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A Tomographic Study of Premixed Turbulent Stagnation Point Flames

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ABSTRACT

The high speed tomographic technique has been used to study premixed flame propagation in stagnation flow stabilized flames. Studies are performed on CH4/Air and C2H4/Air 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 varied from 5% to 7% and the turbulence Reynolds number is 70. The light source is a copper vapor laser which produces 20ns, 5 mJ pulses at a 4KHz repetition rate. Cylindrical lenses transform the 38mm 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. The films are digitized and the flame front extracted from the images by a thresholding technique. A fractal analysis was performed on the flame boundaries in order to characterize the flame geometry and provide an estimate of the flame surface area. The flame area increase was found to give a reasonable estimate of the burning rate when compared with other methods if the effects of flow tube divergence were considered. Characteristic wrinkle sizes were found to be much larger than the length scales of the turbulence in the reactant stream.

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. The scalar field can then be specified by consideration of the burned and unburned states only giving rise to a convenient means of chemical closure. The scalar properties, such temperature or density, which are directly related to the reaction rate can be measured with a relatively simple diagnostic technique based on detecting the Mie scattering intensity from micron sized oil droplets which evaporate at the flame sheet (1,2).

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

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

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

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

The increase in burning rate by turbulence therefore can be deduced by estimating the flame area.

In a previous study (3) we have demonstrated that the reaction rate can be determined from the flame crossing frequencies measured at points along mean flowlines through the flame brush. This method essentially integrates an estimated length scale of the flame wrinkles using Taylor's hypothesis along a flowline. However, for situations where Taylor's hypothesis does not apply, such as stagnation flow stabilized flames, another means of estimating the burning rate is necessary. The objective of this work is to apply the high speed tomographic technique to study premixed flame propagation in stagnation flow stabilized flames.

Experimental details

Tomographic studies were conducted on a range of stagnation point premixed turbulent flames (Table I). In all cases the Damkohler number based on the chemical reaction time and the integral time scale of the reactant stream are much greater than one and so appropriate for investigation by Mie scattering tomography. 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. Turbulence (7%) is generated by a perforated plate placed 50 mm upstream of the burner nozzle and has an integral length scale of 3 mm. The turbulent Reynolds number based on these values is 70 in all cases. The burner configuration, figure(2), 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(mm)
S1	CH_4	1	0.43	105	7.54	9.17
S9	C_2H_4	1	0.76	350	7.84	11.39
S10	C_2H_4	0.85	0.64	249	7.45	13.89
S11	C_2H_4	0.75	0.51	141	6.99	10.09

The light source was a Metalaser copper vapor laser which affords significant advantages for laser sheet imaging. It delivers 5mJ /pulse with 20-30 nsecs pulse width but is also capable of repetition rates upto 10 KHz. Hence it is possible, not only temporally 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 3. Point measurements of the Mie scattering signal have been used to derive scalar spectra, flame crossing frequencies (3) and the probability density functions of flame passage times (5). 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.

Results and Discussion:

The film frames are 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 1 where the flame boundary is clearly visible. A threshold is selected and with an edge finding algorithm the flame boundary can easily be extracted from such images. Due to the steep intensity gradient at the interface the extracted flame shape was not sensitive to the exact value of the threshold. Furthermore, as there are large differences between the light levels in the light and dark zones it was possible to use the digitized images directly without further image processing to remove noise.

The structure of the turbulent flame region in terms of a reaction progress variable is obtained by reconstructing the flame images from the flame boundaries as two state pictures and averaging at least 200 samples. Care was taken to ensure that the film was randomly sampled. A typical 'contour' map of the turbulent flame zone (S1) is shown in figure(4). The reaction progress variable, c, has a value 1 in the products and 0 in the reactants. The spacing between the contours is 0.2. The turbulent zone thickness (δ_T) along the stagnation line was calculated from these average images and is given in Table (I). It is clear from figure (4) that the flame is not flat in the mean but has an indentation at the centerline. The reason for this is unclear but it is characteristic of all the flames studied.

