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Intermittency and Conditional Velocities in Premixed Conical Turbulent Flames

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ABSTRACT

A turbulent premixed ethylene/air conical flame in a large Bunsen type burner has been studied using a two-component laser Doppler anemometry (LDA) system. Conditioned reactant velocity statistics were measured using a silicon oil aerosol, which evaporated and burned through the flame fronts, as the LDA seed. The intermittency was also determined by monitoring the Mie scattering intensity from the aerosol. The unconditioned velocity statistics were measured using aluminum oxide particles. A conditional analysis method was developed to deduced the conditioned product velocities. The method is based on deconvolution of the velocity probability density function (pdf). The difference between the conditioned mean product velocity and the conditioned mean reactant velocity, ΔU, within the oblique region of the Bunsen flame is less than that observed previously in v-shaped premixed turbulent flames. The main reason is that combustion induced flow acceleration is lower for the lean test mixture. The conditioned product rms velocities are almost equal to the conditioned reactant rms velocities meaning that flame generated turbulence is not significant. The unconditioned and conditioned covariance (Reynolds stress) are negligibly small through the flame. Since the flame brush is almost parallel to the burner axis, this result is consistent with the covariances for the v-flames after the data was transformed with respect to the flame co-ordinate.

Introduction

Recent experimental and theoretical studies of premixed turbulent flames have shown that the conditional velocity statistics are important for the understanding of the interactions between fluid mechanical turbulence and combustion. Our previous studies of premixed turbulent v-shaped flames (Cheng, 1984; Cheng et. al., 1984; Cheng and Shepherd, 1986) have shown that the increases in unconditioned rms velocities in the flame zone and the sharp increase in Reynolds stress are caused by intermittent contributions associated with the difference in the mean conditioned velocities in the reactants and in the products zones. This difference is due to combustion induced flow acceleration across the wrinkled thin flame. Similar behavior of the rms intensities was also observed by Gulati and Driscoll (1984) in their study of an oblique turbulent flame using a combined Rayleigh scattering and one component LDA technique.

Therefore, the true nature of flame generated turbulence is revealed only by comparing conditioned rms velocities and Reynolds stresses obtained in the reactants and products zones. Further, the conditioned velocity statistics also provide the data most suitable for comparison with the theoretical predictions of the turbulent combustion model developed by Bray, Moss and Libby (1985). These data are also appropriate for comparison with other models of premixed turbulent flame such as the model of Ashurst

(1985) using the vortex dynamics method and the intermittency model of Chen, Lumley and Gouldin (1985).

The premixed turbulent conical flame (i.e. using large Bunsen type burners with diameter about 40.0 to 50.0 mm), is also one of the simple idealized experimental configurations designed to study the interaction between turbulence and combustion with minimum influence from geometric and flow constrains. It has been used in early studies of turbulent flame propagation and many visualization records have appeared in the literature (for example the paper of Fox and Weinberg, 1962 for determination of turbulent burning velocity). More recently, the studies are mostly focused on measuring the velocity and scalar statistics for various fuels under different incident turbulence intensities. In a series of studies conducted by Yoshida and Gunther (1980; 1981) using thermocouples and saturated ionization probes, it was shown that under typical flow conditions of 6.0m/s and incident turbulence intensities of 5%, the flame exhibited features of a wrinkled laminar flame. A subsequent study by Yoshida (1982) using a two ionization probe technique demonstrated that the flame structures in a 10mm diameter burner are convected at a velocity close to the free stream velocity.

Also using ionization probes, Suzuki and his collaborators (Suzuki, Masaaki, Hirano and Tsuji, 1979; Suzuki, Hirano and Tsuji, 1979; Suzuki, and Hirano, 1983; Suzuki, and Hirano 1984) focused their investigations on determining the orientations of the wrinkled flame fronts. Their most recent work (Suzuki and Hirano, 1984) involved the use of three closely spaced ionization probes to obtain instantaneous flame front velocities and orientations. The results indicated that instantaneous flame front orientations in a rich ($\phi = 1.1$) propane/air flame with $U_\infty=4.5m/s$ and $u_{rms} = 14\%$ are scattered over a range of more than 180^o and that their velocities (with respect to laboratory coordinate) are typically of the order of U_∞ but sometimes reach several times the free stream velocity at locations close to the product zone. Although an explanation was not given for these large flame velocities, it could be caused by the passage of flame fronts parallel to the plane of the ionization probes. This implies that the flame structures are three-dimensional.

Measurements of velocities in conical flames using LDA were first reported by Kleine (1974), and later by Kleine and Durst (1973), Yoshida and Tsuji (1979) and Yoshida (1981). Most of these results are summerized in a recent review paper by Gunther (1983). The centerline measurements of Kleine (1974), (through the flame tip) showed that the turbulence intensities increase within the flame zone and in the product region, the radial rms velocities decayed rapidly while such a decay was not shown for the axial rms velocities. Yoshida (1981) reported measurements of two velocity components and also the Reynolds stress for a natural gas/air flame with $U_\infty = 5.44\ m/s$, $\phi = 0.8$ and $(\overline{u'^2})^{1/2} = 6\%$. The radial profiles for the rms velocities and Reynolds stress at several locations above the burner exit shown that the turbulence statistics were relatively unaffected by combustion. These results are quite different from those observed in our v-flame studies where the unconditioned rms velocities often increase to several times the incident level.

Measurements of scalar-velocity correlation in conical flames were reported in the studies of Moss (1980) and Yanagi and Mimura (1981). Moss (1980) obtained the correlations by monitoring simultaneously the LDA signal and the Mie scattering from TiO_2 or Al_2O_3 seed particles. Yanagi and Mimura (1981) used a combined thermocouple and LDA technique. The results from both studies are consistent with the co-called counter gradient diffusion for turbulent scalar transport.

The first measurements of conditioned velocities in turbulent conical flames were reported by Shepherd and Moss (1981). The conditional function for the one-component LDA system was provided by monitoring simultaneously the large difference between the Mie scattering intensities of the TiO_2 seed particles in the reactants and products zones. The traverse axis for the velocity measurements was inclined at 23^O with respect to the centerline of the burner and the velocity component parallel to this axis was measured. This orientation was about 50^O to the normal of the flame brush. Their results showed that the conditioned mean product velocities were generally higher that the conditioned mean reactant velocities. However, the conditioned rms velocities did not show any significant differences. Their results were later used for comparison with the predictions of the BML model (Bray, Libby, Masuda, and Moss, 1981). Since only one velocity component was obtained, and several assumptions regarding the behavior of the tangential rms velocity had to be made, the usefulness of these data for a comprehensive comparison with the model was limited.

As demonstrated in our previous study (Cheng and Shepherd, 1986) conditioned velocity statistics derived from two orthogonal velocity components are more appropriate for comparison with models predictions, in particular the BML model. Further more, the results provide a better understanding of the turbulence-combustion interactions in this configuration. The objective of this study is to apply the conditional sampling technique for two-component LDA (Cheng, 1984) to measure conditional and unconditioned velocity statistics in premixed turbulent conical flames. In addition to sampling conditionally and unconditionally using different LDA seeding material, the intermittency factor, Ω was also measured by monitoring the Mie scattering intensities from silicon oil aerosol introduced into the flow. Since the intermittency factor is the probability of encountering the products, it can be interpreted as a measure of the inverse mean normalized density in the thin flame limit. The scalar measurements also provided a means for generalizing the conditional analysis method presented previously (Cheng, 1984). The conditional analysis method involves deconvoluting the conditioned velocity probability density function (pdf) weighted by (1–Ω) from the unconditioned velocity pdf.

