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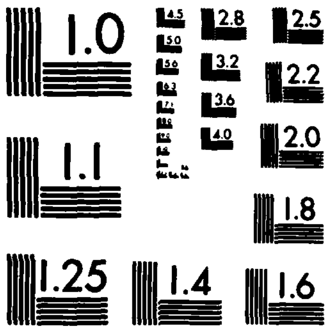

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TWO-POINT RAYLEIGH SCATTERING MEASUREMENTS IN A V-SHAPED TURBULENT FLAME

M. Namazian†
L. Talbot†
F. Robben*
R. K. Cheng*

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†Department of Mechanical Engineering,
University of California, Berkeley

*Lawrence Berkeley Laboratory,
University of California, Berkeley

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A Rayleigh scattering technique for simultaneous measurement of density at two points in a flame was developed. This technique was used to deduce the spatial and time-space correlation and the two-point joint probability density function of the density in a premixed turbulent flame in three orthogonal directions. A grid generated turbulent V-shaped flame at a flow velocity of 7.0 m/s and a half angle of 12° was used. The analysis shows that this flame consists of structures of equal length scale in all three directions which decay as they are convected downstream by the flow. It is also shown

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ABSTRACT

A Rayleigh scattering technique for simultaneous measurement of density at two points in a flame was developed. This technique was used to deduce the spatial and time-space correlation and the two-point joint probability density function of the density in a premixed turbulent flame in three orthogonal directions. A grid generated turbulent V-shaped flame at a flow velocity of 7.0 m/s and a half angle of 12^{o} was used. The analysis shows that this flame consists of structures of equal length scale in all three directions which decay as they are convected downstream by the flow. It is also shown that this flame does not consist of flamelets.

Introduction

In recent years several theoretical descriptions have been given of the structure of turbulent premixed and diffusion flames which make use of a one-point probability density function (pdf) as the primary quantity. The mean and fluctuating components of the various flow and state variables are obtained by forming appropriate moments of the pdf. However, since a one-point pdf contains no information on the length scales associated with various fluctuating quantities, these scales have had to be introduced independently in one or another empirical fashion. Unfortunately, there exists very litle experimental information on the magnitude of these length scales. Information of this nature is of prime importance in the description of the spatial structure of turbulent flames.

Rayleigh scattering has been demonstrated [1] to be a powerful diagnostic method for the measurement of local gas temperature and density, and has been used successfully [2-5] to measure density fluctuations and one-point probability density functions within turbulent flames from analysis of the time series of the Rayleigh signal. It is

A

evident that much additional information can be obtained regarding the spatial and temporal structure of a reaction zone from the statistical analysis of the time series of simultaneous measurements at two separated points [6,7]. The purpose of the present paper is to describe the implementation of the Rayleigh scattering technique for two-point measurements, and to demonstrate some of the information that can be obtained from such measurements. For the purpose of this demonstration representative measurements made within a pre-mixed, rod stabilized flame propagating into a grid-generated turbulent flow are presented.

Experimental and Test Conditions

Figure 1 shows a schematic diagram of the coaxial combustor used for this study. This combustor consists of an inner jet of ethylene-air mixture and an outer flow of air. The velocity of the outer flow air jet was matched with that of the inner jet in order to minimize disturbances at their interface. The inner and outer jet diameters were 5.1 cm and 10.2 cm, respectively. A grid of 5.0mm mesh size and 1mm element size was used to generate turbulence. As shown in Fig. 1 a rod of 1mm diameter was positioned 50 mm away from the grid in order to stabilize the V-shaped flame.

The two point measurements were performed in three directions (see Fig. 1), x along the jet, y normal to the jet and normal to the flame holder and z normal to the jet and parallel to the flame holder. In this paper we refer to the two measurement points as points 1 and 2. Point 1 was always set at 35 mm above the flame holder (i.e., 85 mm above the grid) in the axial plane of the combustor normal to the flame holder. Point 2 was then moved in the x, y, or z direction by δ , the distance between sampled points. For each fixed δ, regardless of the direction of separation of the points, a profile of the measurements across the flame front was obtained by moving the combustor in the y direction.

Throughout this study the equivalence ratio of the ethylene-air mixture was 0.6 and the jet velocity was 7 m/sec, repeating one of the conditions for earlier results obtained by Bill et al. [8]. These conditions produced a flame with a half-angle of 12^o. The Reynolds number based on the mesh size was 2280.

Rayleigh Scattering and Optical Setup

Rayleigh scattering provides a convenient technique for measurement of the temperature and the density of gases. Namer et al.[9] have shown that Rayleigh scattering for ethylene-air mixtures is proportional to the density with an accuracy of better than 5% for the conditions of this study. Therefore the density of the gas can be deduced from:

$$\frac{I}{I_o} = \frac{\rho}{\rho_o}$$

where I is the Rayleigh scattering intensity, ρ is the density and subscript o denotes conditions in the non-reacting flow ahead of the flame.

