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FURTHER EXPERIMENTAL RESULTS ON THE STRUCTURE AND ACOUSTICS OF TURBULENT JET FLAMES

by
R. N. KUMAR
California Institute of Technology
Pasadena, California

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R. N. Kumar
Daniel and Florence Guggenheim Jet Propulsion Center
California Institute of Technology, Pasadena, California

Abstract

The structure of open turbulent jet flames is experimentally studied in the context of their noise emission characteristics. The differences between premixed and (co-flow) non-premixed flames are explored. Recent experiments repeated in an anechoic chamber complement earlier results obtained in a hard-walled bay. The reactants (methane and enriched air) are burned in the premixed, or non-premixed, mode after a length of pipe flow ($\ell/D > 150$). The thick-walled tubes anchor the flames to the tip at all of the velocities employed (maximum velocity, well over 300 ft/sec), thus eliminating uncertainties associated with external flameholders. The time-averaged appearance of the flames is obtained with still photographs (1/60 sec). The detailed structures are revealed through high-speed ($\approx$ 2500 frames/sec) motion pictures. The acoustic outputs of the flames are mapped with a condenser microphone. The recorded data are played back to obtain the amplitude, waveshapes, directionalities, and frequency spectra of the noise. Profound differences are found between the premixed and non-premixed flames in their structures and noise characteristics.

I. Introduction

Research efforts on turbulent flames, in the past, appear to have explored some particular aspect as dictated by relevance to a practical application. Thus, the basic problem of the fundamental structure of turbulent flames has remained alive. There has arisen a new surge of interest in turbulent flames on account of the noise and pollution problems where the most relevant practical aspect is the fundamental structure itself.

Noise production in turbulent flames depends, it is believed, directly on the fluctuations in the local reaction rate in the combusting field (Bragg 1963). Consequently, those interested in the fundamental aspects of turbulent combustion must welcome these problems that are unwelcome in other circles.

Here, we restrict ourselves to the noise problem, where many aspects of the problem have been clarified in recent times (Strahle and co-workers 1971, Smith and Kilham 1963, Kotake and Hatta 1965, Knott 1971, Hurle, et al. 1968, Giammar and Putnam 1970). An examination of the literature indicates that the following points are fairly clear. Combusting jets can be very noisy compared to non-combusting jets. The actual magnitude of the noise increase is yet to be correlated thoroughly with the properties of the jet flame, such as velocity, fuel/oxidizer composition, burner diameter (or the Reynolds number, expansion ratio E, etc.). The differences between the two fundamentally different modes of combustion, premixed and non-premixed flames, have not been thoroughly settled. Elimination of external flameholders must be considered whenever possible. The relation between the noise output and the mechanics of the combustion zone is not understood.

Restricting our attention to the simple open jet geometry, and further concentrating only on the overall correlations, we find various, seemingly inconsistent, results. Smith and Kilham (1963), in their tests on premixed flames of propane, ethylene, and methane with air, found that the acoustic power was proportional to $(UDS_b)^2$ for stoichiometric jet flames. Kotake and Hatta (1965), in their premixed diffusion flames (partly premixed and the rest non-premixed), found that the intensity of the noise output in jet flames was proportional to U^2 at low velocities and to U^4 at high velocities. Giammar and Putnam (1970) studied the flames of impinging fuel jets in two geometries: two opposed jets and the octopus burner (jets from the corners of a cube). In general, they found the acoustic pressure to be proportional to the square of the mass flow rate, although the exponent tended to be less than two when $\dot{m}/D$ (essentially the Reynolds number) was increased, and greater than two when the $\dot{m}/D$ was decreased. Knott (1971), in his experiments on premixed jet flames, found the acoustic power to be proportional to U^4, and in his experiments on non-premixed flames to be proportional to U^2_{fuel}. Although his work represents about the single most comprehensive one on the differences between the premixed and non-premixed flames, some of this experimental techniques leave a few questions unanswered. His removal of a short length of the inner tube, in the co-flow geometry, may not be sufficient to attain premixing of the reactants. Neither does the ℓ/D ($\approx$ 34) he employed seem sufficient to establish fully-developed pipe flow before exit.