Experimental Arrangements and Diagnostic Techniques

Figure 1 shows a schematics of the burner and data acquisition system. The tube burner diameter, D, is 50.0 mm and is 0.5 m long. The fuel/air mixture is supplied by a stagnation chamber fitted with fine screens to supress low frequency turbulence. Incident turbulence in the burner is generated by a perforated plate placed either at the bottom of the burner or at selected distances below the exit. The burner exit is fitted with a ring of pilot flames to enable the stabilization of the turbulent flame under a wide range of equivalence ratios. A cooling water circuit is installed near the exit to prevent preheating of the combustable mixtures. For this study, a lean ethylene/air mixture with equivalence ratio, ϕ, of 0.6 was used. A perforated plate placed at the base of the tube generated incident turbulence level of 10% at the exit. Measurements were made along radial profiles at 50, 75, 100, 125, and 150mm above the burner exit and also along the centerline.

Details of the two-component LDA and the data acquisition systems are included in Cheng (1984). A Spectra-Physics 4.0 watt argon-ion laser is the light source for the two-color (blue 488 nm and green 514 nm) LDA system which uses two Thermal System Inc. (TSI) model 1980A frequency counters. Differential frequency shifting of 2.0 Mhz was employed for the two green beams which measure the radial velocity component. To make conditional measurements of the velocity in the reactants, silicon oil aerosol generated by an atomizer was used. Aluminum oxide particles of 0.3 μm were used for unconditioned sampling of the velocities. The laser and the transmitting and receiving optics were mounted on a three axis stepping motor controlled traverse table interfaced with the data acquisition system.

Typical data rate for each velocity component was about 20 Khz. For conditioned measurements digitizing and recording of the LDA counter outputs were triggered by a co-validation circuit using a coincidence time of 3.0 μsec (Cheng, 1984). At each measurement position, 4096 pair of validated LDA data were recorded and stored on magnetic tape. However, the unconditioned velocities were sampled simultaneously at a fixed frequency of 2.0 khz. This technique is generally accepted as one of the simplest means to reduce the effects of particle concentration biasing.

The intermittency factor was obtained by measuring the Mie scattering intensities from the silicon oil aerosol seeded in the flow. The sampling rate was also 2.0 khz. Typical raw data time trace of the Mie scattering intensity within the turbulent flame brush is shown in Fig. 2. As can be seen, the signal is quite similar to the Rayleigh scattering signal shown in by Namazian et. al. (1984). The essential two state nature of the signal and sharpness of the transistions between the two states is clear. The intermittency factor is defined as :

$$\Omega = \frac{\sum_{i}^{n} (\tau_b)_i}{\tau_T} \tag{1}$$

where $(\tau_p)_i$ is the passage time for the products (or the burned state) and τ_T is the total duration of the data record. The passage time is deduced from the data using a threshold criterion of 50% of the maximum signal to separate the time spent in the burned products and unburned reactants states. Since the transition from reactants to products is sharp, the results of Ω are not sensitive to the choice of the threshold value. The value of Ω for the data trace shown in Fig. 2 is 0.521, therefore the total time spent within the two states are approximately equal.

Conditional Analysis Method

When the overall time mean turbulent flame thickness is large compared to the laminar flame thickness, the flame turbulence can be described by an intermittency model (Cheng, 1984) which expresses the unconditioned mean velocities U and V in terms of the intermittency factor Ω and the corresponding conditioned velocities in the reactants and int the products, subscripted r and p respectively. The mean velocities are :

$$U = (1-\Omega)\, U_r + (\Omega)\, U_p \tag{2}$$

$$V = (1-\Omega)\, V_r + (\Omega)\, V_p \tag{3}$$

the mean square fluctuations are :

$$\overline{u'^2} = (1-\Omega)\, \overline{u'^2}_r + \Omega\, \overline{u'^2}_p + \Omega(1-\Omega)(U_p - U_r)^2 \tag{4}$$

$$\overline{v'^2} = (1-\Omega)\, \overline{v'^2}_r + \Omega\, \overline{v'^2}_p + \Omega(1-\Omega)(V_p - V_r)^2 \tag{5}$$

and the covariance (Reynolds stress) is :

$$\overline{uv} = (1-\Omega)\, \overline{uv}_r + \Omega\, \overline{uv}_p + \Omega(1-\Omega)(U_p - U_r)(V_p - V_r) \tag{6}$$

In principle, the conditioned velocity statistics in the products can be deduced algebraically from this set of equations using experimentally determined values of Ω, the unconditioned velocity statistics and the conditioned reactants velocity statistics. However, in practice, this procedure is not always satisfactory due to the run-to-run variations in the experiments and accumulated error associated with summing or subtracting two sets of experimental data. This error is most significant for data obtained near the cold boundary of the flame zone where the probability of encountering the product states is low and the magnitudes of the unconditioned and conditioned reactants velocities are almost equal.

Although in our previous investigations (Cheng, 1984; Cheng, Robben and Talbot, 1984) the intermittency factor was not measured experimentally, conditional analysis was possible because of the bimodal nature of the velocity joint probability density function (jpdf). The two probability peaks pertaining to the reactants and the products zones did not overlap and the peak for the reactants would be easily identified by comparing the contours of conditioned and unconditioned jpdfs on the $U-V$ holographic plan. As a results, the conditioned velocity statistics for the two zones can be obtained simply by individual statistical analysis of each of the two jpdf peaks.

When the unconditioned velocity jpdf is not distinctly bimodal, which is the case for the conical flame data, conditional analysis by deconvolution is necessary. The conditioned products velocity jpdf $p_p(U,V)$ can be deduced by deconvolving the unconditioned jpdf $p(U,V)$ from the conditioned reactant jpdf $p_r(U,V)$.

$$p_p(U,V) = \frac{p(U,V) - (1-\Omega)\, p_r(U,V)}{\Omega} \tag{7}$$

Of course the results of deconvolution would have the same accumulative error as those obtained using Eq. (2-6) since they are deduced from the same set of raw data. However, the error can be reduced significantly by smoothing the jpdfs prior to deconvolution and this is the the main attribute of this procedure.

To deduce the conditioned mean and rms fluctuations for the products, deconvolving the probability density function (pdf) for each velocity component is adequate. To deduce the conditioned covariance requires deconvolving the jpdfs. Since the two dimensional smoothing algorithm for the jpdfs is complex and not very economical, and the cubic spline fit of the one component pdf is much more straightforward, only the mean and the rms velocities have been obtained.