Two types of optical systems, referred to as the one-beam system and the two-beam system, were used in this study. The one-beam system was used when the separation between sampled points was in the horizontal direction (i.e., y and z) and the two-beam system was used when the separation between the two sampled points was in the vertical direction. Figure 2a shows the one-beam system. A 4 watt argon-ion laser beam was focused at the test section through a 200 mm lens. The focused beam had a 60 μm diameter waist and a 10 mm confocal length (the confocal length is the distance over which the beam is nearly perfectly collimated). This portion of the beam was used to produce the two sampled points by collecting the scattered light from two sections of the beam each 100 μm long. This dimension of the sample volume was determined by an aperture placed in the collection optics at the beam focus. The collected light was filtered by a narrow band pass filter centered at 488 nm and then measured by a photomultiplier.

The two Rayleigh scattering collection systems were mounted on three-dimensional translational stages to faciliate focusing and movement. By moving one of the collection systems parallel to the laser beam we were able to vary δ , the distance between the two sampled points.

The single beam system could not be used when the two points were separated in the vertical direction because in the single beam arrangment the laser beam had to be directed vertically downward and this produced unacceptable back-scattering from the turbulence-generating grid.

Figure 2b shows the two beam system. The laser beam was separated into a blue and a green beam, using a dichroic color separator. Each beam was then brought to focus through separate halves of a lens which had been cut into two pieces as shown in Fig. 2b. When the two parts of the lens were positioned together (forming the original shape of the lens) the two beams would focus nearly at the same point, labeled by point 1 on Fig. 2b (the focal points are not exactly identical due to the difference in wave lengths). However, when the upper half of the lens is moved up by δ the focusing point of the incident beam also moves up by the same amount to point 2 as shown on Fig. 2b. The collection systems were then positioned such that the Rayleigh scattering at these two points 1 & 2 was sampled.

Data Acquisition and Data Reduction

The signals of two photomultipliers were amplified with low noise amplifiers equipped with low pass filters set at 10 khz. The two output signals were then sampled simultaneously with a PDP 11/10 computer equipped with an LPS11 system capable of dual sample and hold mode with direct memory access operation. The data were sampled at a 10Khz rate and stored on magnetic tape for post-processing. At each measurement location 2048 samples of each signal were collected. The same PDP 11/10 computer was used to move the combustor so that the flow field positions were scanned automatically.

The stored data were reduced on the Lawrence Berkeley Laboratory CDC 7600. The effects of photomultiplier noise and background were removed using the method described by Bill et al.[8]. The data were also numerically filtered from DC to 50 Hz to remove low frequency fluctuations which presumably arose from disturbances of the flame by room air currents. This filtering was justifiable because the lowest frequency associated with combustor diameter is 150 Hz.

Results

Part of the information contained in the measured densities at two points separated by δ can be obtained from the spatial correlation coefficient $R(\delta)$. This quantity provides a measure of the relative strength of the density fluctuation structures whose length scale in the measurement direction is greater than δ. The structures with length scales smaller than δ do not contribute to $R(\delta)$. $R(\delta)$ is defined by

$$R(\delta) = \frac{\langle \rho_1'(t) \; \rho_2'(t) \rangle}{\langle \rho_1'(t)^2 \rangle^{0.5} \; \langle \rho_2'(t)^2 \rangle^{0.5}}$$

where δ is the distance of separation of the measurement positions denoted by subscripts 1 and 2 and ρ' is the density fluctuation. In Fig. 3 values of $R(\delta)$ are shown for δ lying along each of the three axes x, y and z. The values of the spatial correlations are very similar in these three orthogonal directions, indicating that the spatial structure of the turbulent flame, under these conditions, is such that the associated length scales are the same in the x, y and z directions. Further, an integral length scale can be derived from the area under these curves, and is found to be approximately 2 mm. By way of comparison, the width of the turbulent flame zone was approximately 4 mm.

The velocity fluctuations in the grid generated turbulent flow in the absence of the flame, as measured using a hot-wire anemometer[10], give an rms turbulence level of 4% and an integral length scale, based on the Taylor hypothesis, of 4 mm in the flow direction. Since the grid generated turbulence is very nearly isotropic, the transverse integral length scale is just 1/2 of the longitudinal integral scale, approximately 2 mm [11]. Thus, for the conditions of this flame, the length scales of the velocity turbulence in the oncoming flow and the densities in the flame are fairly similar. As noted above however, the longitudinal length scale of the density fluctuations in the flame is not larger than the transverse scales.

In the results shown in Fig. 3 measurement point 1 was taken to be in the center of the turbulent flame, where the mean density is midway between the unburned and fully burned values. Essentially identical results are obtined for other locations of measurement point 1 (at fixed x), as long as both measurement points are located reasonably well within the turbulent flame zone.

Further information on these turbulent flame structures can be obtained from the space-time correlation coefficient $R(\delta,\tau)$, defined by

$$R(\delta,\tau) = \frac{\langle \rho_1'(t) \quad \rho_2'(t+\tau)\rangle}{\langle \rho_1'(t)^2\rangle^{0.5} \langle \rho_2'(t)^2\rangle^{0.5}}$$

where τ is the time delay for which the correlation is calculated. Note that, for $\tau = 0$, $R(\delta,0)$ is just the previously defined spatial correlation coefficient, and for $\delta = 0$, $R(0,\tau)$ is just the ordinary autocorrelation coefficient. In Fig. 4 $R(\delta,\tau)$ is shown as a function of τ for several values of δ lying in the x, or flow, direction. Each curve has a maximum whose time delay is proportional to δ, the separation between sampled points. The proportionality factor is about 7 m/sec., the same as the flow velocity. (Previous measurements [8] have indicated that the axial flow velocity through the flame does not change significantly for the present flame conditions.) This indicates that the turbulent density structures in the flame are simply convected downstream by the flow as is suggested by the Taylor hypothesis.