Strahle and Shivashankara (1973) obtained an unambiguous U^3 law for the acoustic power in their open jet flame experiments on premixed gases (propane, ethylene, and propylene, each with air). Shivashankara, et al. (1973) extended their results to include their data and the data of Smith and Kilham in a single correlation with a regression analysis. Within certain ranges of the variables, they quote the acoustic power to be proportional to $U^{2.68}D^{2.84}S_b^{1.35}$. Shivashankara, et al. (1973) also report extensive data on the directionality and acoustic spectra for fuel-rich flames. They found the general behavior of the fuel-rich flames to be the same as fuel-lean flames, although the exponent on the diameter (D) was slightly lower.

When one considers these inconsistencies in the simple power law for velocity scaling, it is probably understandable that considerable uncertainties prevail in the other quantities, such as frequency spectra and directionalities. Kotake and Hatta (1965) and Smith and Kilham (1963) have found the Strouhal number at the center frequency to be reasonably constant, indicating a simple "geometrical" mechanism for noise production in flames. On the other hand, Shivashankara, et al. (1973) do not find this simple picture to be valid and state "...it appears quite improper to try to

use Strouhal Number to nondimensionalize combustion noise peak frequencies...". They also find that the acoustic spectra are, in general, broad and the mild peak always occurs in the 250-700 Hz frequency range for hydrocarbon-air flames.

There are many other experimental variables that may also affect the data. For example, the mechanism of anchoring the flame may have a strong influence on the noise output. Smith and Kilham (1963) made a systematic investigation of the noise output from the main flame as affected by the pilot flame mass output and found regions where the pilot flame apparently does not affect the acoustic power of the main flame. Shivashankara, et al. (1973) also investigated the effects of the pilot flame in a different manner and conclude that the main flame noise far exceeds the pilot flame contribution in the range of their interest.

Another variable in noise measurements is the environment. The various experiments have been conducted in anechoic chambers, open fields, hard walled rooms, etc. These details are summarized in Table A, which is dated May 1973. However, the only significant additions to that table since that date would be the continuing results from Strahle, et al., whose general experimental environment is mentioned in the last row.

Many associated experiments are also possible. There appears to be a general agreement that the local volumetric reaction rate in the combusting field is directly related to the noise production. In the premixed situation, a one-to-one correlation between the fluctuations in the (optically measured) volumetric reaction rate and the noise output was demonstrated by Hurle, et al. (1968). Their results on this important aspect were extended over a much wider range by Shivashankara, et al. (1974). It appears that the wrinkled laminar flame is a sufficiently accurate description of the premixed flame, at least for the purposes of interpreting the noise data. However, it has been amply recognized (Strahle 1971, 1973, for example) that the basic processes behind the non-premixed flames are considerably different from those in premixed flames. Consequently, the basic modeling of the combustion process which plays a key role in analytical treatments will have to be different for that case. In the absence of experimental data, models tend to be speculative and are open to criticism. Considerably varied forms of data on the open jet co-flow non-premixed flames have appeared recently (Kent and Bilger 1972, 1973; Bilger and Beck 1974). These are concerned with the structure and not with noise output, however, and hence it seems worthwhile to obtain the noise data on non-premixed flames.

The basic aim of the present work is to study experimentally the structure and acoustic characteristics of the non-premixed open jet flame. Also, an attempt is made to minimize the usual uncertainties associated with external flameholders. Premixed flames have also been studied here, under otherwise identical conditions, with the intention of having a ready and meaningful basis of comparison with non-premixed flames. Some of these results were presented earlier (Kumar 1974). Those experiments, done in a hard-walled bay, have now been repeated in an anechoic chamber, and the two results are compared. Also, some more interpretation is given.