Shown in Fig. 3 are the conditioned and unconditioned pdfs for the radial velocity component before they are smoothed. The conditioned reactant pdf is shown weighted by $(1-\Omega)$ according to Eq. 7. This set of measurements were obtained at the center of the flame brush corresponding to Ω=0.543. As can be seen the unsmoothed pdfs are quite noisy and the unconditioned pdf is not clearly bimodal. The difference between the unconditioned pdf and the weighted reactant pdf is the deconvolved conditioned product pdf weighted by Ω. Note that the products pdf is noisy in the range of 0–1 m/s. This is due entirely to subtracting the pdfs in a velocity range where the probability of the products velocity is low or zero. The mean and especially, rms velocities deduced from the deconvolved product pdf would contain error due to this noise. As mentioned earlier, this problem is most severe for data obtained near the cold boundary of the flame brush.

The same pdfs after they are smoothed by a 100 points cubic spline fit are show in Fig. 4. Note that smoothing enhences the bimodal feature of the unconditioned pdf. Also the noise is not present in the products pdf.

Results

The radial profiles of intermittency obtained at four positions above the burner exit are compared in Fig. 5. The shapes and trends of the profiles are generally consistent with the normalized temperature profiles of Yoshida (1981). The radial profile obtained at 50mm (x/D = 1) is also consistent with the normalized density profile reported for the turbulent v-flames by Namazian and Shepherd (1986). The overall features and orientations of the flame brush are better shown by the contours of the intermittency constructed by using the radial profiles and the axial profile, Fig. 6.

In Fig. 6, the contours show that the flame brush above the exit rim grows rapidly and meet to form the flame tip at x = 75 mm (x/D= 1.5). Along the centerline axis, the thickness of the flame brush is over 75mm compared to a radial thickness of about 20mm at x = 50mm. The growth rate of the conical flame brush is much more rapid than that observed in turbulent v-flames under similar ethylene/air equivalence ratio but with lower turbulence intensity (5%). If the Ω=0.5 contour is selected to represent the mean orientation of the flame brush, it can be seen that the flame brush above the exit rim is almost parallel to the flow. It only becomes more oblique to the flow near the flame tip region.

Shown in Fig. 7 are the radial profiles of the unconditioned mean axial velocity component U, and the radial component V obtained for $x = 50mm$ where the flame brush extends from $y = 16$ to $27mm$. Also shown are the conditioned mean velocities for the reactants U_r and V_r measured using silicone oil aerosol and the corresponding conditioned products velocities U_p and V_p computed by deconvolution. The U, U_r and U_p profiles (Fig. 7(a)) are not significantly affected by combustion. Within the flame brush, the differences between U_p and U_r are less than $0.2m/s$. This is about the same order of magnitude as the run to run variation shown outside of the flame region by comparing U and U_r. The decrease in axial velocities from the flame centerline is caused by outward deflection of the streamlines as demonstrated by the profiles of the radial velocity component (Fig. 7 (b)). The deflection corresponds to increases in the radial velocity. Both the V and V_r profiles show that the deflection begins before the flame zone. Within the flame, V increases rapidly and peaks at the outer boundary of the flame (y = 28 mm) which is followed by a decrease in the products zone. The V_r profile also increases within the flame but the increase is less significant. The values of V_p are higher than the corresponding V_r which indicate the change in the conditioned velocities across the flame front. These features of the radial velocity profiles are consistent with those observed in the v-flames. Since U_r and U_p are almost equal, the differences between V_r and V_p can be regarded as proportional to the relative velocity (or the slip velocity) ΔU. The value of ΔU shown here is only about 1.0 m/s.

The conditioned and unconditioned rms velocity profiles for the axial and radial components are shown in Fig. 8. The unconditioned axial rms velocity is constant across the burner and remains unchanged through the flame zone. Within the flame brush, the conditioned rms velocity for the reactants $(\overline{u'^2}^{1/2})_r$ is slightly lower than $\overline{u'^2}^{1/2}$ and the conditioned rms velocity for the product $(\overline{u'^2}^{1/2})_p$ is higher. The difference between $(\overline{u'^2}^{1/2})_p$ and $(\overline{u'^2}^{1/2})_r$ is only about $0.1m/s$. The radial rms velocity profiles $\overline{v'^2}^{1/2}$ and $(\overline{v'^2}^{1/2})_r$ both show that the fluctuation intensities decrease towards the edge of the burner. Therefore, the incident turbulence at the boundary of the flame brush is slightly anisotropic ($\overline{u'^2}^{1/2}$=0.7m/s and $\overline{v'^2}^{1/2}$=0.55m/s). Within the flame, $\overline{v'^2}^{1/2}$ shows a slight peak while $(\overline{v'^2}^{1/2})_r$ decreases further to only 0.3m/s at the hot flame boundary. Note that the value $\overline{v'^2}^{1/2}$ attained at the peak is even lower than the free stream intensity.

The conditioned and unconditioned profiles of the covariances $\overline{uv}$ and $\overline{uv}_r$ are compared in Fig. 9. It is evident that there is very little difference between the two profiles. Between y = 5 and 15 mm, the covariances are positive and remain at about 0.1$(m/s)^2$. However, within the flame zone, the covariances are both about zero. This results also indicate that the conditioned products covariance $\overline{uv}_p$ should also be about zero. As mentioned earlier, to compute $\overline{uv}_p$ is complex and requires deconvoluting the two dimensional jpdf. Since, the difference between the two experimentally measured covariances is so small that the results of the deconvolution would not be accurate. In the light of these considerations, it did not seem worthwhile to carry out the deconvolution to obtain $\overline{uv}_p$.

Discussions and Concluding Remarks

Our study of the turbulent conical flame, has shown that the turbulence behavior is different than that of the v-flames. The main difference is that the significant increase in the unconditioned rms velocity is not found through the flame brush. Also the unconditioned covariance is unchanged in the flame zone.

As pointed out in our previous investigation of v-flames (Cheng et. al. 1984), the increase in unconditioned fluctuations seems to be proportional to the relative velocity ΔU. This relative velocity can be inferred by the velocity jump across a one dimensional laminar flame U_τ which is proportional to S_u $(\tau-1)$. Here, S_u is the laminar flame speed and τ is the reactants/products density ratio. For the present ethylene/air mixture of $\phi = 0.6$, S_u is 0.23 m/s and τ is 6.0. Therefore, U_τ is estimated to be 1.14 m/s. This is lower than the $U_\tau = 2.3$ m/s estimated for the $\phi = 0.7$ ethylene air mixture used in our v-flame studies. Since a significant portion of the contributions to the unconditioned rms velocity is from ΔU, the lowered U_τ value for the present test mixture would result in lowering the unconditioned rms velocities.

Another reason for the lack of increase in unconditioned velocity fluctuations concerns with the ratio between U_τ and the incident turbulence which indicates the relative contributions of the first and third terms in Equations 3 and 4. The $U_\tau/\overline{u'^2}^{1/2}$ ratio is 1.8 for the conical flame while the one for the v-flames is 9.0. Therefore, the ΔU contributions in the v-flames are significantly larger than the incident turbulence. Consequently, the effects of ΔU is much more apparent. For the leaner conical flames, where ΔU is less significant compared to the incident rms velocity, a sharp increase in the flame zone is not found.

