Flow in Luminous Jet Diffusion Flames*

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Ethylene and acetylene jet diffusion flames have been studied by two photoelectron correlation techniques. One is laser Doppler anemometry used for determining the local average velocity, turbulence intensity, and velocity probability density. To obtain these, Fourier transform has been performed using the maximum entropy method. The other is the intensity fluctuation spectroscopy of a light scattered from soot clouds. Correlation signals, indicative of spatial distribution of soot-containing eddies, are processed to give the integral scale of the eddies and the spectral density of the scattered-light. As the result, it has been suggested that in the flames tested, turbulence is intensified by a heat-release due to combustion and this augments the eddy structure of the jet, thus enhancing engulfment of the surrounding air and promoting its penetration into the jet core. A discussion is given of the effect of fuel on the size of the turbulent eddy.

Key Words : Combustion, Jet Diffusion Flame, Turbulence, Photoelectron Correlation, Laser Doppler Anemometry, Intensity Fluctuation of Scattered Light

1. Introduction

Turbulent jet diffusion flames are inherently important because they feature the combustion taking place not only in industrial furnaces and boilers but also in some types of internal combustion engines. To improve performance of these combustors and engines and to reduce their pollutant emissions, it is necessary to have a better insight into the process of fuel-air mixing in such jet diffusion type flames. This problem has been long explored from all aspects, but it is still felt that the problem is far from being thoroughly understood. Recently, interpretations have been made of the mixing process by applying the coherent structure concept that has been derived from the studies of isothermal jets (1)(2). In this regard, a number of experimental studies have been carried out; the coherent structure in the shear layer of a two-dimensional flame has been investigated using schlieren photography as well as measuring spatial distributions of densities, temperatures, and other quantities (3)(4). In some studies, statistical quantities of velocity and scalars, their probability densities, and

autocorrelations have been examined (5). Further, measurements of ion current (6) and intensity variations of scattered light from soot clouds (7) have been made to obtain information on the mixing process.

To assess the flow and turbulent mixing in the turbulent jet flames, the laser Doppler anemometry would be most advantageous. However, in the case of a luminous flame burned by an ordinary hydrocarbon fuel, a strong light emission is usual and this greatly deteriorates the quality of the burst signal. To remove this difficulty and to collect reliable data, either of two possible ways has to be used; one is the use of a high-powered laser enough to obtain a high signal-to-noise ratio, and the other is the reinforcement of the burst signal during the processing. The present authors tried to remove the difficulty in the latter direction making use of photoelectron correlation technique, and they found that this method could successfully extract the signal even out of very high background noises caused by flame luminosity (8).

Fig. 1 Experimental apparatus

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In the present study, very luminous jet diffusion flames burned by ethylene and acetylene have been studied in detail first using the photoelectron correlation laser Doppler anemometer for obtaining the local time-average velocities and turbulence intensities. In addition, the correlation method has been applied to measure the scattered-light intensity fluctuations, in order to explore turbulent eddies formed in the luminous flame zone.

2. Experimental Apparatus and Procedure

2.1 Experimental apparatus

Measurements were made of open jet diffusion flames at atmospheric pressure using experimental installations as is shown in Fig. 1. The burner is placed on a movable test bench by which the measuring position may be finely adjusted. In the laser Doppler anemometry of the flow field, an ordinary real-fringe optical system has been used; a light beam from a 2 W Spectra-Physics Model 164 argon-ion laser is split into two parallel beams which are focussed at a measuring position by a lens L_1 . In the case of the scattered-light intensity fluctuation method, a homodyne optical system using a single laser beam has been employed. In both cases, collection of the scattered-light has been made in the forward direction by a Hamamatsu Photonics Co. R464 type photomultiplier tube. The obtained photoelectron pulse train is fed to a Hamamatsu Photonics Co. C1050 type photon counting amplifier for amplification, waveform, and discrimination. The output pulses are processed by a Morigiken ME-364 type 12 bit 128 channel single-clipped digital correlator having a maximum clock speed of 50 MHz, to calculate directly the autocorrelation coefficients of the light intensity fluctuations. The principle of the correlator is such that a signal pulse and a delayed pulse are synchronously detected for counting (8). The result of counting gives an autocorrelation coefficient, which is either displayed on an oscilloscope or picked up by a Melcom 70/20 minicomputer data processing system.

