Flame Structures in the Near Wake of Circular Cylinders

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Gas density measurements of premixed rod-stabilized CH_4/air flames have been obtained in the near-wake region using laser-induced Rayleigh scattering. Profiles of mean density, turbulence density, probability density functions, and spectra were calculated from the data. For the Reynolds number range of this study ($R = 1000$-2000), the flame brush thickness and turbulence intensity increase with distance downstream, while the probability density functions undergo a transition from single peak distributions to bimodal distributions. Probability density functions indicate that intermediate states of the flame structure make significant contributions to the turbulence intensity in the near-wake region for this Reynolds number range. Comparison of the results with laser velocimeter data indicates that this transition process is related to transition to turbulence in the recirculation zone of the stabilizing rods.

Introduction

THE importance of density fluctuations to turbulent transport in gaseous combustion is generally recognized. For example, in their theoretical study of turbulent premixed flames, Libby and Bray[1] have shown that the preferential acceleration of pockets of hot products may lead to turbulent transport in violation of standard gradient transport arguments. Such a result in a premixed flame has been observed in the experimental study of Shepherd et al.[2] The development of Rayleigh scattering as a laser diagnostic for gas density in gaseous hydrocarbon/air combustion has allowed extensive study of the density field in the far wake of premixed rod-stabilized flames.[3-5] The results of these studies have shown that models of premixed flames,[1,6] in which intermediate products within the flame structure are neglected, may be reasonable in many cases.

The purpose of the present study is to use the Rayleigh scattering technique to study flame structures in the near wake of premixed rod-stabilized flames. As noted by Lefebvre,[7] "the great preponderance of available experimental data on flame stability was obtained with bluff-body flame holders...." Despite this fact, few data are available on the details of the flow that would allow a fundamental theoretical description of the stabilization process. The present study provides data in the Reynolds range in which transition to turbulence is known to occur in the recirculation zone of bluff bodies for flows without combustion. The present study complements a study using laser velocimetry to determine the effect of combustion on the recirculation zone of circular cylinders.[8]

The Rayleigh scattering technique, as used in gaseous hydrocarbon/air flame, is reviewed by Gouldin and Dandekar.[5] As they noted, this nonintrusive technique is superior to instantaneous temperature measurements using fine wire sensors because of the inherent frequency response limitations resulting from the thermal inertia of the sensor. The Rayleigh scattering technique for measuring gas density depends on the approximate constancy of the total scattering cross section throughout the reaction zone. Gouldin and Dandekar, using refractive index data for major species in lean methane/air combustion, found that the total scattering cross section decreases by about 2% when products are compared to reactants. They used Rayleigh scatter techniques to measure mean density, turbulence intensity of density fluctuations, probability density functions (pdf's), and spectra of density in the far wake of a V-shaped lean methane/air flame stabilized in grid turbulence. They reported an increase in flame thickness with distance without any increase in turbulence intensity. The pdf's reported were bimodal showing a high probability for cold reactants or hot products; however, intermediate states were not negligible. Normalized spectra did not vary significantly across the flame and were similar to velocity spectra in the reactant flow. These results were calculated using a photon counting technique. Similar results in grid-generated turbulence were reported by Bill, et al.[3] in ethylene/air flames. Here turbulence intensity was calculated and photomultiplier shot noise was removed by assuming a Poisson distribution for noise statistics. Unlike the study of Gouldin and Dandekar, no attempt was made to remove the effect of shot noise from calculated pdf's. A comparison of the statistics for fluctuation intensity with the results predicted by the model of Bray et al.[6] in which intermediate states are neglected suggests that a small correction taking intermediate states into account should result in an accurate determination of density statistics. Namer et al.[4] used the Rayleigh scattering technique in their study of the interaction of a Karman vortex street with a V-shaped rod-stabilized ethylene/air flame. At low Reynolds number they found, as in the studies of Bill et al.[3] and Gouldin and Dandekar,[4] that the pdf's were bimodal with relatively low probabilities for intermediate states. However, at higher Reynolds number where the vortex street was turbulent, the maximum probability for intermediate states was found to be as much as 80%. These results underscore the impact that flows with different turbulence scales have on flame structure. Rajan et al.[9] have recently made instantaneous measurements of density profiles in premixed flames using an optical multichannel analyzer. Their results in the far wake of V-shaped premixed flames indicate that the primary source of density fluctuations at a fixed point is the movement of the flame structure rather than instantaneous fluctuations of the structure. This complements the two-point Rayleigh scattering measurements of Namazian et al.[10] which indicate that a wrinkled laminar flame consisting of a continuous sheet exists for similar experimental conditions.