The lack of changes in the unconditioned covariance can be explained by the fact that the flame brush is not oblique to the burner axis. In fact as mentioned earlier, the Ω=0.5 contour indicates that the flame brush is almost parallel to the x-axis at one diameter above the burner exit. The behavior of the covariance is consistent with the results obtained in the v-flames after they are transformed to the coordinate normal to the flame brush (Cheng and Shepherd, 1986). The transformed mean velocities for the v-flames show that only the velocity component normal to the flame increase within the flame while the mean tangential velocity component remains constant. The mean velocity profiles shown in Fig. 7 is consistent with this description. The transformed rms velocity profiles for the v-flames also show that contributions to the unconditioned rms fluctuations appear only in the normal component. This feature is again shown in Fig. 9. Finally, the unconditioned covariance in the v-flames becomes insignificant after the transformation, and this also explains the lack of difference between the conditioned and unconditioned covariance measured in the present conical flame.

Our investigation has shown that although the characteristics of the flame turbulence measured in the conical flame appear to be different that those observed in the v-flames, based on the analysis of conditioned velocity statistics and the transformed velocities for the v-flames, the differences can be explained satisfactorily. The features of the flame turbulence are basically the same in the two flame configurations. One of the main effects of the high incident turbulence in the conical flame seems to be a masking of the contributions due to the relative velocity ΔU. Since ΔU seems to be proportional to the mixture composition and is not expected to be much larger than a few m/s for most hydrocarbon fuels, it seems reasonable to suspect that with even higher incident turbulence, the contribution from ΔU would not be found.

This may be the reason why Moreau and Boutier (1976) did not find any change in velocity fluctuations in their study of an enclosed flame with incident velocity of about 100 m/s. Our study of turbulent conical flame will continue and include the use of other hydrocarbon fuel as well as decreasing and increasing the incident turbulence.

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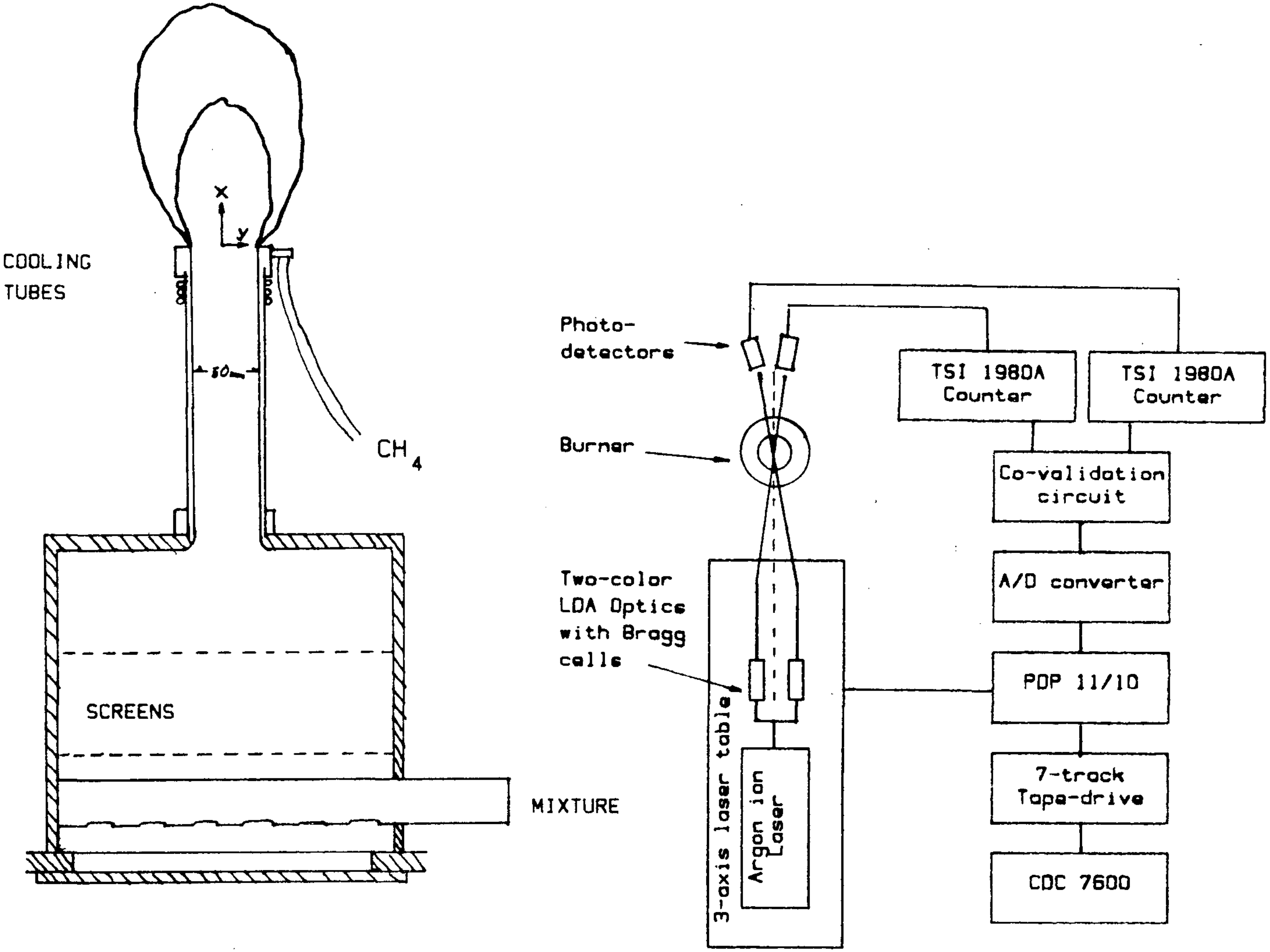