As outlined above the increase in burning rate observed in premixed turbulent flames at high Damkohler numbers can be simply attributed to an increase in the flame surface area due to wrinkling of the surface by the turbulence in the reactant stream. A possible way of estimating the area increase and of characterizing the flame geometry is by performing a fractal analysis on the flame boundaries. Extensive fractal analyses of premixed turbulent flames have been conducted (6,7) 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 (7) in developing flowfields. 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 so a possible ambiguity in the fractal analysis may be avoided in this study. Figure 5, a fractal plot of flame S1, 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_0 (mm)	Δ_L
S1	-0.142	2.26	24.1	1.40
S9	-0.168	1.91	2.51	1.55
S10	-0.141	2.08	31.8	1.47
S11	-0.121	2.19	26.4	1.36

The inner and outer cutoff scales for all cases are very similar although the laminar burning velocity, which may be expected to affect the inner cutoff, varies by a factor of 1.8. The two cutoffs are large in comparison with the integral length scale of the approach flow turbulence (3.0 mm) and the Kolmogorov scale ($\approx$ 0.12 mm) respectively, indicating that it may be difficult to relate directly the wrinkle scales to turbulence scales in the reactant stream.

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. It is also necessary to consider the effect of flow tube divergence which can be marked in these flames. By comparing velocity measurements taken away from stagnation line (8) it is possible to obtain a measure of the area increase due to flow tube divergence (ΔA) for two cases (S1 and S9) which have a large difference in this variable. Values of the total area increase ($(\Delta L)^2\Delta A$) of 3.7 and 3.5 for flames S1 and S9 respectively may be compared with the respective burning rates of 3.8 and 3.3 obtained by an independent method (4). This is a first estimate and further work is necessary to substantiate this conclusion.

Conclusions

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

(2) Flames at high Damkohler were studied and 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) A fractal analysis was applied to the instantaneous flame boundaries derived from digitized high speed movies frames to quantify the area increase of the flame surface area due to wrinkling by the turbulence in the reactant stream. The estimated flame area increase underpredicted the burning rate when compared with another method but better agreement was obtained when the effect of flow divergence were considered.

(5) An evaluation of the significant wrinkle sizes of the flame front indicated that the length scale of the turbulence in the approach flow do not provide a good guide for these values.