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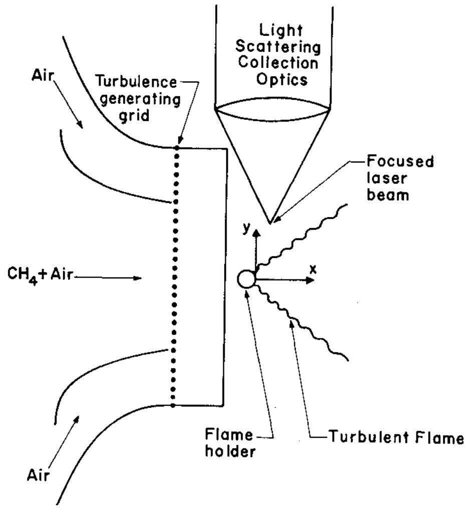

Fig. 1 Schematic of experimental apparatus.

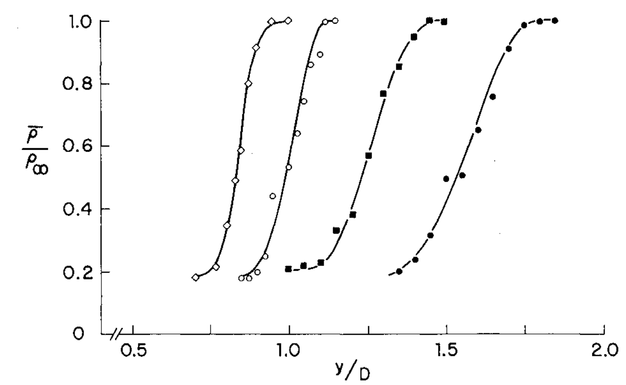

Fig. 2 Mean normalized density profiles: $Re=2000$; $D=12.5$ mm; ◇, $X/D=0.5$; ○, $X/D=1$; ■, $X/D=2$; ●, $X/D=3.5$.

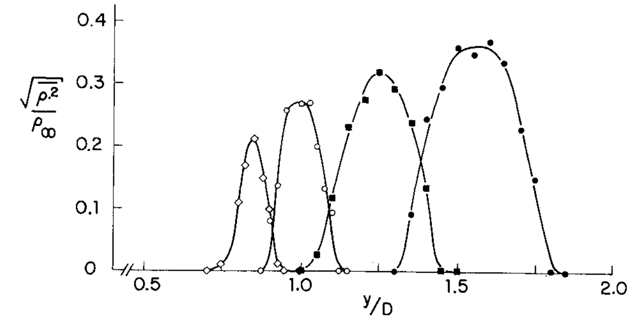

Fig. 3 Turbulence-intensity profiles: $Re=2000$; $D=12.5$ mm; ◇, $X/D=0.5$; ○, $X/D=1$; ■, $X/D=2$; ●, $X/D=3.5$

The near wake of bodies has been studied, particularly in regard to the problem of blowoff. A review of these studies has been made by Lefebvre.[7] Temperature in the recirculation zone has been measured by Zukoski and Marble[11] using the sodium line reversal technique, and more recently by Kundu et al.[12] using platinum-platinum rhodium (silica-coated) thermocouples. These results indicated that temperature within the recirculation zone was almost uniform and less than the adiabatic flame temperature.