Fig. 1 Experimental Schematic

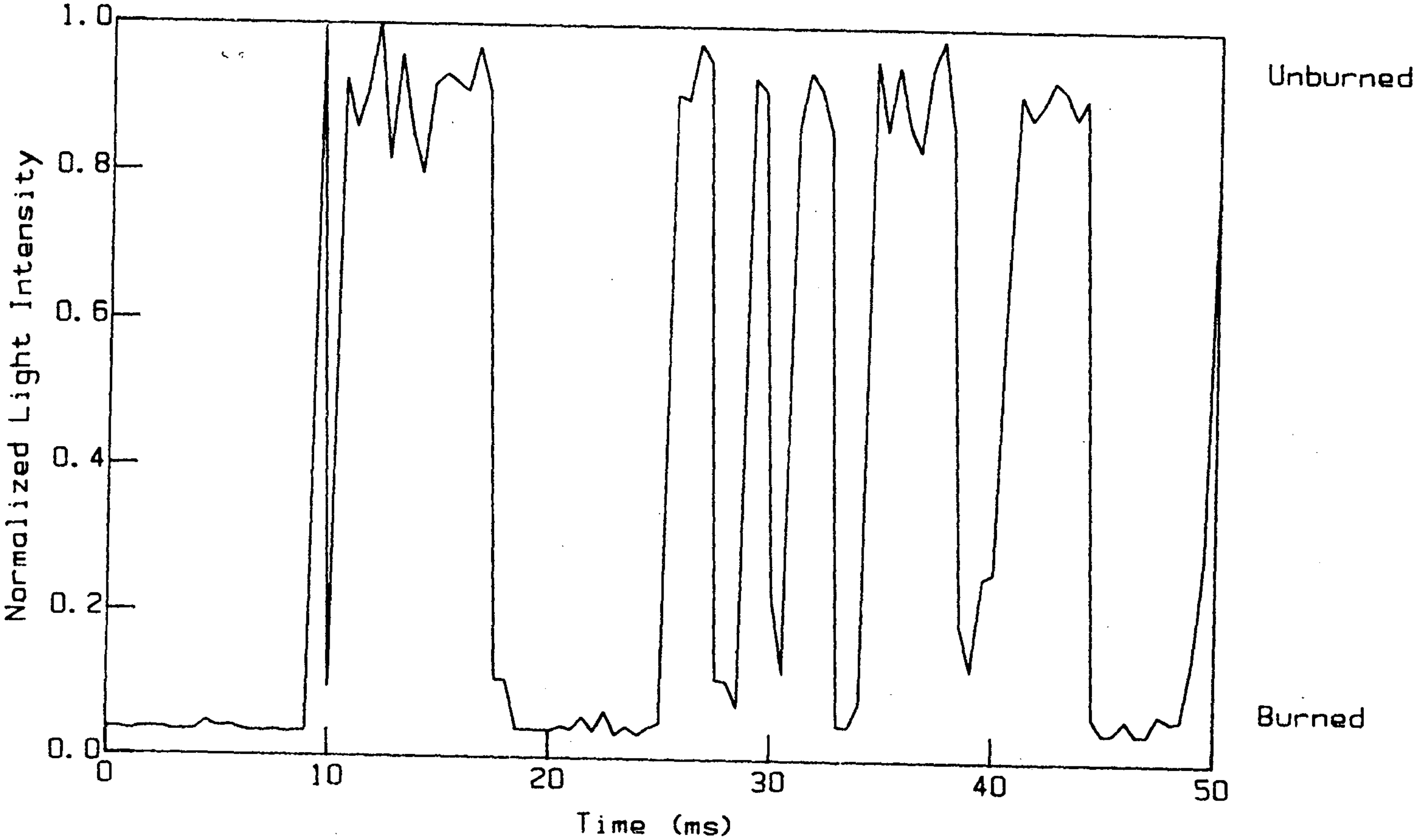

Fig. 2 Typical Mie scattering data. Normalized raw data, x =50mm Ω=0.521

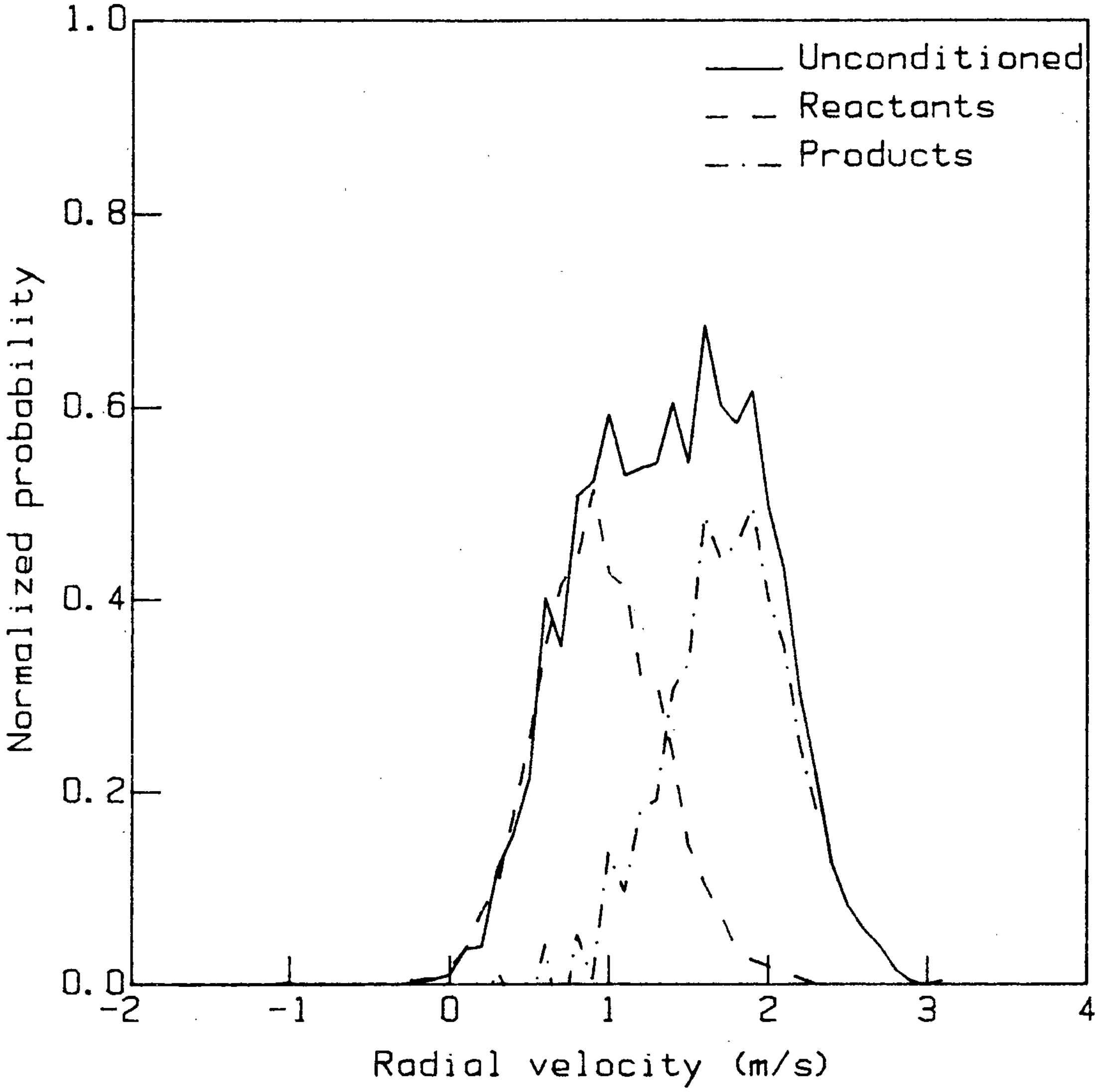

Fig. 3 Unsmoothed radial velocity pdfs. $x = 50mm$ $\Omega = 0.543$