II. The Experimental Details

As described earlier (Kumar 1974), the details are as follows. Figure 1 shows the simple apparatus constructed. It is capable of burning the reactant gases in the premixed or non-premixed mode, after flow in two concentric tubes. The length-to-diameter ratios $\ell/D = 470$ for the inner tube and $\ell/D = 173$ for the outer tube are believed to have established fully-developed pipe flow before exit. The details of the tubes are shown in Table I. The open jet configuration was chosen partly for simplicity and partly because it has been extensively used in the past. Thus, comparative studies are rendered easy. It is recognized that entrainment of ambient air can introduce uncertainties regarding the dynamics and particularly, in the combusting case, in the stoichiometry and a host of related effects (ignition, extinction, flammability, etc). An external co-flow of an inert gas (nitrogen, for example) or experiments in an inert atmosphere seem desirable, but have not yet been studied.

The mixing chamber M/C (5" I.D. and 10" long) is completely filled with 3/8"-diameter glass beads. The flow metering orifices are short screws into which are drilled smoothly-flared holes of the desired diameter. The pressure ratio across each orifice was usually of the order of ten (the worst case being three). Consequently, the mass flow rate was calculated through $\dot{m} = A^* P_o / C^*$ with the familiar nomenclature.

The concentricity of the internal tube with the external tube was arranged through two 0.011"-thick stainless steel (shim stock) strips placed more than two diameters (1") upstream of the exit. The flow disturbance due to these centering strips should be practically negligible.

Acoustic measurements were made with a $\frac{1}{2}$"-diameter condenser microphone (B&K 4134) which was mounted on a beam that pivoted on an axis passing through the exit centerline of the burner. The microphone was driven by a B&K 2801 amplifier, the output from which was continuously recorded on one channel of an Ampex FR-600 tape recorder at a tape speed of 60"/sec. The data were subsequently played back on an oscilloscope, either in the normal time-base or through a Tektronix 3L5 spectrum analyzer.

The experimental conditions of stoichiometry and exit velocities are shown in Table II. An attempt was made to maintain the stoichiometry and shear (between the co-flowing streams) constant as the mass flow rate was varied. In the S-series experiments, the shear was nearly constant around 18 per cent. In the O-series experiments, the shear was substantially less, the worst case being 14.9 per cent. It is believed that these values of shear are sufficiently mild not to alter adversely the basic conclusions of this work on combustion noise.

The first part of each run was a 30-second continuous record, with the microphone placed at an angle of nearly 45° from the axis of the flame; the second part of the run was a continuous record with the microphone position gradually varied (in nearly 20 seconds) in a circular path from 0° (perpendicular to the flame axis) to 90° (in line with the flame axis).