From Fig. 4 it is clear that the maximum value of the space-time correlation drops as the separation between points is increased. The decrease in the maximum with δ implies that the structures decay as they are convected by the flow. Further, in Fig. 4 it can be noted that the correlation becomes broader in time as δ is increased, indicating additional structural changes other than simple decay are occurring.

In Fig. 5 the space-time correlation is shown for the situation where points 1 and 2 are separated in the transverse y direction. In this case the maximum is always located at $\tau = 0$. This is found for both of the transverse (y and z) directions.

Further information on the structure of the present flame can be obtained by analyzing the joint probability density function (jpdf) of the two-point Rayleigh scattering density measurements. Fig. 6 shows the jpdf of densities measured at two points with separation of 1.2 mm across the flame (y direction). The inset in the figure shows the relative position of the sampled points with respect to the flame brush. Note that point 2 lies further into the flame zone than point 1. Also note that the density axes are normalized by the unburned gas density.

Since the laminar flame thickness(about 0.5 mm) is considerably smaller than the turbulent flame zone(about 4 mm), the jpdf of the densities principally shows the probabilities of finding either burned or unburned gas at the point of measurement [8]. In Fig. 6, the jpdf has three peaks, indicating that the probability of the combination of burned gas at point 1 and unburned gas at point 2 is zero. Further, this is found to be true for all positions of the two points across the flame.

In the low intensity turbulence regime of the present experiments it is generally agreed that the physical structure of the turbulent flame zone consists of a wrinkled laminar flame which fluctuates in position and shape. Under these conditions the wrinkled laminar flame is continous, with no ruptures or pockets of flame. On the other hand, higher turbulence intensity of the proper length scale would cause progressive disintegration of this wrinkled flame, with the formation of discontinuities in the structure and isolated flamelets. In Fig. 7a a schematic of the flame zone consisting of flamelets is shown. If there were flamelets in the present flame, then there should be some cases where there was burned gas at point 1 while there was unburned gas at point 2. Since this has not been found (the missing peak in Fig. 6) we conclude that there are not any flamelets in the present flame. In addition, the same reasoning shows that the present flame cannot be as highly convoluted as sketched in Fig. 7b. However, flame orientations sketched in Figs. 7c, d and e are possible.

For the cases where the axis of the separation between the points lies either in the flow direction, x, or in the plane of the flame, z, the jpdf's show four peaks, indicating the presence of all possibilities of burned and unburned gas at the sampled points. More detailed information on the structure of the flame may be obtained by analyzing the magnitude of each peak for a given separation, and work along these lines is in progress.

Summary

In this paper we describe a Rayleigh scattering technique which makes it possible to simultaneously measure the density of the gas in a flame at two points. Two independent sets of collection optics, and a method of splitting the laser beam and varying the separation of the two sampled points are used. We applied this technique to a grid-generated turbulent V-shaped flame, burning premixed ethylene-air mixture at

equivalence ratio of 0.6 and a flame half angle of 12^{o}. Spatial and space-time correlations of the density are obtained at a point 85 mm above the grid in three orthogonal directions. Based on these analyses we conclude the following: The flame consists of structures whose length scales are the same in three directions. These structures are convected downstream at the flow velocity. Based on the analyses of the joint probability density function of the two-point Rayleigh scattering density measurements we conclude that there are no flamelets in the present flame.

There is still much additional information in a field of two-point measurements which can be extracted with the use of more sophisticated analytical methods. In summary, we have a new diagnostic tool for analyzing and interpreting the structure of turbulent combustions zones. Future experimental work should exploit this diagnostic technique.