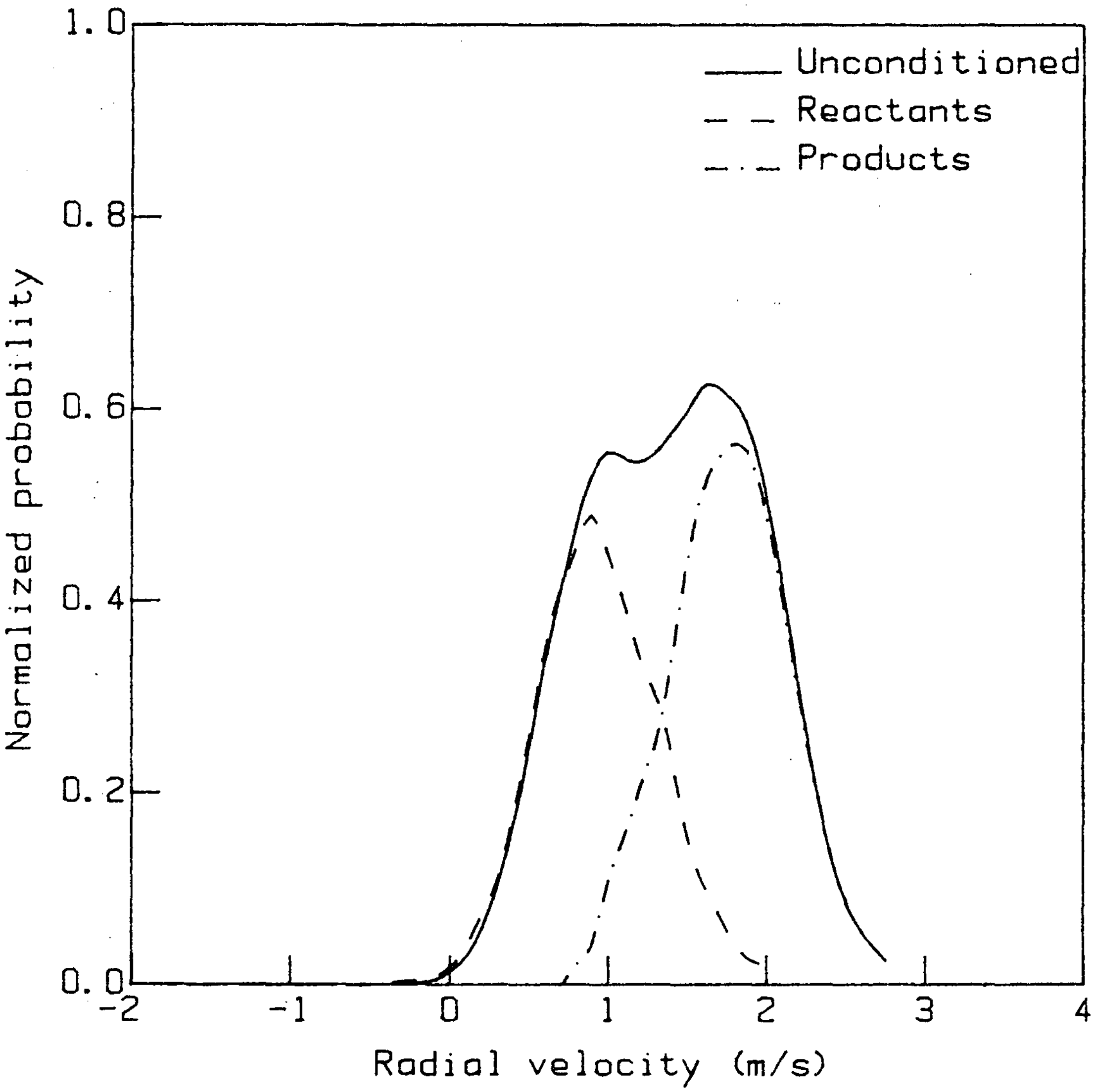

Fig. 4 Smoothed radial velocity pdfs. $x = 50mm$ $\Omega = 0.543$

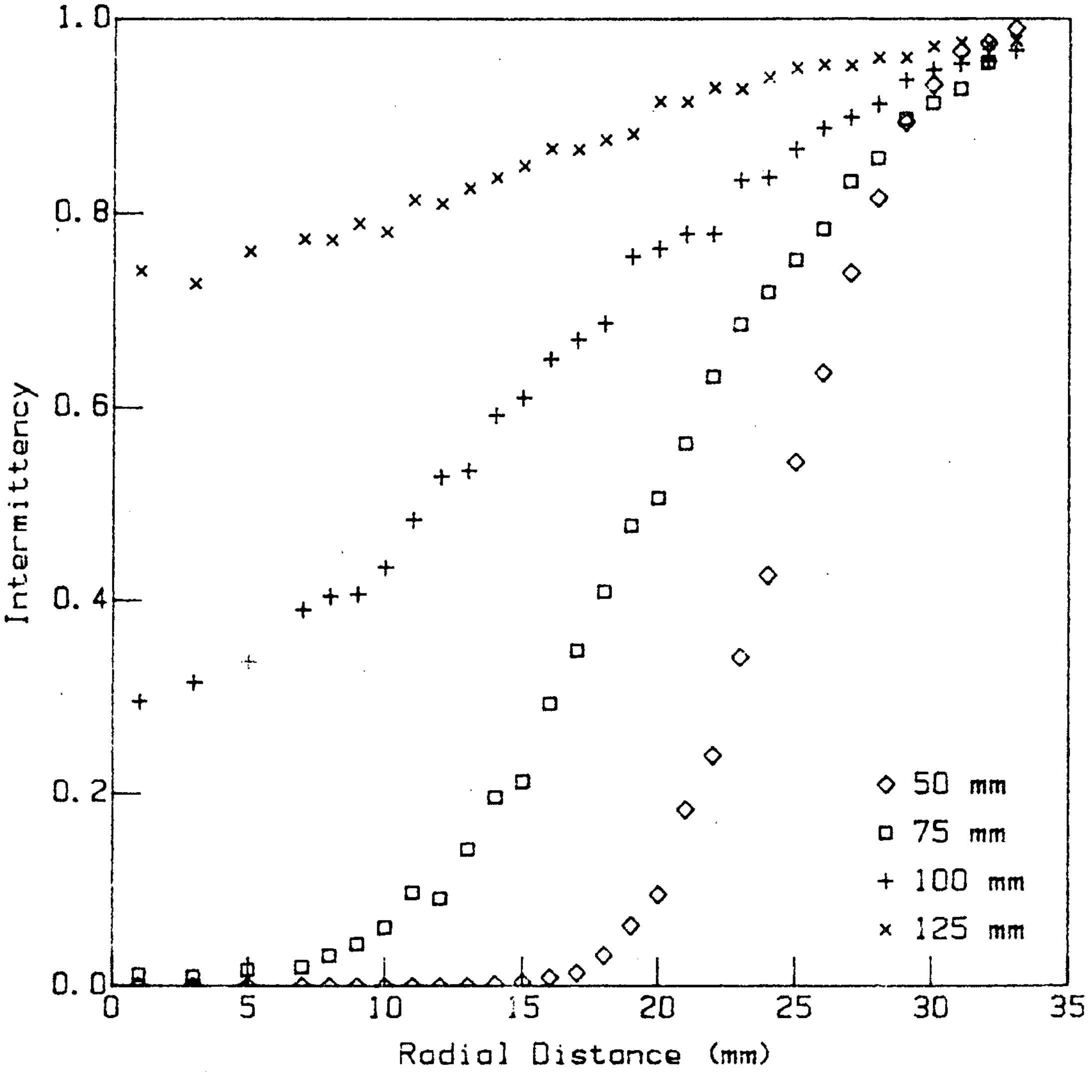

Fig. 5 Radial profiles of intermittency.