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SCHEMATIC

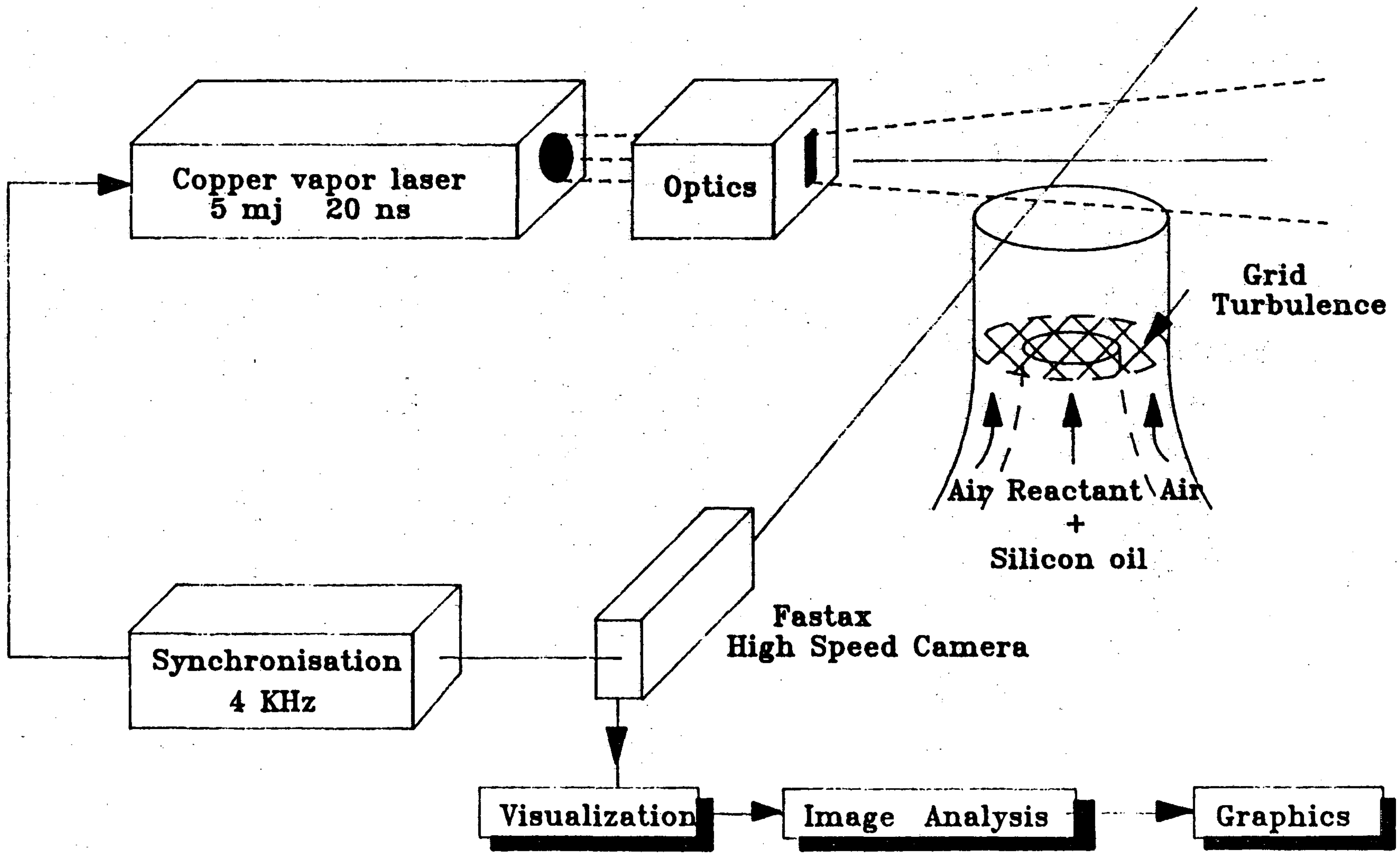

FIGURE 1

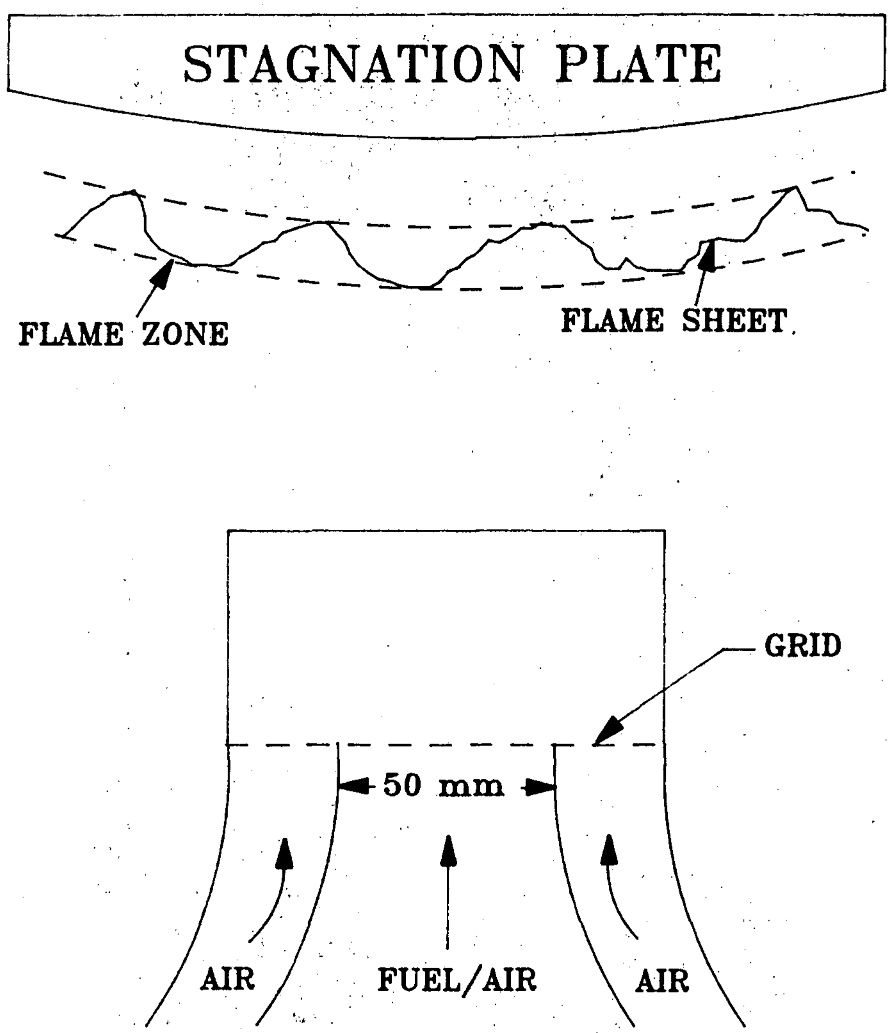

