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ABSTRACT

A high speed tomographic technique is used to quantify the spatial scalar structure of stagnation flow stabilized premixed flames. Studies are performed on CH_4/Air and C_2H_4/Air turbulent flames with equivalence ratios ranging from 0.75 to 1.0. The gas velocity at the nozzle exit is 5 m/s, the turbulence intensity is 7%, the integral length scale 3 mm and hence the turbulence Reynolds number is 70. The light source is a copper vapor laser which produces 20 ns, 5 mJ pulses at a 4 KHz repetition rate. Cylindrical lenses transform the 38 mm circular laser beam to a sheet 50 mm high and 0.6 mm thick. A high speed Fastax camera is used to record the tomographic images formed by the scattering of light from oil droplets seeded in the reactant flow which disappear at the flame front. The films are digitized and the wrinkled flame front extracted from the images by a thresholding technique. The integral scalar length scales proposed in the model of Bray-Champion-Libby are deduced from the tomographic movies by numerically constructing flame crossing sequences from the burned and unburned probability density functions of flame crossing length and performing a spectral analysis of these sequences. The integral scalar length scales are found to be similar to the integral length scales of the incident turbulence. A fractal analysis was performed on the flame boundaries to characterize the flame geometry and provide from an estimate of the flame surface area a measure of the turbulent burning rate. The flame area increase is found to underestimate the turbulent burning velocity when compared with direct measurements of the flow velocity at the cold boundary.

Introduction

In most premixed laboratory burners and practical combustion devices, the flame sheet or laminar flamelet model provides a good physical description of the flame/flowfield interaction of the premixed turbulent flames. The scalar field can then be specified by consideration of the burned and unburned states only and a convenient means of chemical closure is obtained. The models of Bray-Moss-Libby (BML) (e.g. [1]) and Bray-Champion-Libby (BCL) [2] make use of this chemical closure such that the reaction rate is directly related to the scalar length scales. In the BCL model, the scalar length scale, $\hat{L}$, is expressed in terms of the flame crossing frequencies, ν, and a convection speed u_n. The principle is that at a point within the flame brush the flame crossing frequency is proportional to the length scales of the flame wrinkles which can be estimated using Taylor's hypothesis. In a previous study [3] we have demonstrated that the burning rate of rod-stabilized v-flames and large Bunsen flames can be determined from ν measured at points along mean flowlines through the flame brush. However, for situations where Taylor's hypothesis does not apply, such as stagnation flow stabilized flames[4], direct measurement of the scalar length scales is necessary.

The development of the BCL model for the stagnation flow stabilized flame configuration is currently the main emphasis of their theoretical work. The unique features of the stagnation point flowfield makes possible the consideration of the two-dimensional flowfield in BCL rather than being limited to a one-dimensional description of the flame zone as in previous models. In the earlier BCL model, the reaction rate for the stagnation flow stabilized flames is also based on the flame crossing frequency, and to transform the inverse time scale, ν, into a length scale, the RMS fluctuation of the incident turbulence was used. As shown by our previous study, however, it was not possible to transform the flame crossing frequency into a meaningful scalar length scale [3] because of the lack of a mean convection velocity tangential to the flame brush,

In a more recent model [5], the reaction rate, $\bar{w}$, i.e. the rate of creation of products at points within the flame zone, is expressed in terms of a inverse length, $\nu_{\bar{c}}$, representing the number of crossings per unit distance along a mean reaction progress variable, $\bar{c}$, contour.

$$\bar{w} = w_c \, \nu_{\bar{c}} \tag{1}$$

$\nu_{\bar{c}}$ is modeled as

$$\nu_{\bar{c}} = \frac{g\bar{c}(1-\bar{c})}{\hat{L}_{\bar{c}}} \tag{2}$$

where g =2 for an exponential distribution of crossing lengths and g = 1 for a gamma-two distribution [8]. The quantity $\hat{L}_{\bar{c}}$ can be interpreted to represent the normalized integral length scale of the distance between flame crossing along a $\bar{c}$ contour. In the case of unstrained flame fronts the average reaction rate occurring at each flame crossing, w_c, is related to the laminar value by the direct cosine , σ_c, of the angle between the $\bar{c}$ surface and the normal to the instantaneous flame surface

$$w_c = \frac{1}{|\sigma_c|} \rho_r S_L \tag{3}$$

where S_L is the unstrained laminar burning speed.

For flames with high Damköhler numbers, classified as wrinkled laminar flames, the turbulent burning rate, $\rho_r S_T$, can be related directly to the increase in flame area A_L. The turbulent burning speed S_T is defined by the mass flow rate $\dot{m}$ through a streamtube

$$\dot{m} = \rho_r S_L A_L = \rho_r S_T A_T \tag{4}$$

where A_T is the effective cross sectional area of the streamtube. The ratio of the turbulent/laminar burning rate $\overline{W}$ is

$$\overline{W} = \frac{\rho_r S_T}{\rho_r S_L} = \frac{A_L}{A_T} \tag{5}$$

The increase in burning rate due to turbulence can, therefore, be deduced by estimating the flame area if it is assumed that the laminar burning velocity does not vary significantly from its unstrained value. The objective of this paper is to characterize the spatial structure of premixed turbulent stagnation flow flames, in terms of $L_{\bar{c}}$, $\nu_{\bar{c}}$ and g and to determine the increase in flame area from a fractal analysis.