As mentioned previously, the present study complements laser velocimetry measurements reported under the same experimental conditions as this study. Axial velocity in the recirculation zone was measured in flows with and without combustion. Freestream turbulence with an intensity of 4% was introduced by an upstream grid. The mean stream velocity and equivalence ratio were fixed at values of 2.6 m/s and 0.65, respectively. The flow over a circular cylinder was studied at Reynolds numbers of 1000 and 2000 and a triangular cross-sectional cylinder at a Reynolds number of 2000. Profiles of mean velocity and turbulence intensity were determined from the data. The results indicate that the effect of combustion was to increase the length of the recirculation zone, to dampen velocity fluctuations, and to increase the magnitude of recirculation velocities. Comparison with reported data for similar cold flows without approach turbulence (Bloor,[13] Leder and Geropp,[14] and Geropp[15]) suggests that the increase in the length of the recirculation zone at this Reynolds number is due to a delay in transition in the wake of the cylinder which results from the increased viscosity due to heat release.

The Rayleigh scattering measurements presented below are obtained at axial locations between the stabilizing rod and the end of the recirculation zone as determined by laser velocimetry. For the results with $R=2000$, the length-to-diameter ratio, L/D, of the recirculation zone was approximately 3.75, while at $R=1000$, $L/D=5.5$.

Experimental Methods

In Fig. 1, a schematic of the existing experimental setup is shown. A 10-cm square coaxial, horizontal, open jet is used in which premixed methane and air flow through the central 7.6-cm section. Air flows through the outer section to shield the inner flow from mixing with stagnant surroundings. The methane/air jet exits from a smooth contraction section designed to prevent separation.[16] The area contraction ratio is 25:1. The contraction is preceded by a settling chamber with three 100-mesh wire screens. Air is supplied by a commercial blower through a diffuser.

A biplane square grid was placed 15 cm upstream of the tunnel exit to generate turbulence. The mesh size of the grid elements were 0.1 cm in diameter. A V-shaped flame was stabilized on bluff bodies positioned 22 cm downstream of the grid.

The optical system for Rayleigh scattering is similar to that described by Bill et al.[3] The optics system described below was fixed. Measurements at different transverse and axial positions were effected by translating the flow system. A Spectra Physics 3-W argon/ion laser is used as the source of monochromatic light (514.5 nm at 1.3 W). The laser beam is focused to a 100-μm waist by two lenses. Scattered light from the beam is focused by an $f/1.2$, 55-mm focal-length camera lens to a pin hole approximately 250 μm in diameter. The scattered light is then collimated and filtered by a 1.0 nm bandpass filter centered at 514.5 nm. The filter may be rotated in order to align it with respect to the collimated light. The filtered light is then focused to the surface of an RCA 1P21 photomultiplier tube. The voltage output from a shunt resistor, isolated by an instrumentation amplifier, was digitized by a 12 bit A/D converter. The sampling rate for all cases in this study was 1000 samples/second. Results were analyzed using a DEC PDP11/23 computer. As in the studies of Bill et al.[3] and Namer et al.,[4] unrelated background light was removed by measuring light picked up when the collection optics were moved slightly to allow the pinhole to block light directly scattered by the laser beam. This unrelated light was measured at each measurement location.

Photomultiplier shot noise was also removed from the turbulence-intensity results as Refs. 3 and 4 by measuring a photomultiplier signal fluctuations outside the flame where no density fluctuations exist. At locations in the flame the variance due to shot noise is then determined by assuming Poisson distribution and adjusting the shot noise variance for changes in the mean photomultiplier current. The variance due to shot noise is then subtracted from the total signal variance. No attempt was made to remove the shot noise

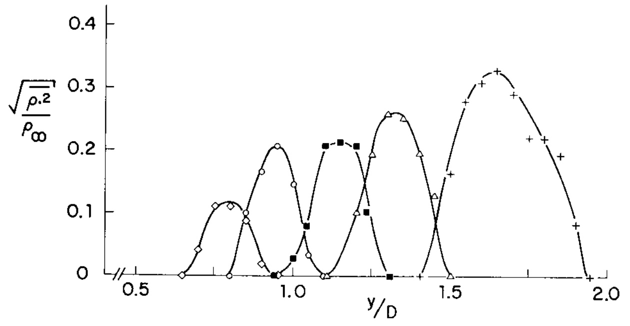

Fig. 4 Turbulence-intensity profiles: $Re = 1000$; $D = 6.25$ mm; ◇, $X/D = 0.5$; ○, $X/D = 1$; ■, $X/D = 2$; △, $X/D = 3$; +, $X/D = 5$.