2.2 Flow measurement

The use of the above-mentioned digital correlator can reduce statistically the uncorrelated background noises generated by a flame luminosity. This enables measurement of velocity even in luminous region as has been reported previously (8). At the same time, self-producing soot particles in the luminous zone can be used as the light scatterer. However, proper particle seeding was necessary to detect burst signals in the surrounding flow and in the case of non-burning jet stream. For this reason, a talc powder was seeded to measure flows in these soot-free situations.

The beam splitter employed was a Kanomax Model 1915 rotary type and the focusing lens L_1 had a focal length of

500 mm. The beam angle was 5.7° which produced a measuring volume having a waist beam diameter of 0.27 mm. The light collection lens L_2 had a 135 mm focal length and a 0.2 mm pinhole was placed in front of the photomultiplier tube. To reduce the effect of flame luminosity, an interference filter of a wavelength of 514.5 nm was placed in between.

The autocorrelation data gained were processed by the maximum entropy method for conducting Fourier transformation to yield the velocity density function (PDF). From the obtained PDF, the time-averaged axial velocity $\bar{U}$ and the root-mean-square turbulence velocity u' were obtained. Refer to previous report (8) for further details. Before conducting the Fourier transformation, some numerical treatments were needed for reducing errors originating from several sources, one of which was pedestal on the correlogram due to the flame luminosity.

2.3 Analysis of the scattered-light intensity fluctuation

Another technique employed in the present study was to detect the autocorrelation of the scattered-light intensity fluctuations, which could give an estimate of spatial spread of soot-containing zone or simply the soot cloud. As has been suggested by Magnussen (7), the information of this kind is indicative of the turbulent eddies and is useful to explore a turbulent mixing taking place in the burning zones. While he employed direct frequency analysis for obtaining the power spectrum, the present authors used again the photoelectron correlation method for the same objective. The autocorrelation coefficient of the scattered light yields directly the integral time-scale of the fluctuation, and the power spectrum may be obtained by Fourier transformation of the correlation data. The homodyne optical system to obtain the autocorrelation can easily be arranged by omitting the beam splitter and focusing and collection lenses from the original anemometer setup. A non-convergent laser beam was used so as to remove the flight-broadening effect. The view area was limited by a pinhole having a 0.2 mm aperture in place of the light collection lens L_2 . The angle between the incident beam and the direction of the light detection was 15° .

3. Flow in Flames

3.1 Flame tested

The burner nozzle used for the experiments had an inner diameter of $d = 2$ mm and a rim thickness of 3 mm. Fuels used were ethylene and acetylene. Besides these flames, an isothermal nitrogen jet was tested for comparison. In all tests a gas was issued upward in the vertical direction, and the velocity at the nozzle exit was kept constant at 32 m/s. This corresponds to a Reynolds number $Re = 7,100$ for the ethylene jet. Under these conditions, flames formed were quite turb-

lent in appearance. For the ethylene flame, visual observation gave a flame height of 480 mm and a length of transition to turbulent flow of 33 mm. For the acetylene flame, the respective lengths were 360 mm and 20 mm. The ethylene jet flame was much smoother in the form and less turbulent than the acetylene flame.

To extend velocity measurement to the positions outside of the visible flame region, a 0.47 m/s low-speed air seeded with tracer particles was constantly fed from a concentric duct having a diameter of 300 mm. The tracer was a talc powder having a mean diameter of about 2 μm and was seeded into the air using a kind of cyclone mixer. Figure 2 shows schematically the laser beam arrangement, together with the denotations of axial distance x and radial distance r .

3.2 Mean axial velocity and turbulence intensity

In Fig.3 the axial mean velocity $\bar{u}$, relative turbulence intensity $u'/\bar{u}$, and

Fig. 2 Measuring position of a jet diffusion flame

Fig.3 Distributions of mean axial velocities $\bar{u}$ and turbulence velocities u' on the burner centerline

root-mean-square turbulence velocity u' , measured on the burner axis, are plotted against non-dimensional axial distance from the nozzle, x/d , for two flames and a non-burning jet. Data obtained under seeded conditions are indicated by dark plots.