Acknowlegements

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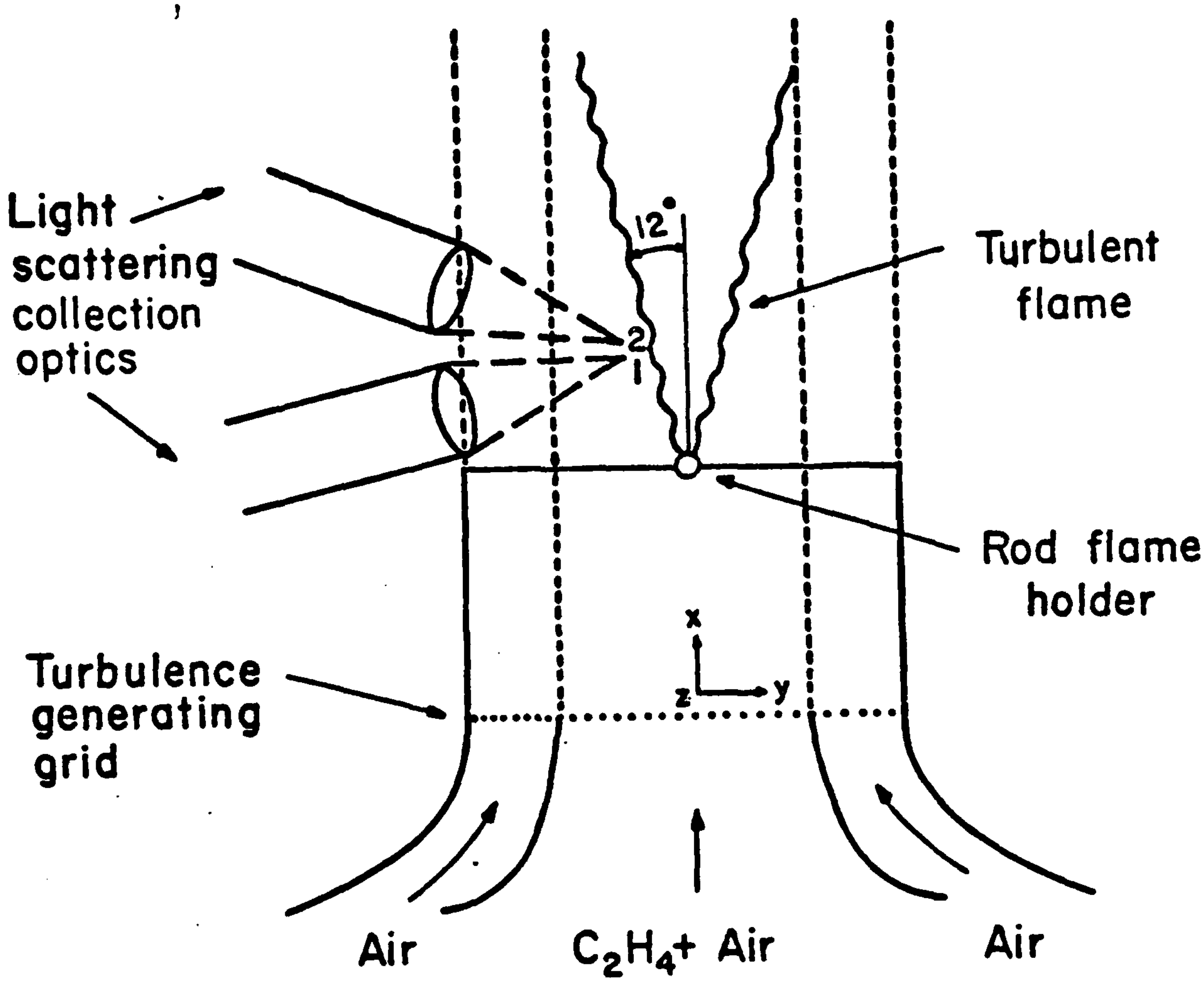

FIG. 1. SCHEMATIC OF THE EXPERIMENTAL APPARATUS FOR TWO POINT RAYLEIGH SCATTERING MEASUREMENTS.