Experimental details

Since the scalar fields of these premixed flames consist essentially of burned and the unburned states separated by a thin flame sheet, the scalar properties, such as temperature or density, can be determined by the relatively simple diagnostic technique of measuring the intensity of light scattered from micron sized oil droplets which evaporate at the flame sheet [7,8]. This seeding technique has been used extensively to measure the reaction progress variable $\bar{c}$ and conditional velocity statistics. To obtain tomographic images of the flame zone, the oil droplets are illuminated by a laser sheet and the Mie scattering in the direction normal to the laser sheet is photographed. The flame sheet is marked as the interface between light (cold reactants with seed particles) and dark (hot products without particles) regions on the tomographic record.

Tomographic studies were conducted on a range of stagnation point premixed turbulent flames (Table I). In all cases the Damköhler numbers based on the chemical reaction time and the integral time scale of the reactant stream are much greater than one. Figure (1) shows a schematic of the experimental setup. A uniform axisymmetric flow of premixed fuel/air mixture at 5 m/s is provided by a 50 mm diameter nozzle with a coflowing air stream at the same velocity which shields the inner flow from interaction with the room air. The reactant flow turbulence (7%), generated by a perforated plate placed 50 mm upstream of the burner nozzle, has an integral length scale of 3 mm and the turbulent Reynolds number, based on these values, is 70 in all cases. The burner configuration has been described in detail elsewhere [4]. The stagnation plate was placed 100 mm downstream of the nozzle exit.

Table I

Flame No.	Fuel	ϕ	S_L	Da	ρ_u/ρ_b	δ_T	$\bar{\nu}_{\bar{c}}$	$\bar{L}_{\bar{c}}$	$\overline{Cos\theta}$	I
			(m/s)		(mm)		(100/mm)	(mm)		
S1	CH_4	1	0.43	105	7.54	9.17	9.5	3.0	0.69	0.9
S9	C_2H_4	1	0.76	350	7.84	11.39	10.8	3.2	0.63	1.2
S10	C_2H_4	0.85	0.64	249	7.45	13.89	9.9	3.3	0.68	1.1
S11	C_2H_4	0.75	0.51	141	6.99	10.09	9.2	2.9	0.69	0.8

The light source was a Metalaser copper vapor laser which affords significant advantages for laser sheet imaging. It delivers 5 mJ per pulse with a 20-30 nsecs pulse width but is also capable of repetition rates up to 10 KHz. Hence it is possible, not only to resolve the instantaneous flame shape but also to follow the evolution of the flame with time. By the use of cylindrical lenses, the 38 mm diameter laser beam is transformed to a laser sheet 0.6 mm thick by 50 mm high. The reactant flow is seeded with silicone oil droplets (approximately 1 micron diameter) generated by a blast atomizer. The droplets evaporate at the flame front ($\approx$ 500K) and so the instantaneous flame surface is then marked as the interface between light (unburnt gas) and dark (burnt gas) regions in the laser sheet, see figure 2. Point measurements of the Mie scattering signal have been used to derive scalar spectra, flame crossing frequencies [3] and pdfs of flame passage times [6]. The laser sheet is recorded at 4 KHz by a high speed 16 mm Fastax camera which provides a trigger pulse for the laser. Film is a convenient and economical means of recording and storing the large amount of data necessary for statistical analysis.

Data Analysis

The film is projected onto a screen and digitized by a video camera to give 512 X 512 pixel images with 256 gray scales of light intensity. A typical digitized image of a stagnation flame (S1) is shown in figure 2 where the flame boundary is clearly visible. A threshold is selected and the flame boundary is extracted using an edge finding algorithm. The insert in Figure 2 shows the histogram of pixel intensity (range of 200 grey levels) and illustrates the two states nature of the images.

These tomographic records contain the spatial information of the flame structures and Chew et al [5] have utilized such records to investigate of the spatial structure of a Bunsen flame. The Bunsen configuration, however, does not seem to be the most ideal for the study of scalar length scales as the turbulence structure is not constant over the whole of the flame brush. The flow divergence also varies across the flame and Bunsen flames, especially at the tip, are very sensitive to the large flow disturbances caused by the interaction of the combustion products and the outer air. Earlier experiments [4] have shown that in these turbulent stagnation flames, however, the length scale of the turbulence is approximately constant and the flow divergence is prescribed by the flow geometry.

There are various methods for deducing the scalar length scales from these records. A first attempt was to obtain the scalar length scales, $L_{\bar{c}}$, directly from spatial correlation maps was not successful. Due to the size of the field of view of the movie film ($\approx$ 50 mm) and the average distance between flame crossing ($\approx$ 10 mm), the number of crossings along a $\bar{c}$ contour was too low to obtain a statistically satisfactory result. Zhang et al [9], have shown that, if it is assumed that the distribution of flame crossing arises from a random process, it is possible to reconstruct a scalar sequence from the burned and the unburned pdfs of flame crossings and hence obtain statistical information such as scalar integral scales. A modification of this technique is used here to calculate the scalar integral length scale. Zhang et al [9] produce random sequences by ordering the the crossing sizes of both burned and unburned pdfs progressively from the smallest to the largest sizes, the proportion of each size being determined by its probability. The order is then shuffled until a random sequence has been obtained. This technique can become cumbersome if large data sets are required.