FIGURE 2 Burner configuration

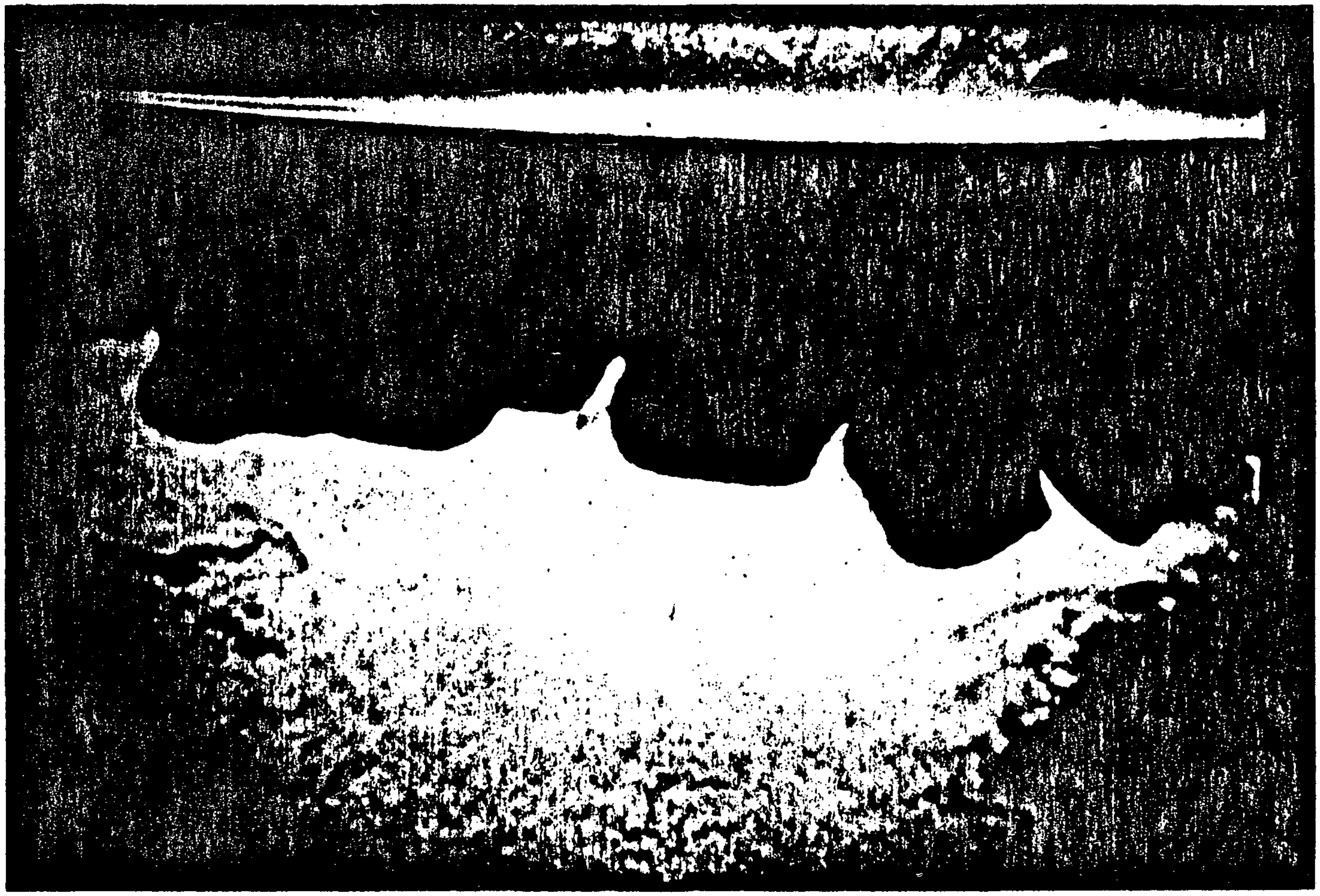

FIGURE 3 Tomographic records of S1.
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