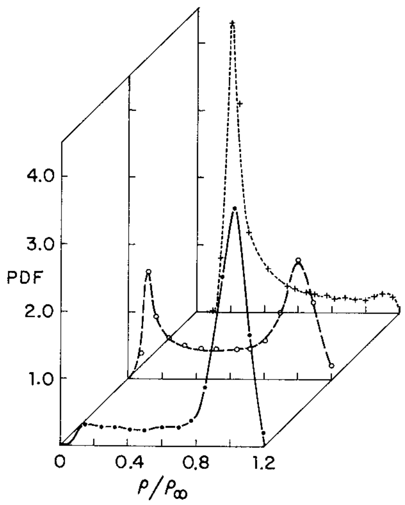

Fig. 5 Probability density functions at three transverse locations for $Re = 2000$, $D = 12.5$ mm, $X/D = 3.5$; +, $Y/D = 1.45$; ○, $Y/D = 1.6$; ●, $Y/D = 1.7$.

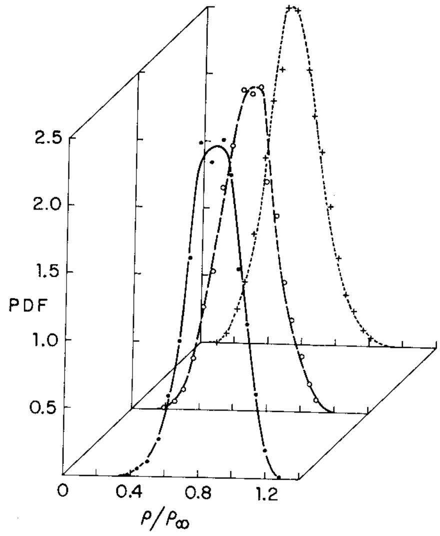

Fig. 6 Probability density function at three transverse locations for $Re = 1000$, $D = 6.25$ mm; $X/D = 0.5$; +, $Y/D = 0.85$; ○, $Y/D = 0.8$; ●, $Y/D = 0.75$.

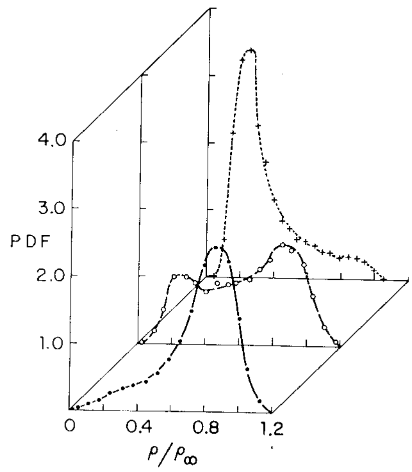

Fig. 7 Probability density functions at transverse locations for $Re = 1000$, $D = 6.25$ mm, $X/D = 3.0$; +, $Y/D = 1.25$; ○, $Y/D = 1.3$; ●, $Y/D = 1.47$.

from the calculated pdf's; hence, these results are somewhat modified by the photomultiplier noise. As in previous studies,[3-5,9,10] no correction has been made for signal fluctuations caused by beam refraction. Estimates of beam refraction in flames by Weinberg[17] indicate that such errors should be negligible.

Results and Discussion

Rayleigh scattering data were obtained in the near-wake region of three bluff bodies: circular cylinders 12.5 and 6.25 mm in diameter and a triangular (equilateral) cross-sectioned cylinder having sides of 12.5 mm. The mean axial upstream velocity was 2.6 m/s and the equivalence ratio was fixed at 0.65.