In the method employed here, a cumulative probability function is generated from each crossing length distribution and a random number generator is then used to provide a cumulative probability value from which a crossing length may be obtained by means of a look-up table. The effective resolution is thus limited only by the discretization of the pdfs. The sequence of flame crossings was obtained by alternately sampling the burned and unburned pdfs in this manner. In the present simulations, the sampling resolution was 0.5 mm with an average of approximately 200 crossings per sequence and spatial frequency spectra of the sequence were obtained by fast Fourier analysis. In a comparison of the numerically simulated spectrum of an exponential distribution of flame crossing sizes with its analytical solution, excellent agreement was obtained (Fig. 5(a)).

Results and Discussion:

The mean structure of the turbulent flame region in terms of a reaction progress variable, $\bar{c}$, is obtained by reconstructing the flame images from the instantaneous flame boundaries as two state pictures (0 for the unburned, 1 for the burned) and averaging at least 200 frames. A typical 'contour' map of the turbulent flame zone, in this case S1, is shown in figure(3). The reaction progress variable, $\bar{c}$, is 0 in the reactants and 1 in the products and the spacing between the contours is 0.2. The turbulent zone thickness (δ_T) along the stagnation line was calculated by the steepest gradient method from the $\bar{c}$ contours and is given in Table I. It can be seen in figure 4 that the flame is not flat in the mean but has an indentation at the centerline which is probably due to a small imbalance in the shielding air-flow.

Flame crossing lengths were obtained by superimposing a $\bar{c}$ contour onto the instantaneous two state flame images. By reading the intensity value of the image along the $\bar{c}$ contour line (either 0 or 1) the lengths of the burned and unburned segments were obtained. Probability distributions of these segments were derived for all the flames along the $\bar{c} = 0.5$ contour where the crossing frequency is highest. Due to the small number of crossings away from the middle of the flame brush the statistical significance of the pdfs at these positions is not clear and these results are not presented.

Figure 4 shows the pdfs of the burned and the unburned flame crossing length for flame S1. Although the pixel resolution is 0.155 x 0.121mm the effective spatial resolution of the results is determined by the laser sheet thickness (0.6 mm) and crossing lengths shorter than this were considered to be indistinguishable from pixel noise and so are not included in the distributions. For purposes of illustration, the unburned distribution is compared to an exponential distribution and the burned distribution to a gamma-2 distribution with the appropriate mean values. This comparison is of interest as these distributions have been used in theoretical studies [1,2]. This difference in the observed distribution shape, even when the mean values are the same, was also found in an earlier study of the pdfs of crossing times in a similar system [6]. Chew et al [5], however, found the distributions to be similar and of an exponential type. Those distributions, however, could arise from the variations which occur in the mean wrinkle sizes along the Bunsen flame brush which are due to changes in the local turbulence conditions.

The mean spatial crossing frequencies, $\nu_{\bar{c}}$, for all the flames studied are also given in Table I. The results for all flames are very similar ($\approx 0.1 mm^{-1}$) although the laminar burning speed for the flames varies by almost a factor of two. This indicates the importance, in these flames, of the approach flow turbulence structure in determining the scalar spatial scales.

An estimate of the scalar integral scale may be obtained from the experimental distributions by the numerical method outlined above. A three-point median filter is first applied to the pdfs which removes random noise from the distribution without modifying the underlying distribution shape. Spectra for each case are calculated by applying an FFT to 100 sequences of, on average, 200 randomly generated flame crossing lengths having a spatial resolution of 0.5 mm. Figure 5 shows the normalized flame crossing spectrum for the $\bar{c} = 0.5$ contour of the case S1 which is compared with the spectrum for the exponential distribution with the same mean crossing length. In the usual way, the value of the normalized spectrum as the frequency tends to zero is used to obtain an estimate of the scalar integral scale, $L_{\bar{c}}$. It can be seen from the values presented in Table I that in all cases this scale is very close to the integral length scale of the approach flow turbulence (3 mm) showing once again its dominant role in determining the spatial structure of the scalar field. A similar result was found by Chew et al [5].

The factor g in Equation (2), which relates the mean spatial crossing frequency, $\bar{\nu}_{\bar{c}}$, to the integral length scale, $L_{\bar{c}}$, may now be evaluated. An inspection of the distributions, figure 4 (a) & (b), would indicate a value between that of the gamma-2 ($g = 1$) and the exponential ($g = 2$) and this is indeed the case although the values are closer to the former number with a mean of 1.26.

The angles between the $\bar{c}$ contour and the normal to the instantaneous flame front, θ, were also determined by performing a least mean square fit of the flame fronts and the $\bar{c}$ contour around the intersection points and comparing the slopes of the fitted lines. The slopes were not very sensitive to the number of points (nine in this case) used in the fit. The pdfs of cos θ were very similar to those reported by Chew et al [5] with a maximum probability at cos $\theta = 1$ and the mean values at $\bar{c} = 0.5$ for all the cases is $\theta \approx 50^{\circ}$ (Table I). It should be noted that these cosines may differ from the direction cosines of Equation 3 due to three dimensional effects. If flame orientation is not considered, i.e. if the instantaneous flame front is assumed to be parallel to the $\bar{c}$ contours, the consistency of the present results may be assessed by integrating $\overline{\nu_{\bar{c}}}$ along the stagnation line which should give a value for $\overline{W}$ of unity. The variation of $\overline{\nu_{\bar{c}}}$ may be approximated [3] by $\bar{c}(1-\bar{c})$ using the experimental value at $\bar{c} = 0.5$ as a scaling factor and $\bar{c}$(x) may be obtained from data such as Figure 3. The results of the integration, I, are given in Table I and are found in all cases to be close to one.