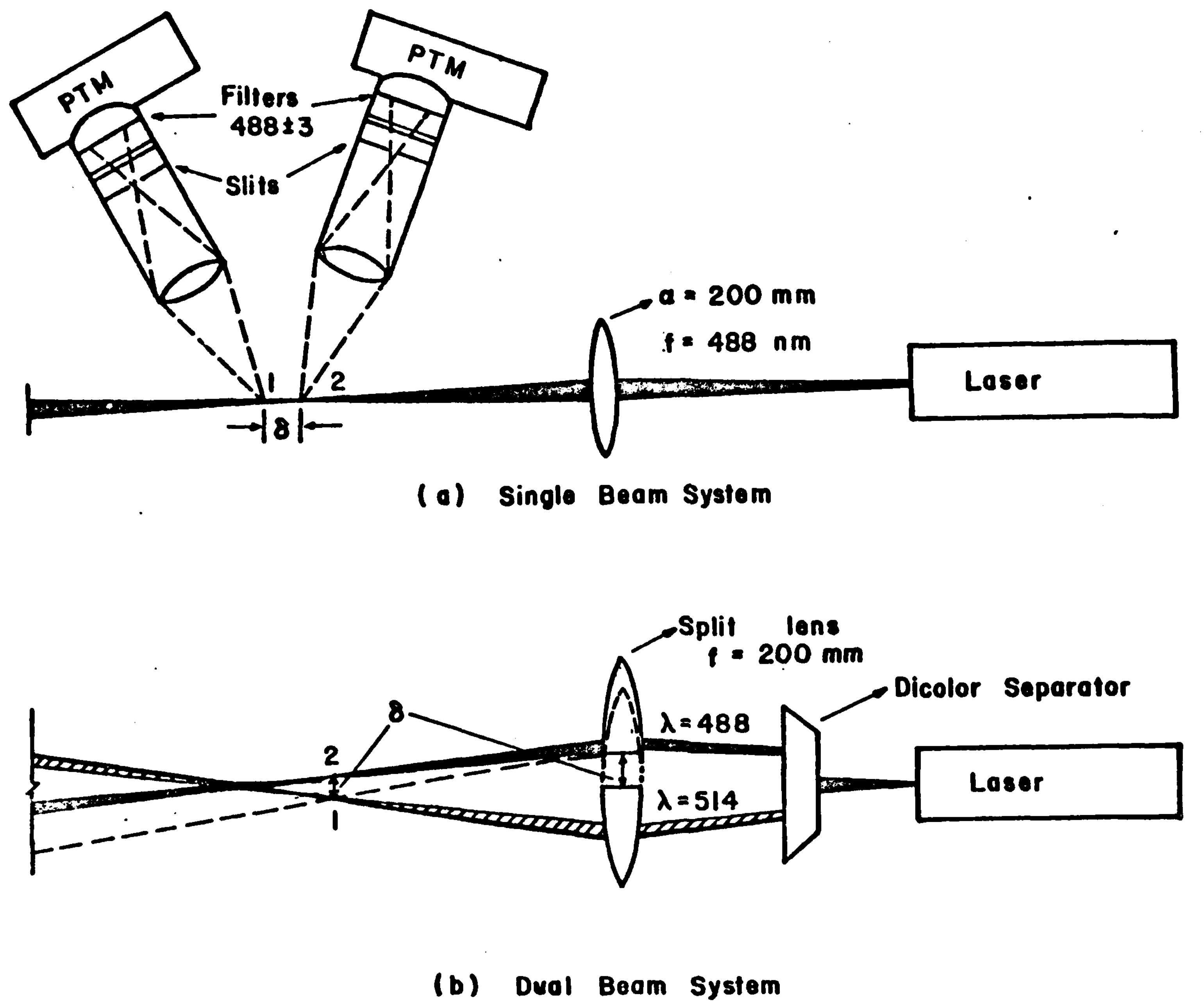

FIG. 2. THE OPTICAL SET-UP FOR TWO POINT RAYLEIGH SCATTERING TECHNIQUE. SINGLE BEAM SYSTEM PROVIDES SEPARATION BETWEEN POINTS IN HORIZONTAL DIRECTION AND DUAL BEAM SYSTEM IN VERTICAL DIRECTION.

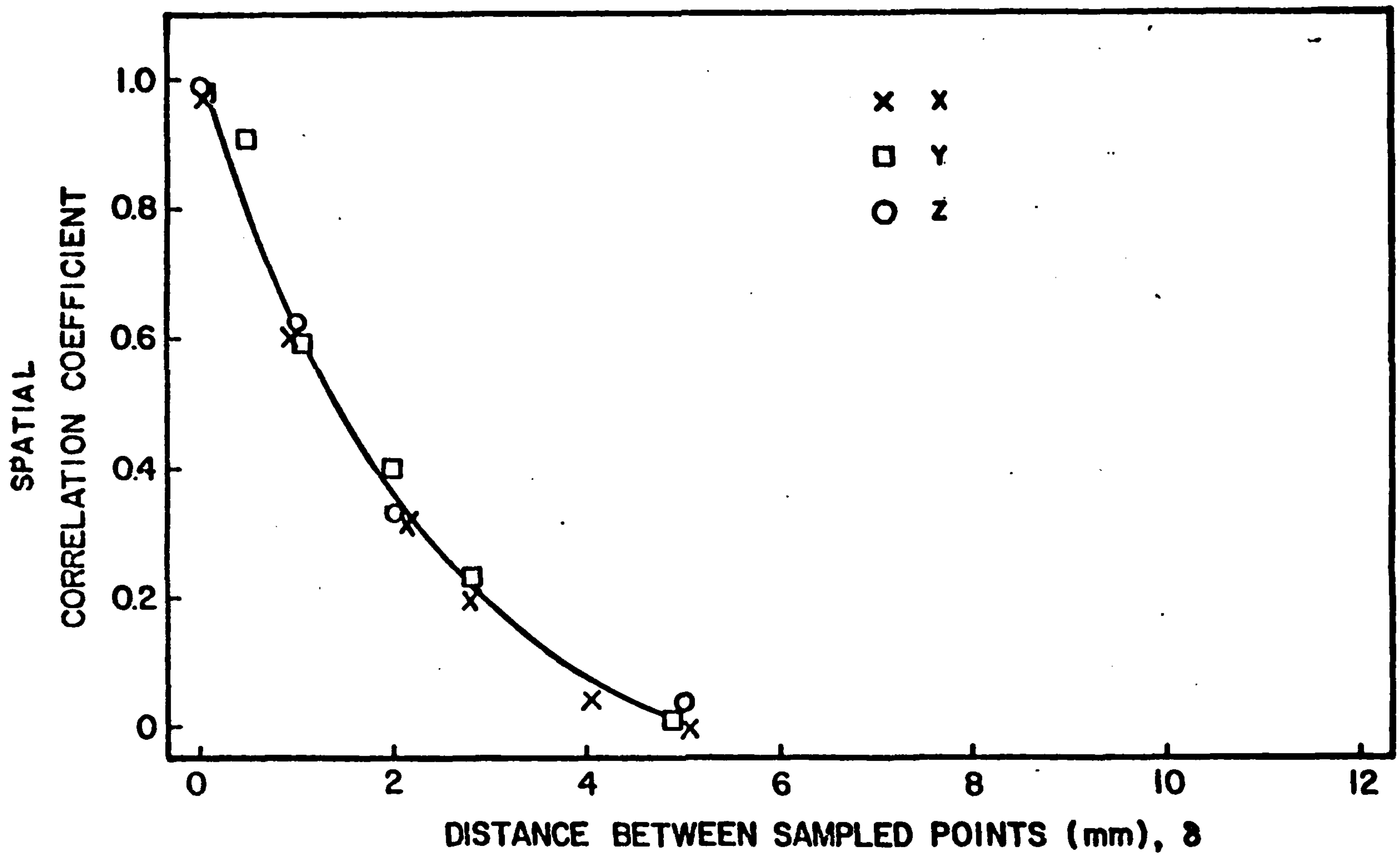

FIG. 3. THE DENSITY SPATIAL CORRELATION IN A TURBULENT FLAME IN THREE ORTHOGONAL X, Y, AND Z DIRECTIONS. MEASUREMENT POINT 35 MM DOWNSTREAM FROM THE FLAME HOLDER.