It is noted from Fig.3 that the axial mean velocity $\bar{u}$ fall fast at the nozzle exit and then decreases gradually with x/d . In all positions $\bar{u}$ is much higher in the jets with flame than in the cold jet. The position at which $\bar{u}$ suddenly falls is very close to a point where the flame is the most luminous. This suggests that an expansion due to strong local heat-release retards the decrease in the axial velocity (9). The rms turbulence velocity u' is also the highest near the nozzle exit in either case. It may be seen that the peak level of u' is the highest in the acetylene flame and the lowest in the ethylene flame. As might be expected from a comparison between ethylene and acetylene flames, it is likely that u' in the downstream positions is considerably influenced by local heat release.

In the next place, it may be seen that the relative turbulence intensity $u'/\bar{u}$ is the highest at a position where $\bar{u}$ quickly decreases with x/d . The peak value of $u'/\bar{u}$ is much lower in the flame than in the cold jet near the nozzle exit. This outcome might be attributed to the laminarization owing to a higher

Fig. 4 Radial distributions of mean velocities $\bar{u}$

Fig. 5 Half-value diameter of velocity distributions D_u against x/d

temperature in the flame (10). In the cold jet, $\bar{u}$ is quite low at the position of the maximum $u'/\bar{u}$, while in flames $\bar{u}$ is still high at this position. This would suggest a possibility that turbulence is intensified to a certain degree by heat release.

In the case of the acetylene flame, the $u'/\bar{u}$ value is seen to drop greatly just behind the peak position and again rises until a value as high as 30 % is reached in the range of x/d greater than 150. This large drop in $u'/\bar{u}$ may possibly be attributed to combined effects of the change in the velocity profile in the shear layer and the laminarization caused by temperature rise. Similar phenomenon has been observed in a hydrogen-air jet flame (11). The increase in $u'/\bar{u}$ in the range of large x/d may be partly because of the decrease in $\bar{u}$ and partly because of the intermittent engulfment of air from the surroundings as will be discussed later.

In Fig. 4 radial distributions of mean axial velocities $\bar{u}$ are shown for a few positions of x/d . It can be pointed out from them that in the flame case the tendency of the profile toward a flat

Fig. 6 Radial distributions of relative turbulence intensities $u'/\bar{u}$

Fig. 7 Radial distributions of rms turbulence velocities u'

radial distribution is retarded considerably unlike in the case of cold jet. Thus the jet width is expected to be smaller than that of the cold jet. In Fig. 5 half-value diameters $D_{1/2}$ calculated from the $\bar{u}$ versus r/d distributions are plotted against x/d for all cases. From this diagram, the jet half-angle is found to be 7.7° for the cold jet, while they are 6.6° and 5.9° for ethylene and acetylene flames, respectively. The same tendency that the presence of combustion reduces the jet angle has been recognized from another experimental study (11).

In the $\bar{u}$ versus r/d relations in Fig. 4, a discontinuity in velocity readings may be observed at the junction between seeded and non-seeded cases. Clearly, this occurs at the flame-air boundary and it may represent the fact that a high-speed sooting stream and the outer low-speed air stream alternately pass there. It may be assumed that the non-seeded case corresponds to the high-speed stream, while the seeded case does to the outer stream. In other words, this phenomenon might indicate the intermittency taking place in the flame boundary.

In Figs. 6 and 7 radial distributions of relative turbulence intensities $u'/\bar{u}$ and of rms turbulence velocities u' are shown respectively. At a large distance from the nozzle, there is a peak in the $u'/\bar{u}$ profile at a radial position close to the flame front. This peak is much higher in the acetylene flame than in the ethylene flame. At these radial positions, the u' profiles indicate a characteristic swelling, suggesting the fact that turbulence may be intensified

Fig. 8 Probability density function of mean axial velocity for jet flames and a cold jet, at $x/d = 50$

Fig. 9 Probability density function of mean axial velocity for jet flames and a cold jet, at $x/d = 70$

to a certain degree at the flame-air boundary where the greatest local heat release would take place.