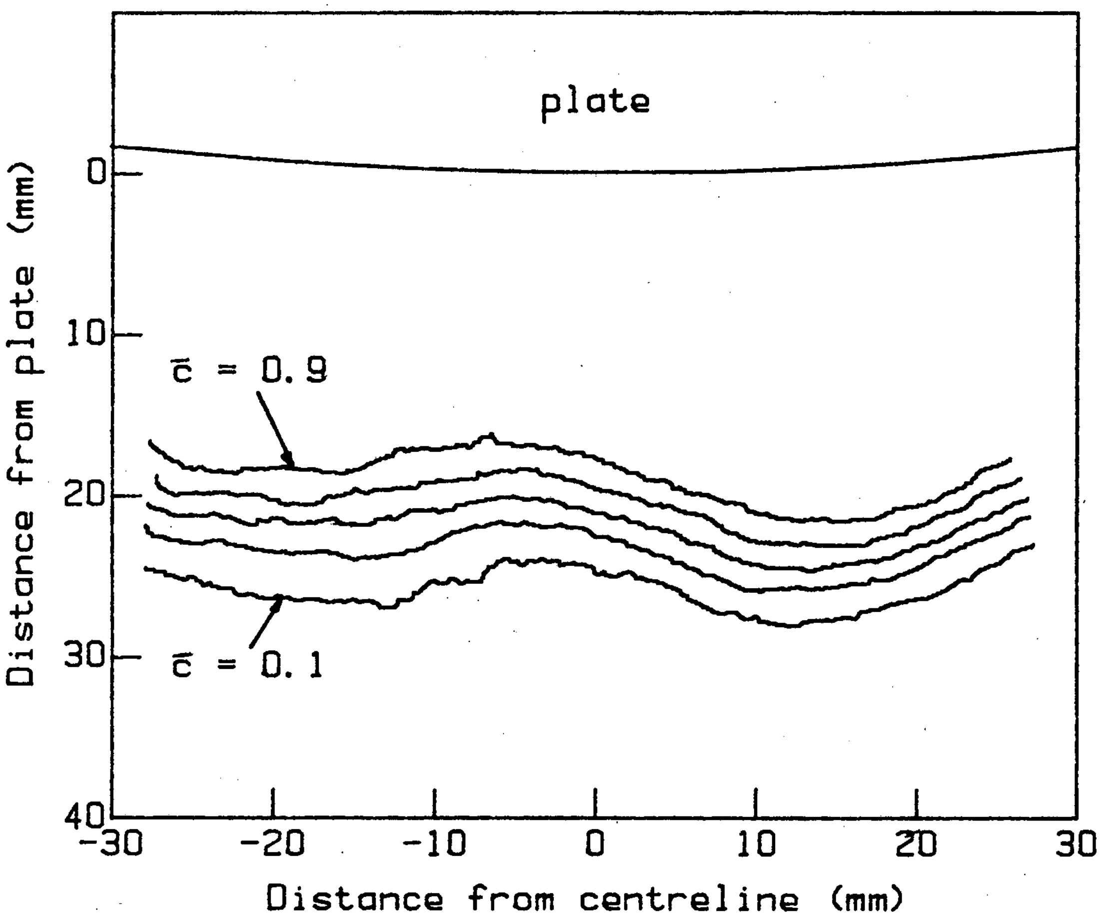

FIGURE 4 Contours of progress variable, $\bar{c}$, deduced from instantaneous flame boundaries of S1.