In principle, the flame geometry and surface area can be derived from the changes in flame orientation distribution across the flame zone, but, as the detailed distribution of $\overline{\cos\theta(\bar{c})}$ is not known, an alternate means of estimating the flame area and hence the burning rate (Equation 5) is available from a fractal analysis of the instantaneous flame fronts. Extensive fractal analyses of premixed turbulent flames have been conducted [10,11] and the fractal parameters (the inner (ϵ_i) and outer (ϵ_o) cutoffs and fractal dimension (D)) are found to change significantly with downstream distance in developing flowfields such as V-flames [7]. As mentioned above, an earlier study of the present flow field [4] has shown that turbulent conditions in the reactant stream do not change significantly with downstream distance, avoiding one possible ambiguity in this fractal analysis. Figure 6, a fractal plot of flame S1 obtained by the technique used in reference [11], is an ensemble average of two hundred flame boundaries and is typical of all the flames studied. The fractal parameters derived from such plots are given in Table (II) where ΔL is the ratio of the mean flame length at the inner and outer cutoffs.

Table II

Flame No.	$1-D$	ϵ_i (mm)	ϵ_o (mm)	Δ_L	ΔA
S1	-0.142	2.26	24.1	1.40	1.96
S9	-0.168	1.91	25.1	1.55	2.40
S10	-0.141	2.08	31.8	1.47	2.16
S11	-0.121	2.19	26.4	1.36	1.85

The inner and outer cutoff scales for all cases are very similar although the laminar burning velocity, which might be expected to affect the inner cutoff, varies by a factor of 1.8. The outer and inner cutoffs are also large in comparison with, respectively, the integral length scale of the approach flow turbulence (3.0 mm) and the Kolmogorov scale (≈ 0.12 mm), indicating that it may be difficult to relate directly the range of wrinkle sizes to the turbulence scales in the reactant stream which has been suggested elsewhere [10]. An estimate of the increase in flame area may be obtain from ΔL by assuming that the wrinkle sizes are similar in the orthogonal direction and then the area increase, ΔA, is

$$\Delta A = ({\epsilon_i}^2/{\epsilon_o}^2)^{1-D}$$

The values of the area increase calculated from the fractal analysis are given in Table II. These results are found to underestimate the burning rate when compared with values obtained by direct measurement of the flow velocity at the cold boundary of the flame brush [4]. The burning rates for S1 and S9 form the direct measurements are 3.8 and 3.3 respectively. It is not clear whether this difference can be explained solely in terms of variations in the laminar burning velocity (S_L in Equation 5) due to the straining field.

Conclusions

(1) A tomographic study has been perform to investigate the spatial scalar structure of premixed turbulent stagnation point flames.

(2) Flames at high Damköhler number were studied with a fine oil aerosol which evaporated at approximately 500 K was used to visualize instantaneous flame front shape in a laser sheet.

(3) A copper vapor laser light source provided the advantages of good temporal resolution coupled with repetition rates up to 10 kHz.

(4) The tomographic moviers were analyzed to characterize the scalar structures in terms of the mean spatial crossing frequency and integral scalar length scale and to determine the increase in flame area and hence the overall burning rate by fractal analysis.

(5) The scalar integral length scale between flame crossing is found to be close to the turbulence integral length scale and the mean crossing length is of very similar sizes in all the cases investigated. This indicates the dominant role played by the turbulence, in determining the scalar spa-

tial structures. The distributions of burned and unburned crossing sizes were found to be different at $\bar{c} = 0.5$ as other studies have shown. The proportionality constant which relates the scalar integral scale to the mean crossing frequency distribution was found to be close to unity.

(6) The fractal analysis was applied to the instantaneous flame boundaries to quantify the area increase of the flame surface due to the wrinkling by the turbulence in the reactant stream. The estimated flame area increase underpredicted the burning rate when compared with direct measurements of the flow velocity at the cold boundary.