3.3 Probability density distribution

In processing the autocorrelations to obtain velocities and the related quantities, the data processor calculated the probability density function or PDF of the axial velocity u . Such PDF's are reproduced in Figs. 8 and 9, for various radial distances of r/d at two axial distances of $x/d = 50$ and 70, respectively. It can be seen first that on the axial line $r/d = 0$, the PDF profile looks symmetric around the mean velocity and is close to normal distribution, while at a radial position near the flame front, namely, $r/d = 8$ for ethylene and $r/d = 6$ for acetylene, in the case of $x/d = 70$ in Fig. 9, the PDF is skew in the positive direction and has a long wing in the high velocity side. The skewness in the flame front is more evident in the acetylene flame than in the ethylene flame. For both cases, in the outer side of the flame front the PDF has a narrow and symmetric profile. Possibly, the skewness observed at the flame boundary can be attributed to the fact that a high-speed stream intermittently passes this fixed position. Thus we may have such a picture that the engulfing eddies entrain the surrounding air into the flame jet core. In the case of the nitrogen jet, little skewness can be seen probably because such eddies are very small in size. Thus it may be conceived that the presence of such engulfing eddies is specific to the flame jet, in which combustion enlarges the eddy, thus promoting the air entrainment.

A close observation at an axial position $x/d = 70$ further indicates that the PDF profile on the axis has a longer wing in the low velocity side. This coincides with the results of Takagi and others⁽⁹⁾, suggesting that the surrounding low-speed air can affect the flow in the jet axis.

In Fig. 10 similar PDF results obtained for different seed concentrations in the outer air flow are given for two radial positions of $r/d = 5$ and 6, at an

Fig.10 Probability distribution functions of velocity at various concentrations of tracer particles

axial distance of $x/d = 50$ in the acetylene flame. In unseeded cases the velocity of soot stream is recorded, while in highly seeded cases the air speed may be obtained. Since the flow at the flame-air boundary is intermittent as has been mentioned earlier, the PDF would be bimodal and in fact the profile changes depending on the concentration of the seed particles. Thus the velocity readings gained under the unseeded condition are close to the velocity that is conditionally sampled from the fuel-rich sooting zone. In the positions remote from the flame-air boundary, this effect is believed to become less.

4. Autocorrelation and Spectrum of the Scattered-Light Intensity

In the previous chapter, turbulence in the flame front and the air-engulfing eddies were studied in detail. These eddies make fuel engulf air and distribute air pockets in the boundary between the fuel jet and the quiescent surrounding air. In the interface stretched by such eddies, micromixing between the fuel and the air would proceed, forming zones of fuel-rich mixture. Since almost the same amount of air would be engulfed into each small fuel pocket, the mixture formed there would be fuel-overrich and a lot of soot might be produced which might disperse by turbulent diffusion. For this reason, a close correlation may be expected to hold between the soot-containing zone and these engulfing eddies. Further, mixing between soot particles and air during the subsequent stages of eddy break-up would be governed by turbulent eddies. Thus it may safely be said that the time-variation of the scattered-light intensity is indicative of the soot-containing eddies and gives some information about turbulence. On this supposition, the integral scale of autocorrelation coefficients of the scattered-light intensity fluctuation has been calculated as an indicator of the turbulence scale.

In Fig.11 a few examples of the autocorrelogram obtained on the burner axis in the ethylene jet diffusion flame are given, in which τ in abscissa represents the time difference. Each curve looks close to an exponential function, and the delay time is seen to increase with the axial distance x/d . In some other cases obtained at off-axis positions, a

Fig.11 Examples of autocorrelogram of scattered-light intensity fluctuation

periodic oscillation was superimposed on the curve. This period of oscillation might represent the dimension of soot cloud so to speak. Based on the correlograms obtained, we may find out the time integral-scale of soot cloud τ_L through integration. Further, τ_L might be converted into the spatial scale on the Taylor hypothesis, namely

$$L_x = \bar{u} \tau_L \quad (1)$$

In Fig. 12 the spatial integral-scale L_x obtained on the burner axis is plotted against x/d for two flames used in the present study. In the case of ethylene flame, L_x slightly decreases first and then increases rather quickly with the axial distance x/d . In the acetylene flame, L_x also has a minimum point at $x/d = 50$, and it reaches the maximum at $x/d = 130$. The minimum point is located at a position at which the flame is the most luminous just in the downstream of the highest relative turbulence intensity $u'/\bar{u}$, as may be expected from Fig. 3. Whole course of L_x with x/d might suggest the turbulence eddies are broken up into finer ones until the minimum position is reached, and then they increase in size partly by strong heat addition due to combustion and partly by coalescence due to vortex pairing. The fact that the acetylene flame has a larger L_x than the ethylene flame may come from a larger eddy structure established in the flame. Thus a faster entrainment of air into the jet core might have been assured in the acetylene flame.

