probability of presence of the flame front varies linearly with $\langle c \rangle (1 - \langle c \rangle)$ for all the experimental conditions studied.
- For the range of u'/S_L investigated in this work, 0.25 to 0.82, the flame surface density has not shown much variation.
- The BML model provides a good trend for the flame surface density. The BML coefficient is constant over the range of progress variable where the probability of presence of the flame front is statistically significant. The BML coefficients at maximum surface density obtained in this work agree with the previously reported results and display an inverse power law dependence on the integral length scale when normalized by the laminar flame thickness. Results from DNS studies are in qualitative agreement with the present work.

NOMENCLATURE

a	thermal diffusivity
$\delta(c-c_f)$	instantaneous flame front position
δ_L	laminar flame thickness
δ_T	thickness of turbulent flame brush
ρ_r	density of reactants
σ_y	mean direction cosine
θ	individual flame front orientation angle
Λ	turbulence length scale

Φ	fuel/air equivalence ratio
Σ	mean flame surface density
Σ'	instantaneous flame surface density
Σ'_{xy}	instantaneous two-dimensional flame surface density
Σ_{xy}	mean two-dimensional flame surface density
Σ_{max}	maximum mean flame surface density
$\langle \rangle$	indicate a mean value
c	instantaneous progress variable
$\langle c \rangle$	mean progress variable
$\langle c \rangle_{max}$	maximum value of the mean progress variable
$\langle c \rangle (1 - \langle c \rangle)$	probability of presence of the flame front
∇c	spatial flame front gradient
g	constant (of the order unity)
$g/(\sigma_y L_y)$	BML (Bray-Moss-Libby) coefficient
l_o	flamelet stretch and curvature correction
K	constant
Le	Lewis number
L_y	characteristic length related to flame wrinkling
$P(c)$	probability of there being a flamelet surface in a given pixel
S_{L_o}	laminar burning velocity
S_L	normal laminar burning velocity
u	mean velocity
u'	turbulence intensity
$\langle w \rangle$	mean rate of conversion of reactants into products per unit volume
x, y, z	Cartesian coordinates

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