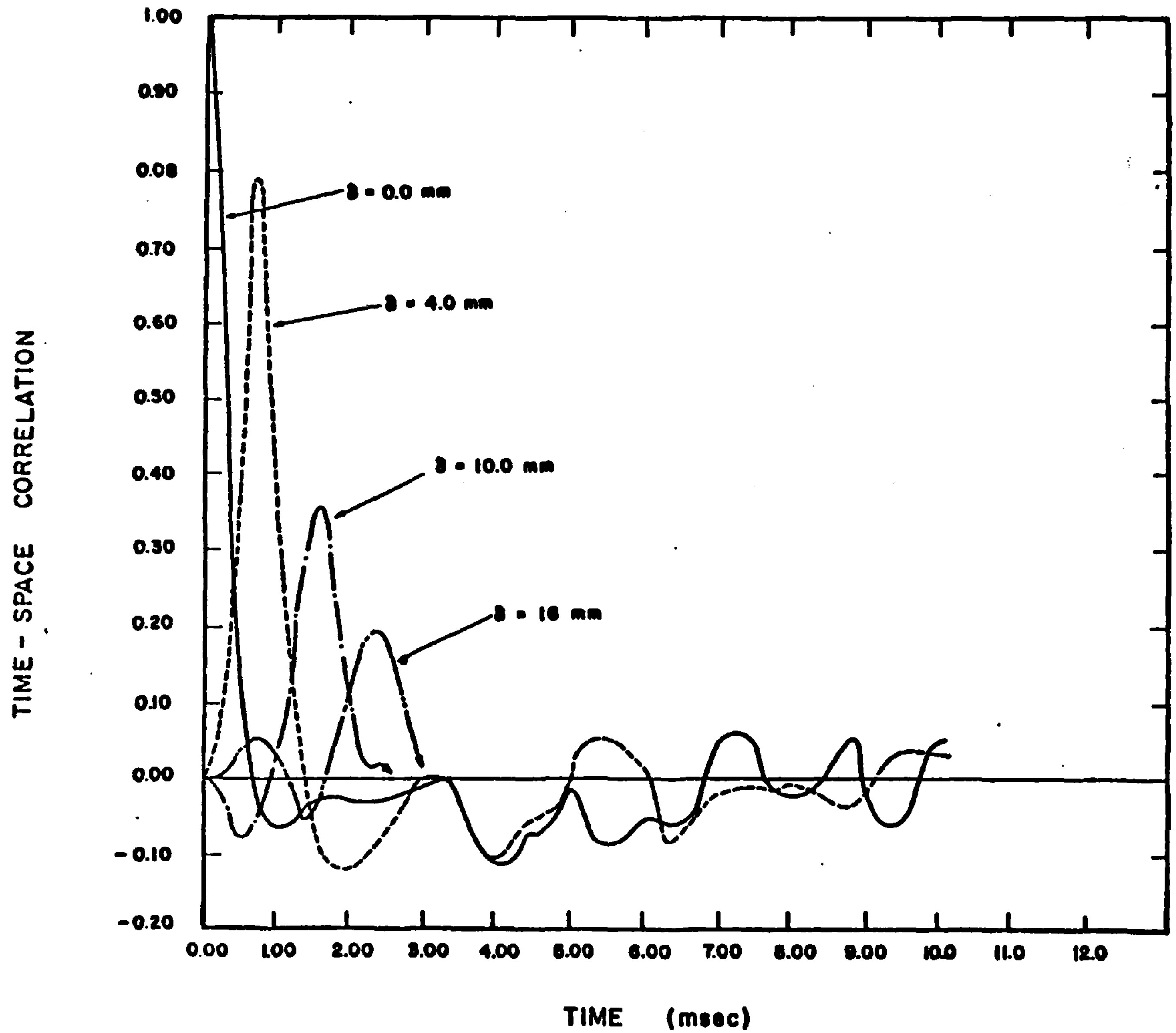

FIG. 4. TIME-SPACE CORRELATION VERSUS THE DELAY TIME FOR SEPARATION OF δ IN THE VERTICAL DIRECTION.