Figure 13 shows radial distributions of L_x for several axial distances for each flame. In the case of ethylene flame, a relatively large value of L_x may be seen near the flame-air boundary, and the L_x value at the same radial position increases quickly with axial distance. In the acetylene case, an increase in L_x with axial distance may be observed in the flame front but the final value is much smaller than that in the ethylene case. Another difference that characterizes the acetylene flame is that the L_x value decreases with radial distance r/d , or in other words, bigger eddies exist in the central part of the fuel jet. This difference seems to arise from a larger amount of heat release that may take place well in the upstream of the flame because of wider flammability limits. Possibly, an expansion of gas associated

Fig. 12 Axial distributions of integral scales of intensity fluctuation L_x

with faster reactions causes a larger structure of eddies. Similar result has been yielded from an experimental study by Magnussen⁽⁷⁾ at a high Reynolds number of $Re = 52,500$ in an acetylene open jet flame. On the contrary, a relatively large scale in the outer region as observed in the ethylene jet flame has been also reported by Takagi and others⁽⁵⁾, based on the anemometry made of a hydrogen-air open jet flame. Presumably, this difference in the L_x profile can be attributed to the discrepancies in the calorific value of fuel used and in other factors such as flammability limits. This will require further clarification.

Power spectral density of the scattered-light intensity has been obtained from the correlation data by Fourier analysis. Because a single set of autocorrelation data does not suffice to yield spectra covering the whole wavenumber range, four to six correlation data gained at different clock speeds under the same condition were used for the analysis. In Figs. 14, 15, and 16 the normalized spectral densities g are plotted against wavenumber k , where g represents energy contained in a unit change in the wavenumber.

In the ethylene case, it is known from Fig. 14 that the g value on the burner axis increases with axial distance x/d in the range of low wavenumbers. However, no great change is seen in g in the radial direction in this case as may be observed from Fig. 15. In contrast, in the acetylene flame, both axial and radial changes in g are only little at a low wavenumber, as can be seen from Figs. 14 and 16, suggesting that the acetylene flame has more uniform structure of turbulence than the ethylene flame. Another fact that deserves attention is that the ethylene flame has a peaking in the middle range of wavenumbers, which is believed to represent the dimension of

Fig. 13 Radial distributions of L_x

turbulent eddies. Clearly, the wave-number that gives the peak is dependent on the x/d position and decreases as x/d increases. In the case of acetylene flame such a peaking cannot be seen probably because the eddy augmentation has occurred at far upstream positions.

In the range of high wavenumbers, g decreases with k at a power close to or slightly smaller than $-5/3$, which is suggested by Kolmogorov's universal equilibrium theory of turbulence. As far as a similarity between spectra of turbulence and those of scattered-light intensity is assumed, it can be suggested that local isotropy roughly holds in this high wave-number range. On the same assumption, judging from the slope in this range,

Fig.14 Spectra of the scattered-light fluctuation at various axial positions on the centerline $x/d = 0$

Fig.15 Spectra of the scattered-light fluctuation at various radii for ethylene flame

Fig.16 Spectra of the scattered-light fluctuation at various radii for acetylene flame

viscous dissipation might be promoted considerably by the presence of hot flame⁽⁷⁾⁽⁹⁾. This is suggested from the fact that the negative slope increases considerably with radial position r/d at $x/d = 110$ in the case of ethylene flame in Fig. 15.

5. Conclusions

In the present study, ethylene and acetylene turbulent jet flames have been studied using two optical methods, one being laser Doppler anemometry for the determination of the flow, and the other being scattered-light intensity-fluctuation correlation technique for estimating the spread of the soot-containing eddies. The obtained results may suggest that at the Reynolds number tested, turbulence is intensified to some extent by a flame, and that combustion augments the structure of turbulent eddies as a result of the expansion due to heat release, thus promoting the engulfment of the surrounding air into the jet core. At the same time it is shown that these eddies are affected considerably by the change in the fuel. In the acetylene jet flame, eddies having a large spatial integral-scale are distributed uniformly in the jet, and as a result the penetration of air into the core is faster. In the ethylene flame to the contrary, this penetration is slower owing to small eddies in the central region.

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