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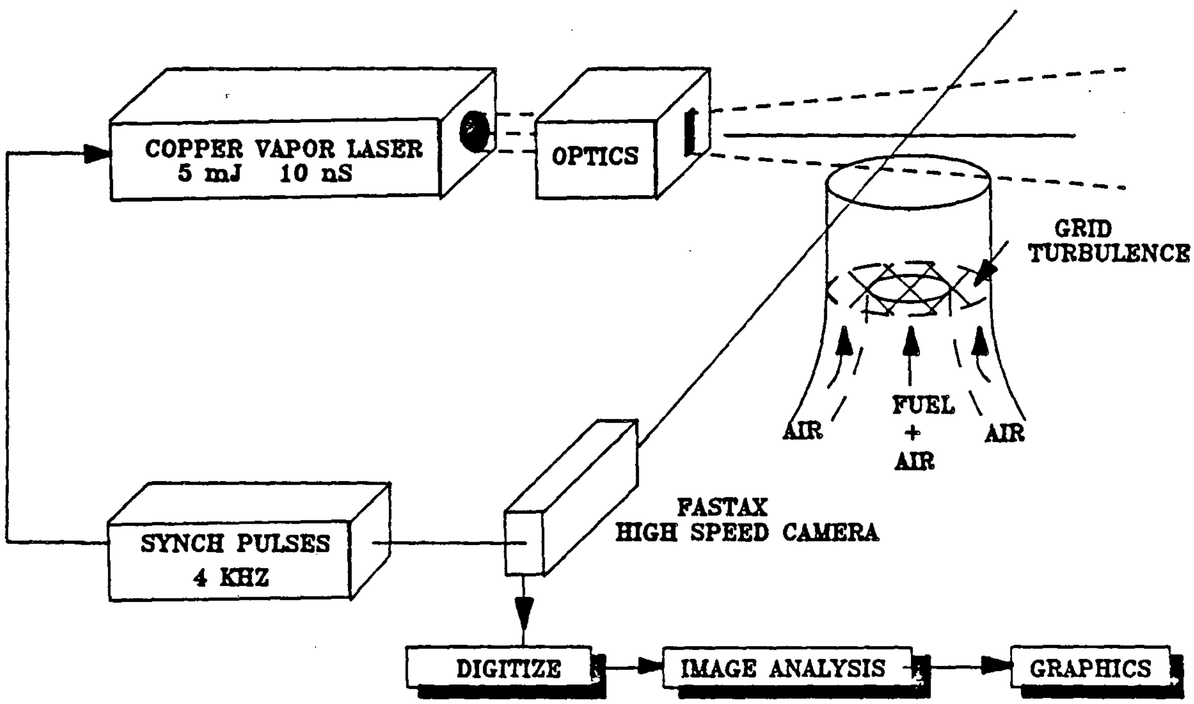
SCHEMATIC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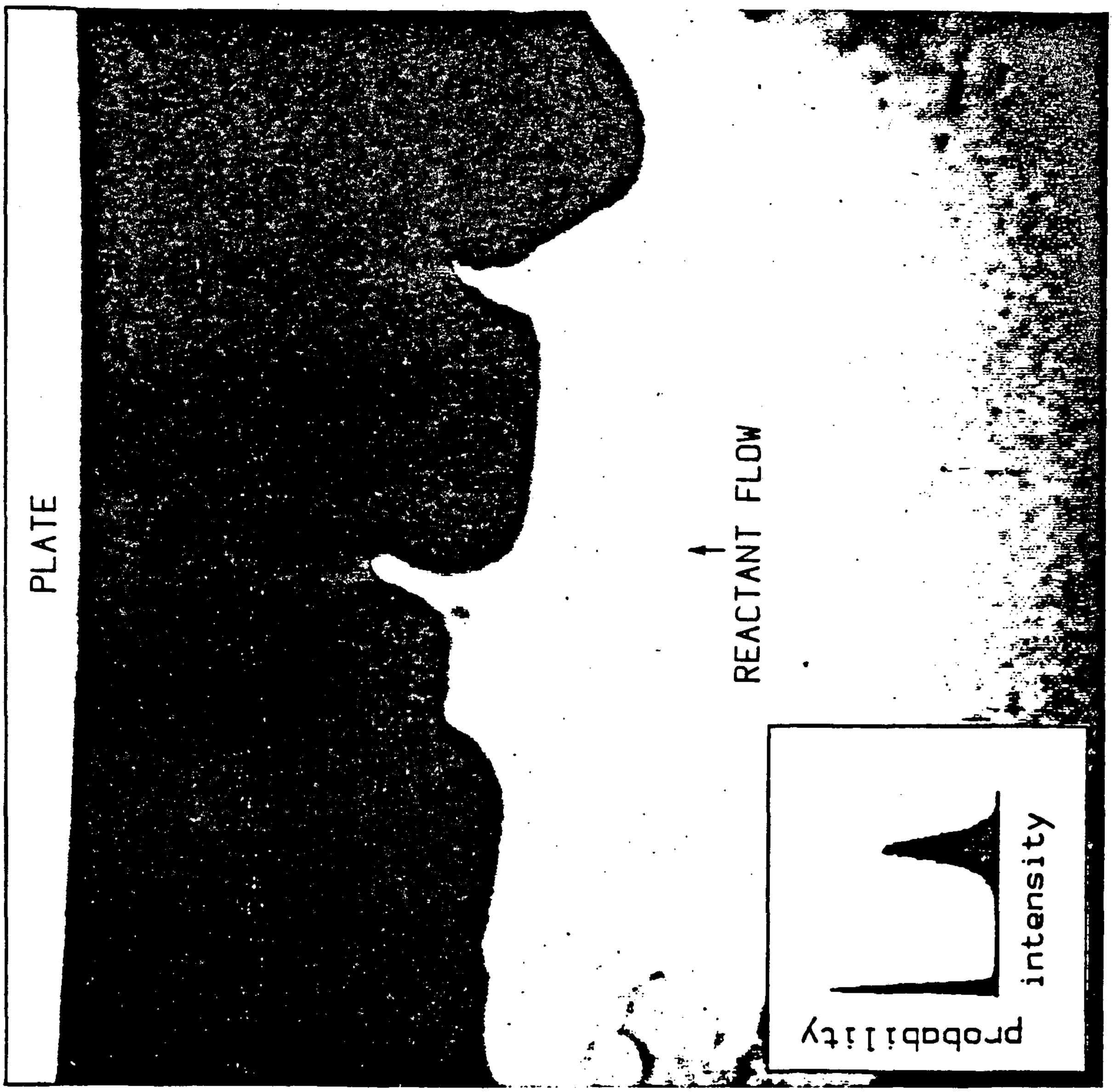
GRAPHICS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