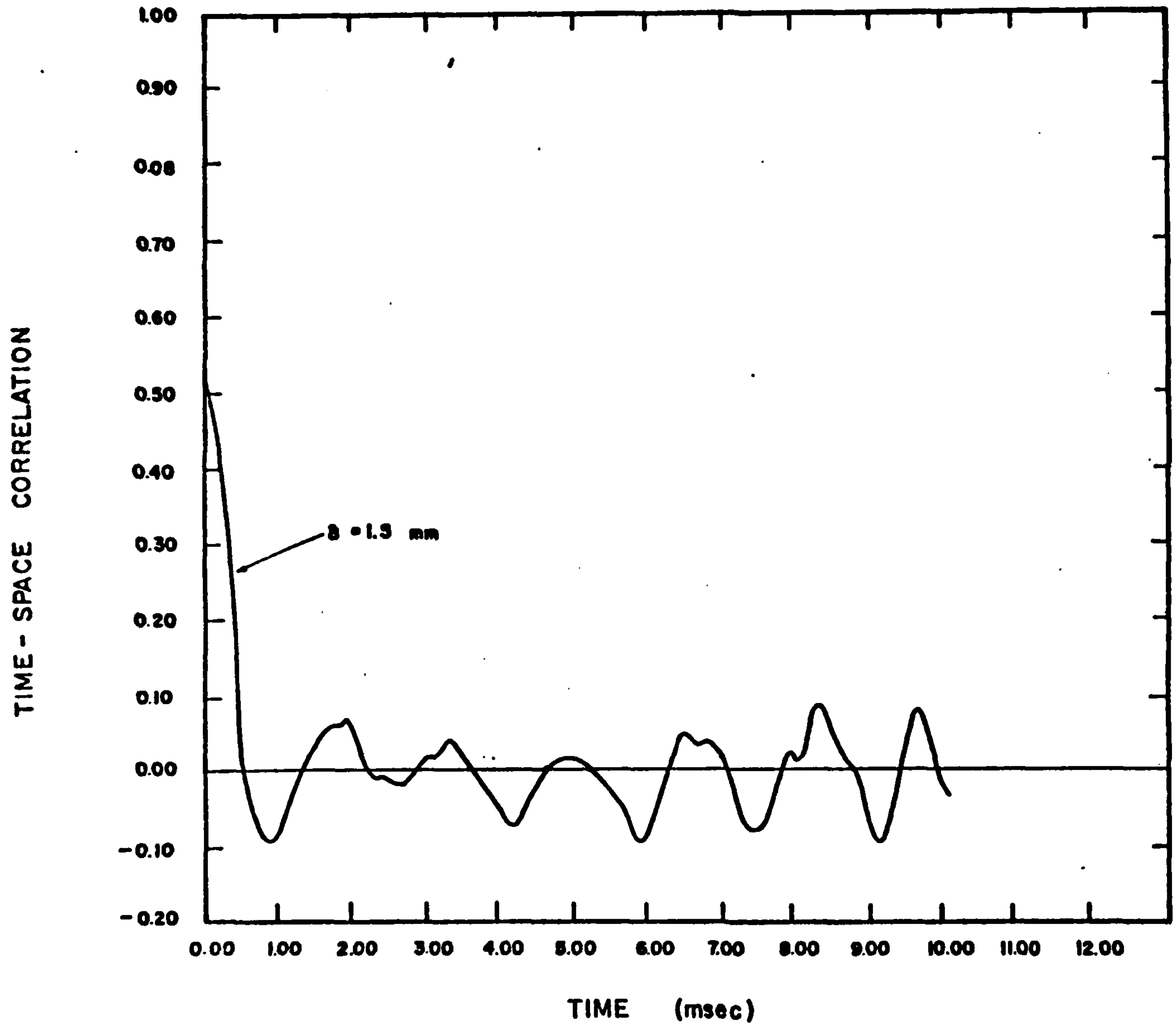

FIG. 5. TIME-SPACE CORRELATION VERSUS THE DELAY TIME FOR SEPARATION δ IN Y DIRECTION.