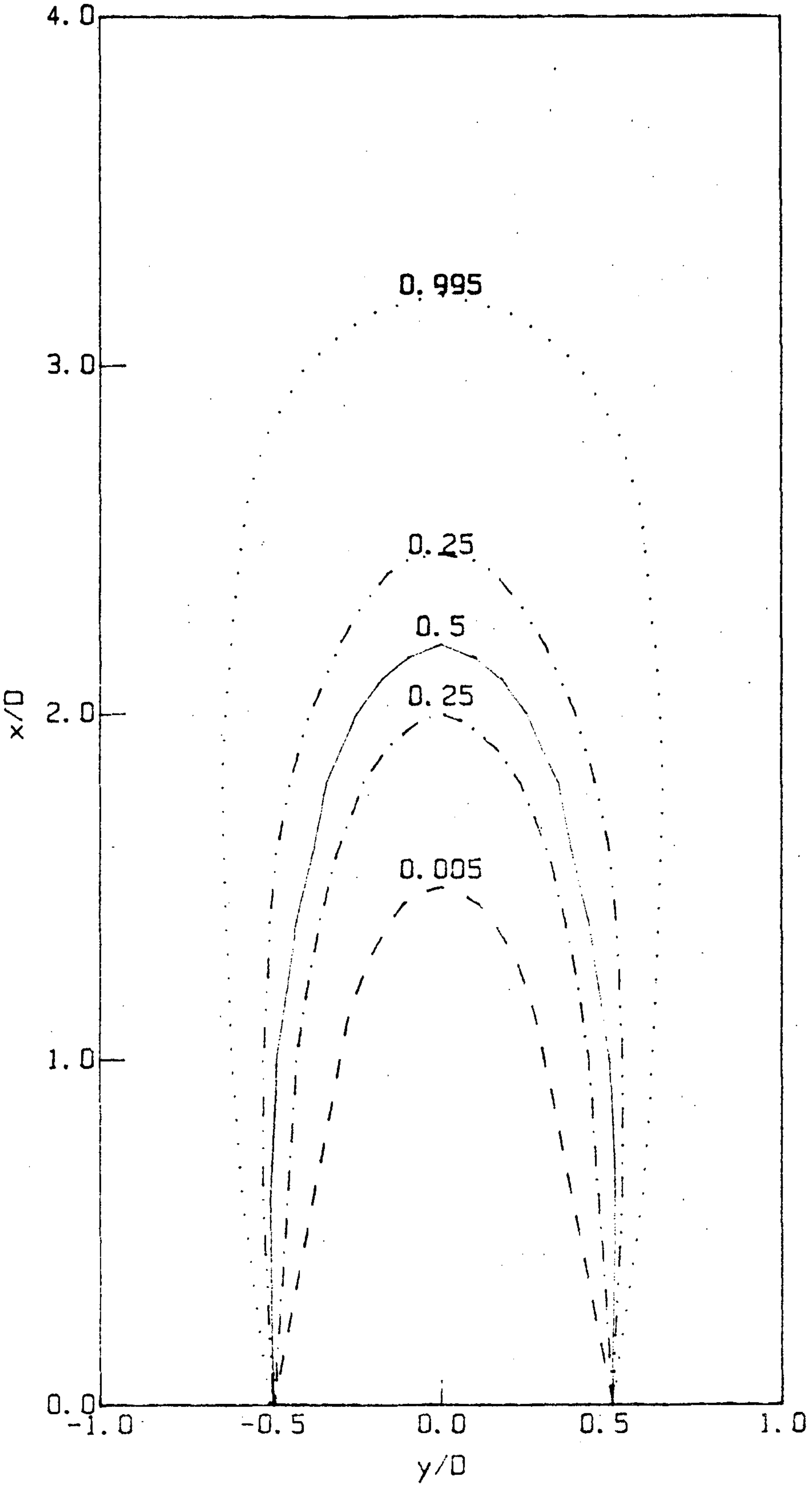

Fig. 6 Intermittency contours.

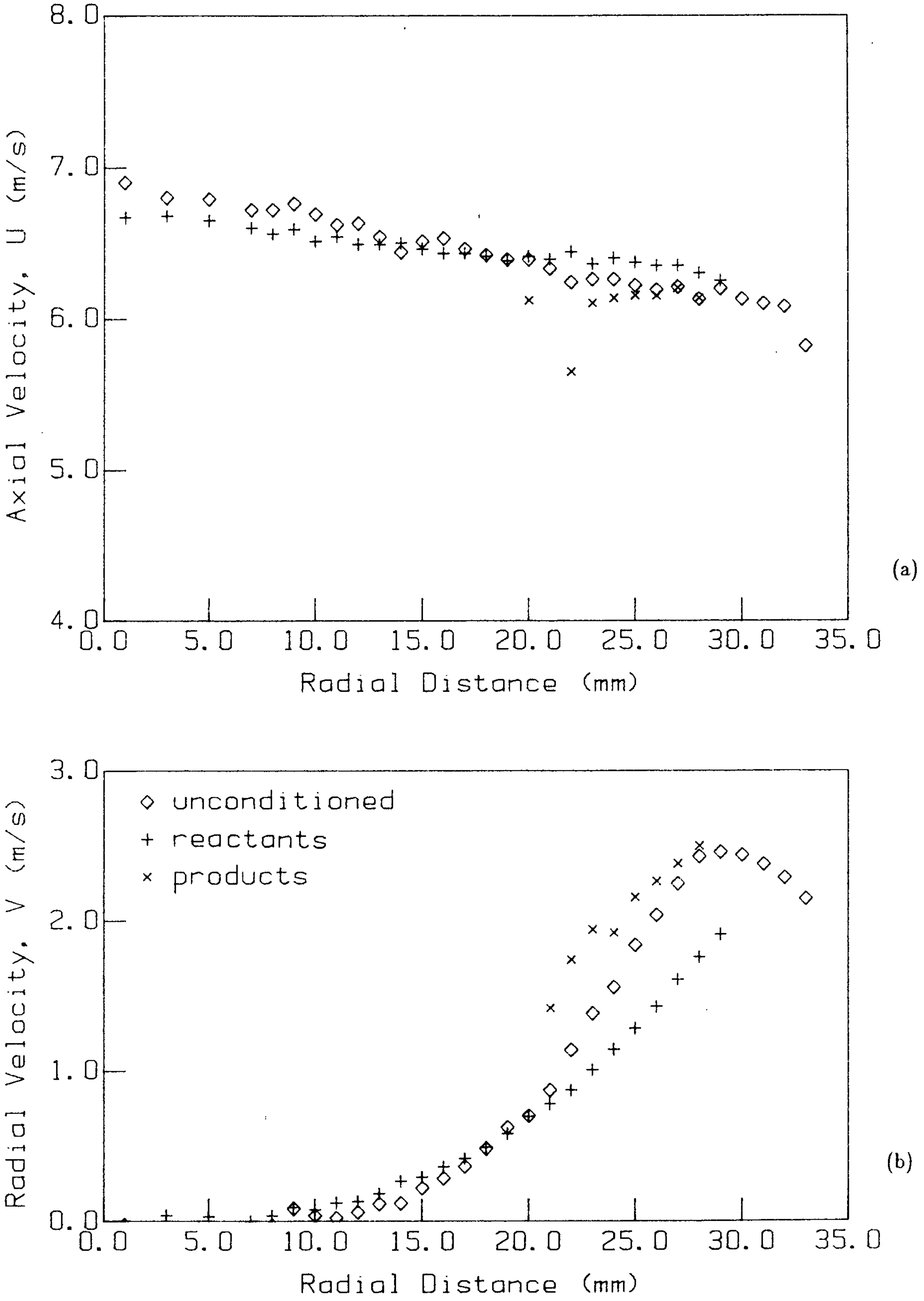

Fig. 7 Conditioned and unconditioned mean velocity profiles. $x = 50mm$ (a) Axial component (b) Radial component