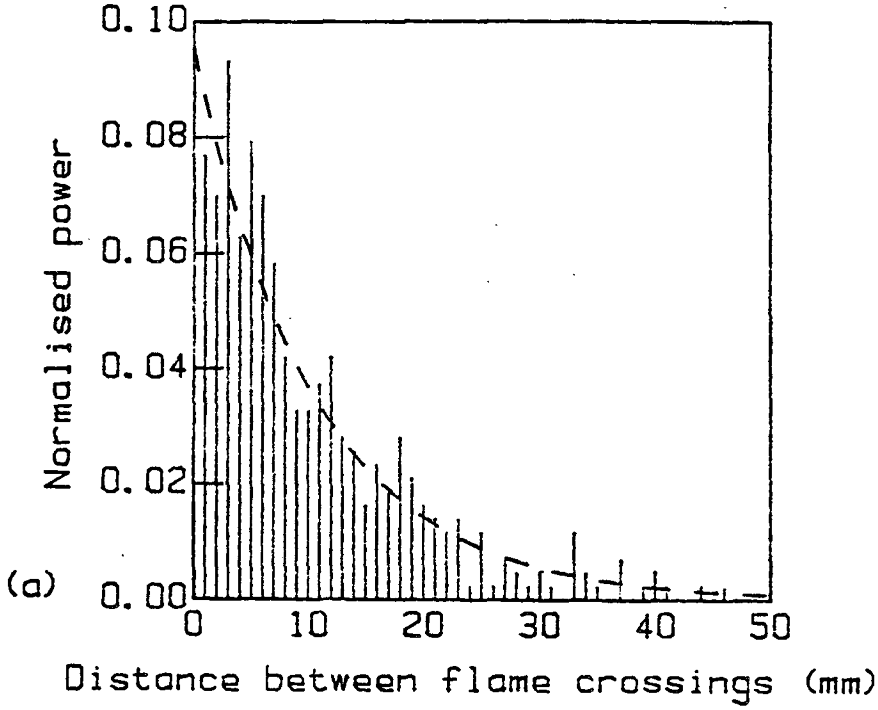
probability
intensity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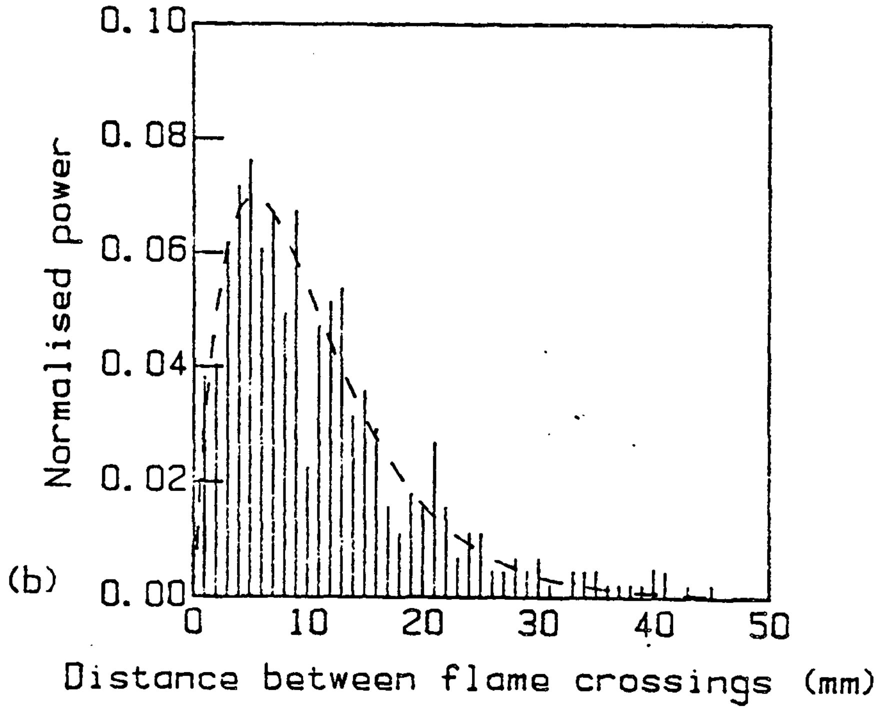
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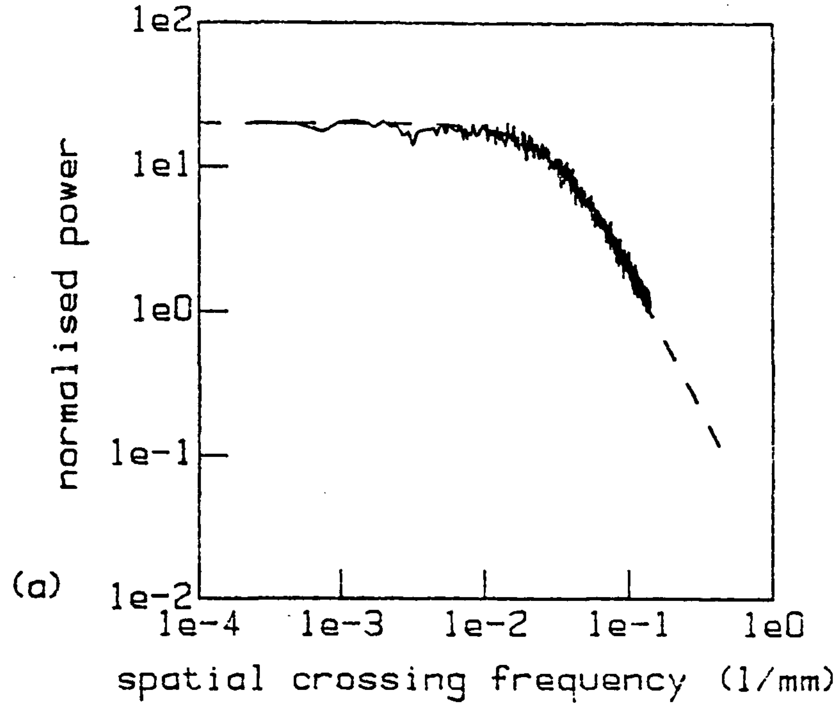