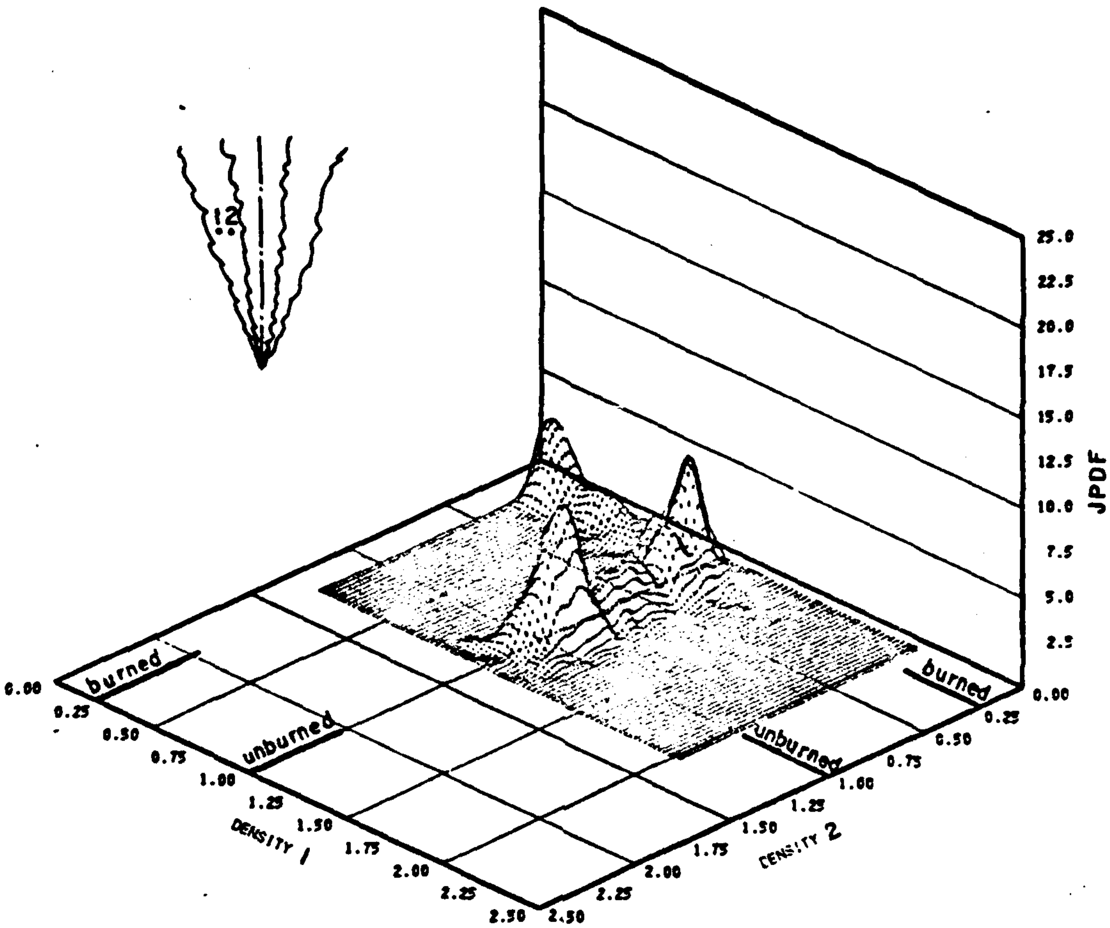

FIG. 6. JOINT PROBABILITY DENSITY FUNCTION OF THE TWO-POINT RAYLEIGH SCATTERING DENSITY MEASUREMENTS. THE POINTS 1 AND 2 ARE SEPARATED BY 1.2 MM ACROSS THE FLAME AS SHOWN IN THE INSET.

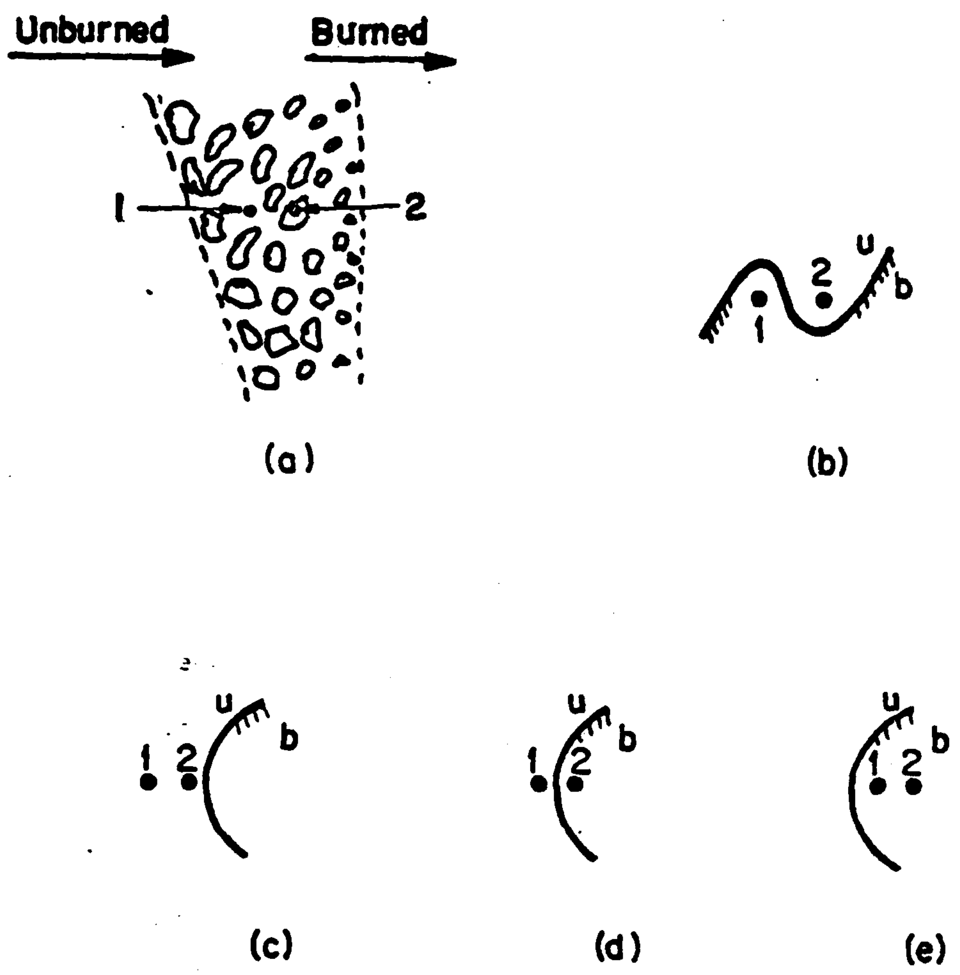

FIG. 7. EXAMPLES OF POSSIBLE FLAME STRUCTURE AND ORIENTATION WITH RESPECT TO THE TWO MEASUREMENT POINTS. FLAMELETS (a) AND CONVOLUTIONS (b) ARE UNLIKELY IN THE PRESENT FLAME. THE ORIENTATIONS SHOWN IN (c), (d) AND (e) EACH CONTRIBUTE TO ONE PEAK IN FIG. 6.

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