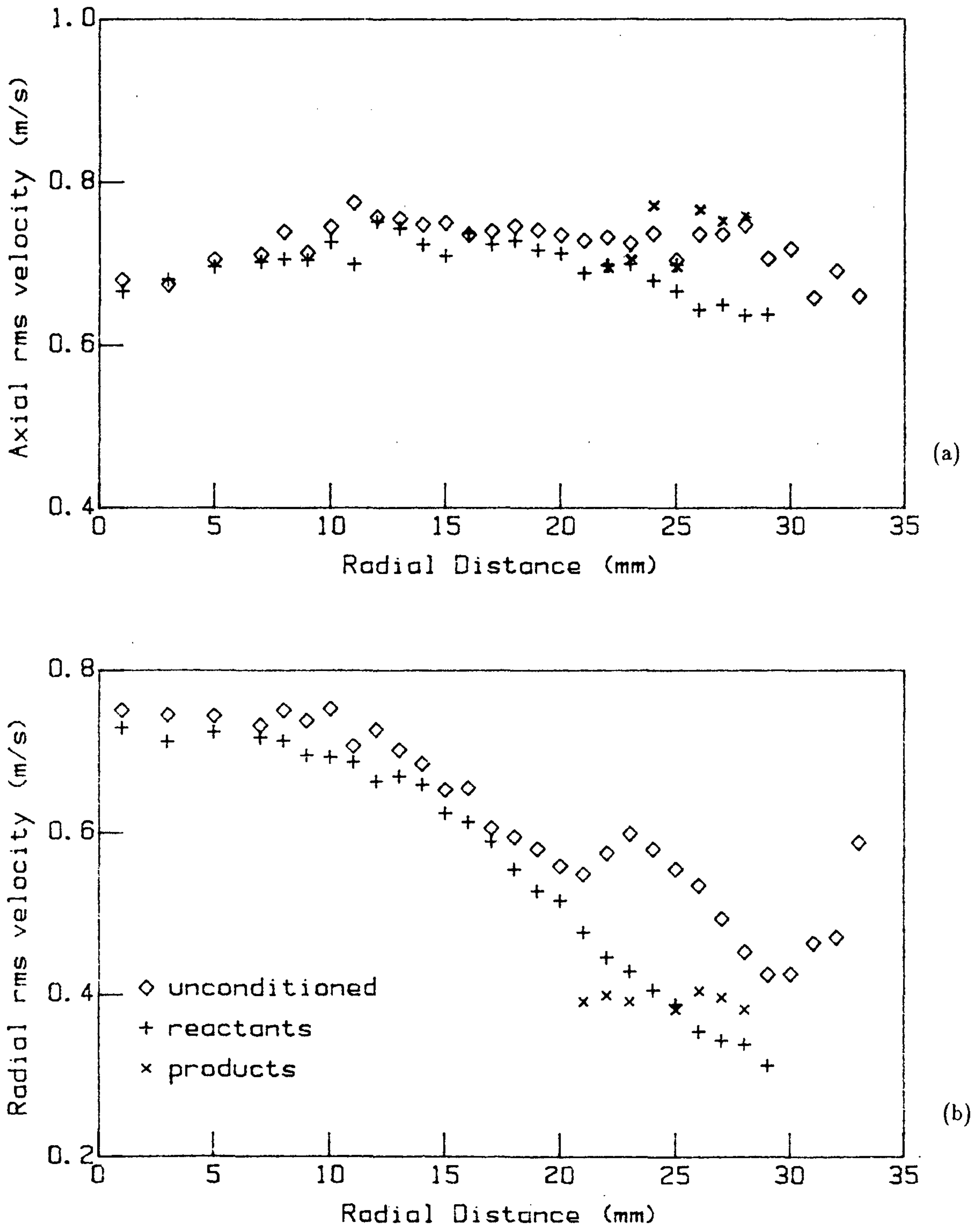

Fig. 8 Conditioned and unconditioned rms velocity profiles. $x = 50mm$ (a) Axial component (b) Radial component

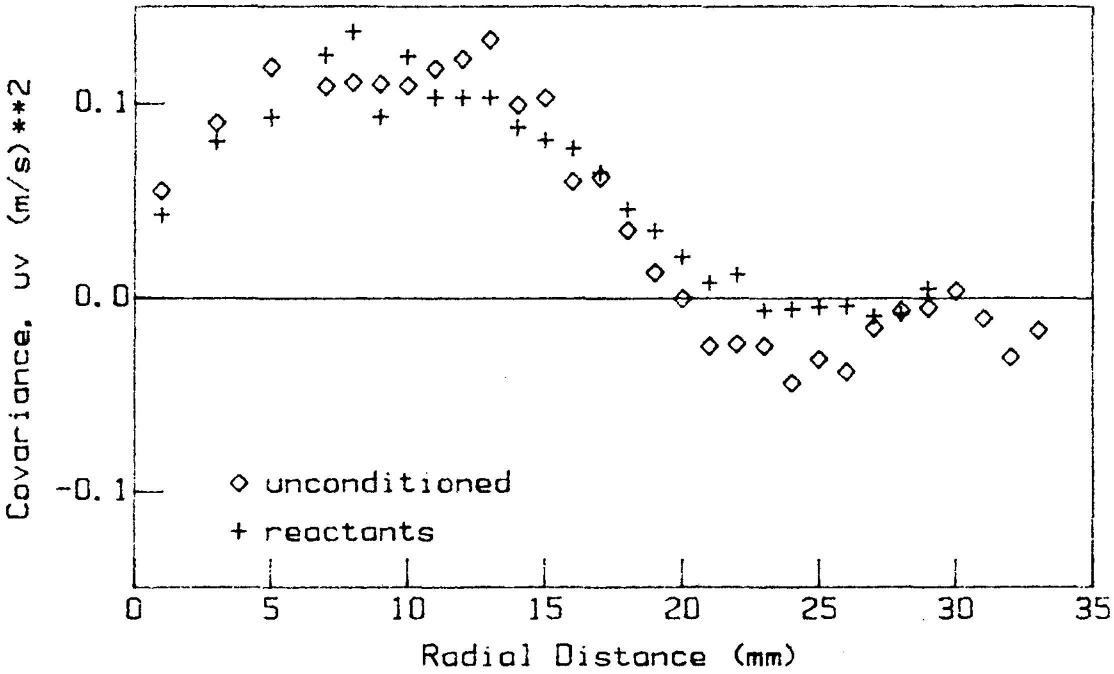

Fig. 9 Conditioned and unconditioned covariance. $x = 50mm$

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