Distance between flame crossings (mm)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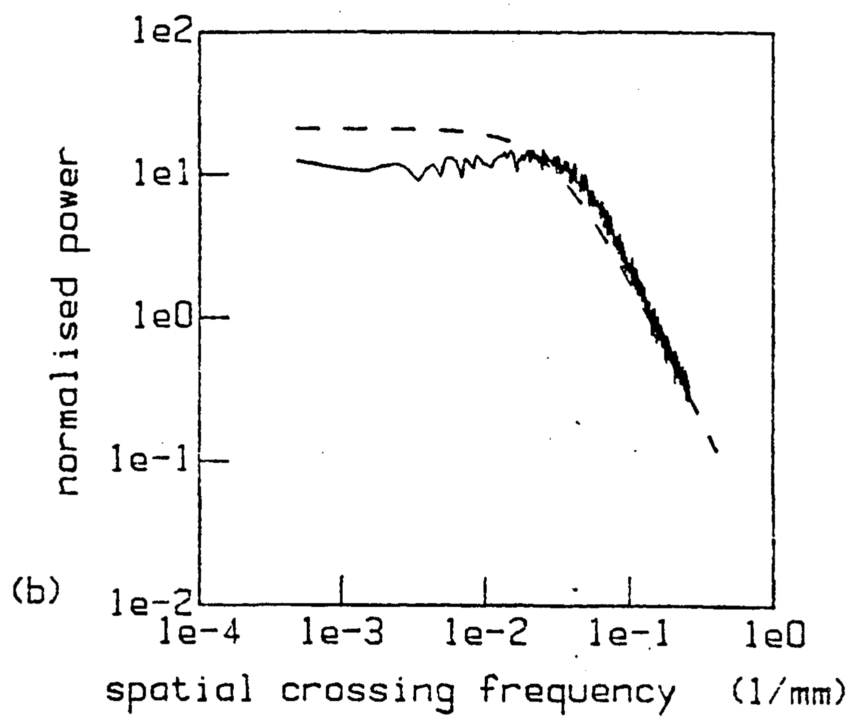
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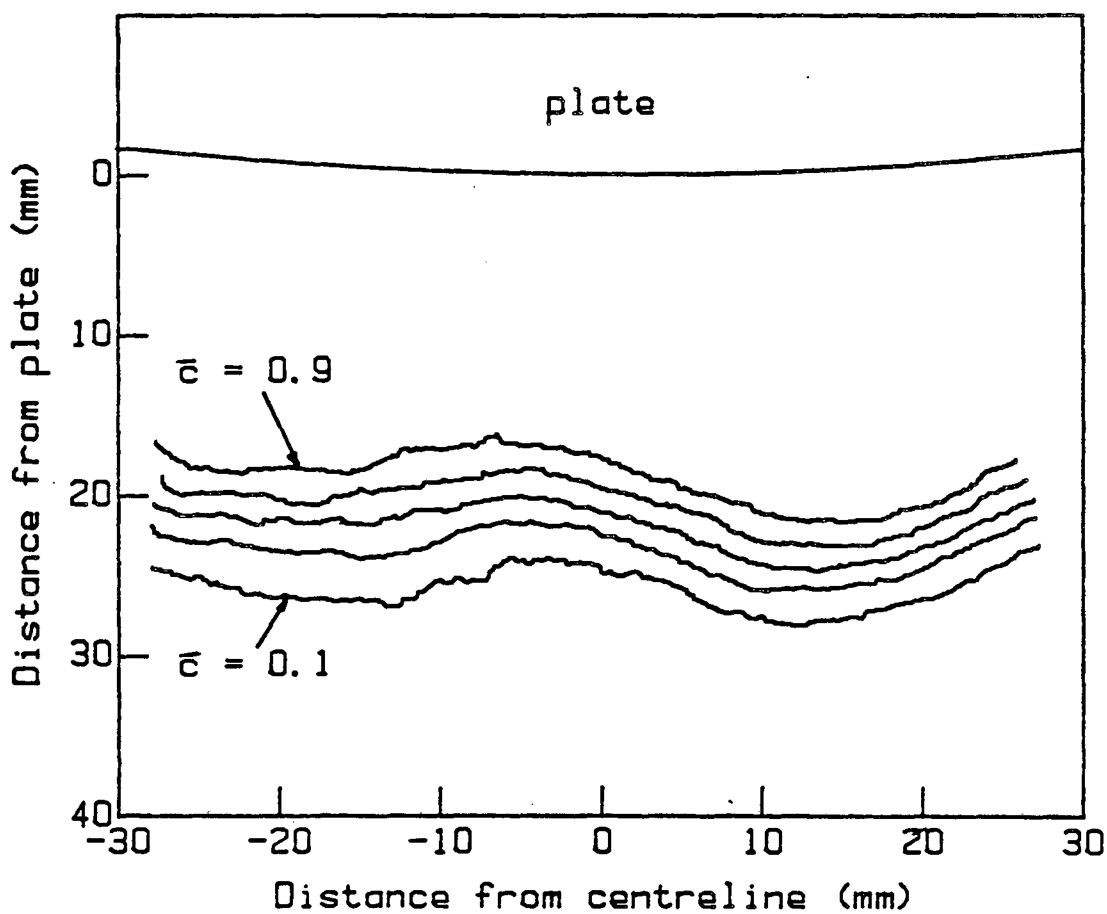
spatial crossing frequency (1/mm)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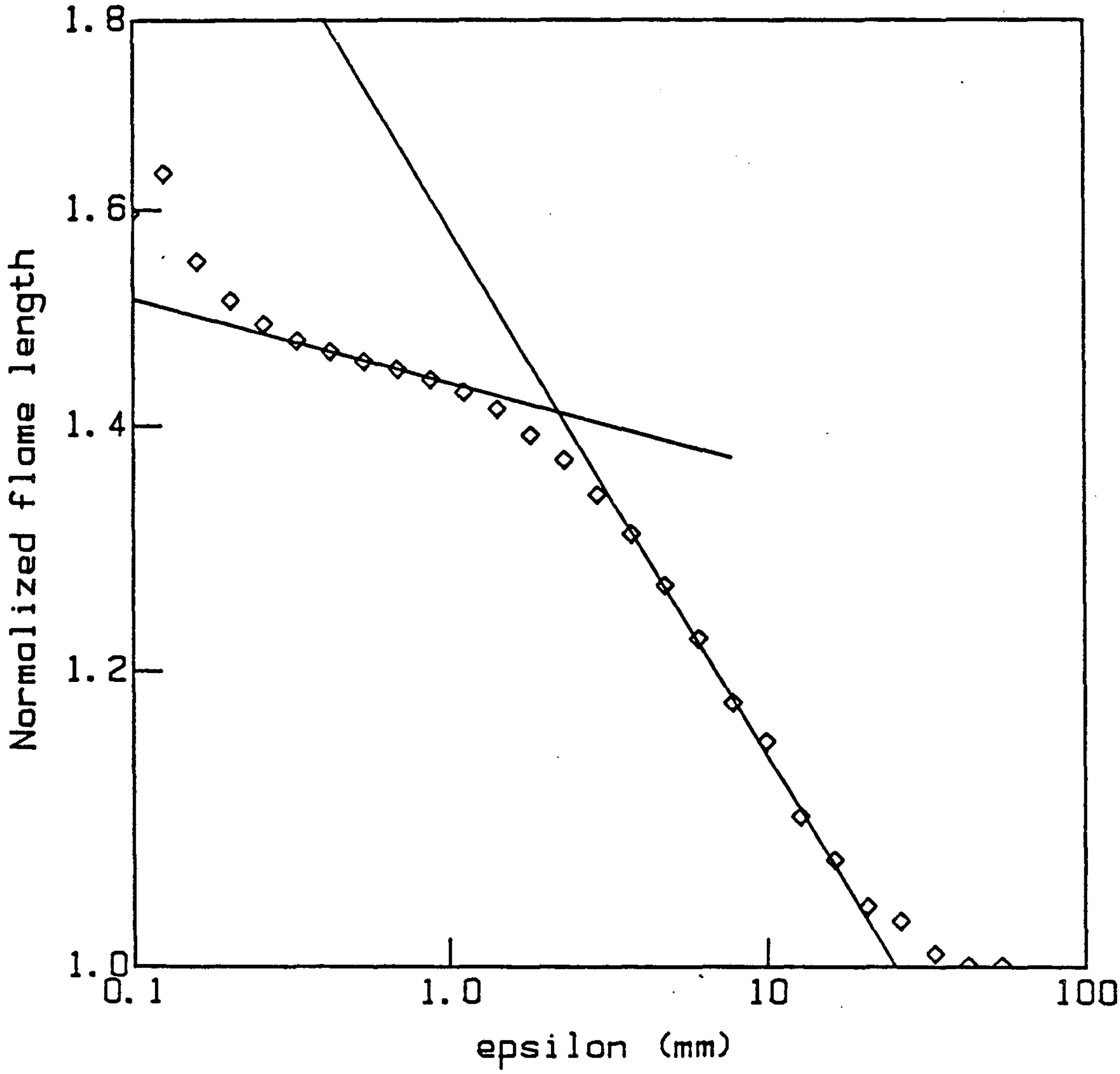

1.8
1.6
1.4
1.2
1.0
Normalized flame length
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1.0
10
100
epsilon (mm)

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