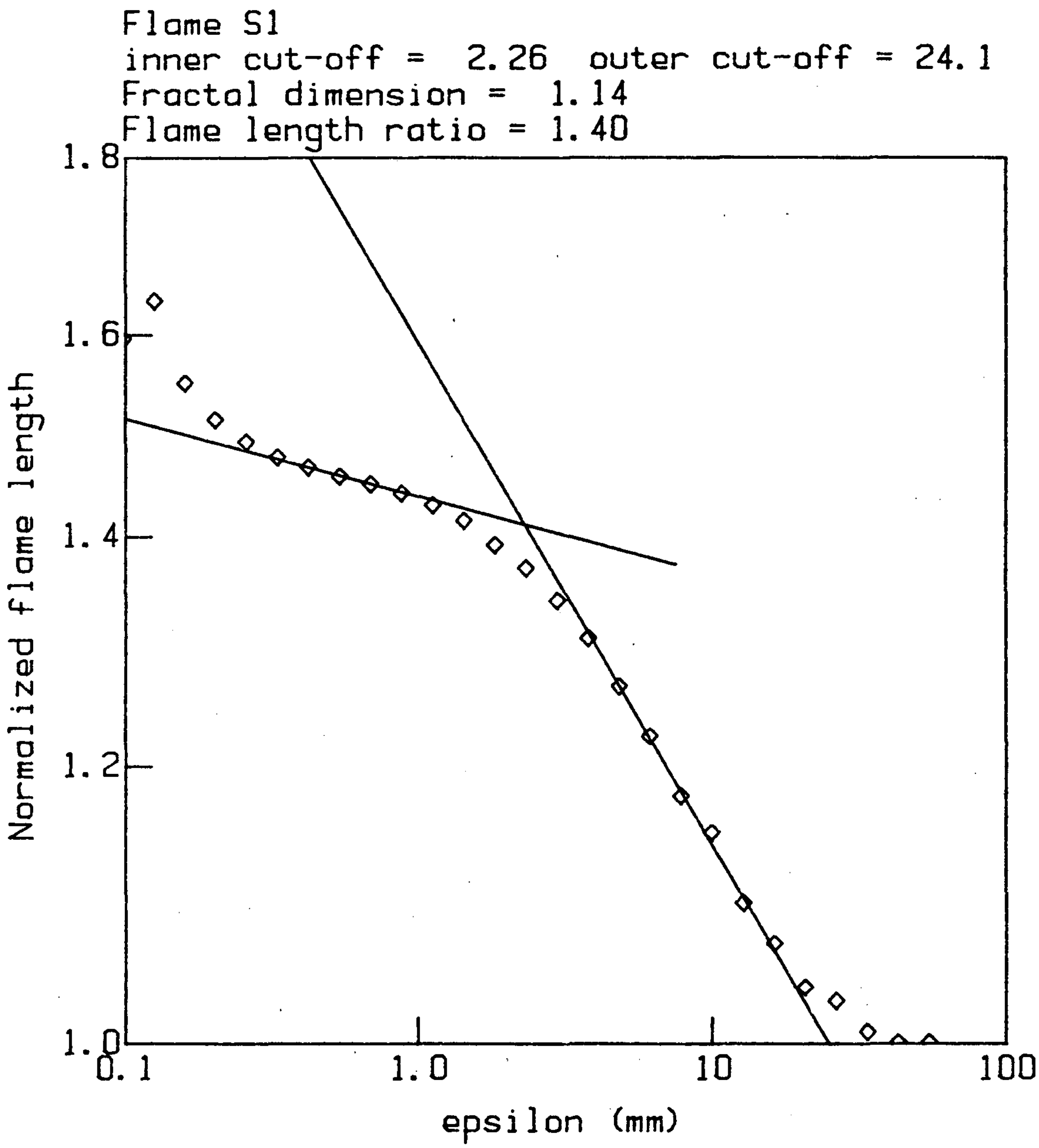

FIGURE 5 Fractal plot for S1

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