In Fig. 2, mean density profiles are presented at four axial locations for the 12.5-mm circular cylinder. The corresponding Reynolds number was 2000. The development of the flame brush and the increase in thickness with downstream distance may be seen clearly and is comparable to reported results in the far-wake region. At the axial location $X/D = 0.5$, the flame brush thickness is approximately 3 mm, only slightly greater than the laminar flame thickness of 2.2 mm.[18] By the end of the recirculation zone, $X/D = 3$, the flame brush has increased to 6 mm.

The increase in flame brush thickness with distance downstream is further emphasized in Fig. 3 by the corresponding increase in the size of the density fluctuation regions. In addition, the maximum in turbulence intensity increases from 21% at $X/D = 0.5$ to approximately 36% at $X/D = 3.5$. Our laser velocimetry data[8] indicates that this increase occurs while the maximum in turbulence intensity for velocity increases from 14 to 28%. The flowfield within the recirculation and outer layer is turbulent when combustion is present although the levels of turbulence intensity are decreased compared to the cold flow. At a given axial location, the maximum in turbulence intensity occurs within the recirculation zone. The intensity decreases to the freestream value at approximately $Y/D = 2$. With increasing downstream distance, the turbulence intensity in the recirculation zone increases and is accompanied by an increase in turbulence in the outer layer where the flame brush is located. For example, the turbulent velocity intensity corresponding to the flame brush location shown at $X/D = 0.5$ in Fig. 3 is is 5%. This is only slightly higher than the freestream value. At $X/D = 1$, the intensity is approximately 13% at the flame brush location.

Gouldin and Dandekar[5] have argued that the increase in flame brush thickness is due to turbulent dispersion; that is, "the lateral distance over which the instantaneous flame travels increases with axial distance due to the cumulative effect of all turbulence-induced random displacements of the flame in the plane of observation." They rejected the explanation that the growth is caused by flame instabilities triggered by turbulence since their spectra of density fluctuations show

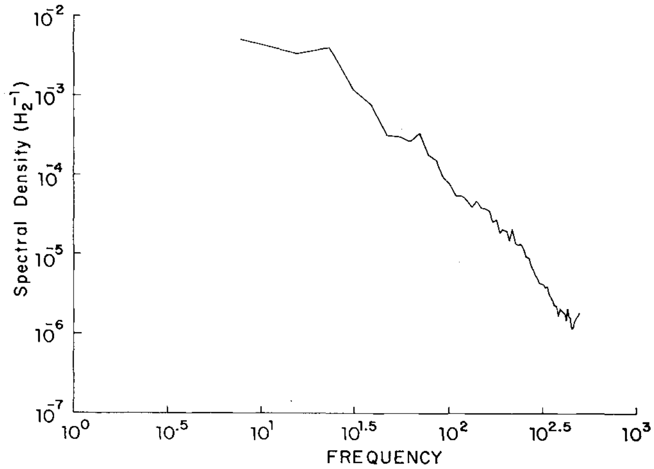

Fig. 8. Power spectrum of density fluctuations at point of maximum turbulence intensity for $Re = 2000$, $D = 12.5$ mm, $X/D = 3.5$.

no distinct peaks. Otherwise the lack of distinct peaks would imply, implausibly, that flame instabilities are present at all frequencies. Furthermore, such instabilities accompanied by an increasing flame brush thickness would imply an increase in flame surface are and turbulent flame speed. No increase in flame speed was observed.

The instantaneous density profiles measured by Rajan et al.[9] under similar experimental conditions appear to justify this conclusion, since density fluctuations that could be attributed to instantaneous changes in the flame structure were only 8% as compared to turbulence intensities of 25-40% when measured at a stationary point.

Spectra for this study also show no significant peaks. This suggests that in the near wake the increase in flame brush thickness is also due to turbulent dispersion. However, unlike the studies in the far wake, there is a substantial and systematic increase with downstream distance in turbulence intensity of density fluctuations. This increase correlates with the increase in turbulent velocity fluctuation discussed above caused by the combustion delayed-transition process in the recirculation zone. (Recall that for flows without combustion turbulent bursts occur at about $R = 400$.[13])

The impact of the increased velocity fluctuations on density fluctuations is more apparent at a reduced Reynolds number. In Fig. 4, profiles of turbulence intensity of density fluctuation are shown at five axial locations within the recirculation zone of the 6.25-mm circular cylinder ($R = 1000$). For this circumstance, the maxima of turbulence intensity of velocity fluctuations were found to vary from 12 to 26%, and the length-to-diameter ratio of the recirculation zone increased to 5.5. A comparison of Figs. 3 and 4 indicates that the turbulence intensity (density) is less for the $R = 1000$ case at all comparable normalized axial locations. If a comparison of turbulence intensities is made at comparable downstream locations, X, then the density fluctations are approximately the same. An inspection of the data indicates that the data are better correlated with X/L, where L is the length of the recirculation zone. Turbulence-intensity levels (density) do not reach the levels reported in the far wake of stabilized flames for either $R = 1000$ or 2000 until the end of the recirculation as a result of the ongoing transition process.

In order to investigate the nature of the density fluctuations further, probability density functions were calculated from the Rayleigh scattering measurement time series. Figure 5 represents pdf's at three transverse locations in the flame at the end of the recirculation zone for the $R = 2000$, $D = 12.5$ mm case. (Note that the pdf's are broadened by shot noise.) The results are quite similar to those reported in far-wake studies; i.e., on opposing sides of the flame, either hot products or cold reactants predominate. At the location corresponding to a maximum in intensity, the distribution is bimodal with intermediate states contributing approximately 30% to the mean density level.

At an axial location closer to the stabilizing rod, the results were quite similar except the probability of intermediates increases. Without instantaneous profile data, such as that of Rajan et al.,[9] these results are difficult to interpret. However, investigations of the pdf's for the $R = 1000$ case, where the turbulence intensities are lower, suggest that the dominant cause of the increase in density fluctuations is the increase in lateral movement due to velocity fluctuations. For example, in Fig. 6, the pdf's at three transverse locations are shown for $X/D = 0.5$. Unlike those in Fig. 5, the pdf's are approximately symmetrical and centered on the mean density ratio. The flame thickness at this location is approximately the same as that of the laminar flame. The pdf's show that the structure is well resolved and fluctuations are due to slight transverse motion of the structure. Figure 7 shows pdf's at the downstream axial locations $X/D = 3$. The transverse movement has increased so that a bimodal distribution is now apparent for the distribution corresponding to the peak in density fluctuations. However, the probability of intermediate states in the flame structure is considerable. At $X/D = 5$, the transverse movement has increased to the point where the probability of the intermediates of the thin flame structure being observed is decreased significantly. The pdf's calculated for this position are similar to those shown in Fig. 5. Thus our data suggests that the increase in intermediate states with decreasing distance from the flame stabilizer is merely the increasing probability of observing the thin flame structure over the smaller distance of the flame's "random walk."

Figure 8 presents the spectral density of fluctuations at $X/D = 3.5$ at the location of maximum fluctuations for the $R = 2000$ case. This spectrum is typical of those at all other locations. Note the spectral density falls by four orders of magnitude from the maximum values. This indicates that the sampling rate was sufficiently high to provide good estimates of turbulence intensity. No peaks contributing significant power are observable. Thus, as in the study of Gouldin and Dandekar,[5] density fluctuations reported here are not likely to be due to flame instabilities.

Finally, quite similar results were obtained for a equilateral triangular, cross-sectioned cylinder (sides of 12.5 mm). No significant qualitative differences were noted for this case and that of the 12.5-mm-diameter circular cylinder.

Conclusions

1) The flame brush increases in size in the near wake of bluff bodies due to dispersion caused by transition to turbulence in the recirculation zone for $R = 1000$ and 2000.

2) Intermediate states may not be neglected in the prescription of the probability density function for flame structures in the near wake at intermediate Reynolds numbers.

3) In the near wake, the density fluctuations increase as turbulent dispersion decreases the probability of intermediate states being observed.

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