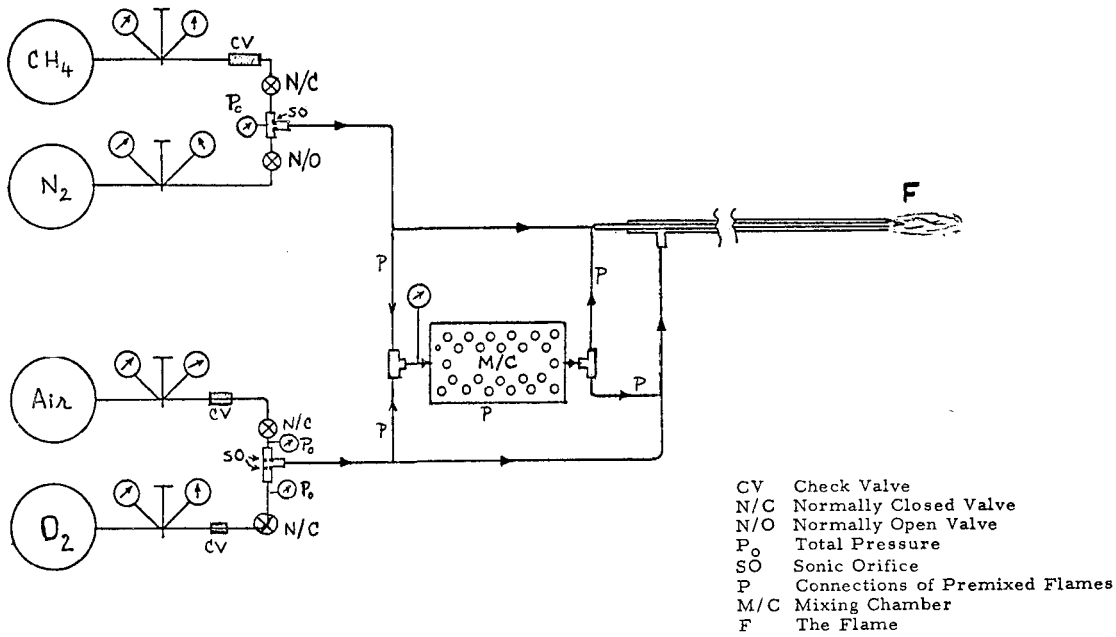


Figure 1. Apparatus Constructed.

Table I. The Details of Flow Tubing

	Length inches	O. D. inch	I. D. inch	Wall Thickness inch	Exit Flow Area inch^2
outer tube	69.5	0.5	0.402	0.049	0.0779
inner tube	71.5	0.25	0.152	0.049	0.0182

At the time of these experiments, an anechoic chamber was not available, and means had to be found to minimize possible errors resulting therefrom. Recognizing that the acoustic amplitudes should decay like the square of the distance from the source, a fairly large bay was chosen (21'X17'). There was no roof for this bay. All the measurements were made in the horizontal plane so that reflections from the hard floor would probably be less severe than otherwise. The measurements were also made as close as desirable so that the large amplitudes near the flame would mask the smaller amplitudes of the reflected sound.

There are obvious limitations on how close one can move the microphone to the flame before introducing near-field errors. The distance was approximately three times the lowest significant wavelength and considerably more for the higher frequencies. Even with all of these precautions it was clearly stated that "the absolute values of some of these measurements must be suspect. However, comparison between results for premixed and non-premixed flames should be valid."

Later, the anechoic chamber facility at JPL became available. The O experiments indicated in Table II were repeated in the anechoic chamber (see fig. 4). The chamber characteristics are extensively documented by Massier and Parthasarathy (1972). Three of the relevant characteristics are also reproduced here in figs. 5 (a)-(c).

III. The Experimental Results

The recorded data appeared as a continuous signal from the microphone. This continuous record was played back in (randomly selected) short segments on the oscilloscope set with the normal time base. A large number of such segments superposed on each other gave a fairly good indication of the amplitude of the noise level. The recorded directionality was obtained on the oscilloscope with the sweep rate set approximately equal to the traverse rate of the microphone around the flames. The 90° position placed the microphone directly in front of the flames. The hot gas flow over the microphone generated spurious signals of very large amplitudes. These are seen in the flame directionalities in figs. 2 and 3. The attention of the reader is particularly drawn to the fact that the directionality traces of the first 3 velocities (150, 191, and 242 fps) have been obtained at twice the calibration level used with the other 2 velocities (277 and 290 fps) in fig. 2.

A few (randomly selected) segments from the continuous signal-time record, studied together, give a good indication of the waveshape; it is again to be noted that at the lowest velocity (150 fps) the waveshape has been obtained at a calibration level which is twice that of the rest of the velocities.

The frequency spectra obtained with a Tektronic 3L5 spectrum analyzer are calibrated with a Hewlett Packard 204C oscillator. The single frequency signals which appear as line pulses at slow sweep rates are spread out somewhat at the higher

TABLE II. EXPERIMENTAL CONDITIONS OF THE RUNS

Run No.	Type	Fuel Q 10^{-2}cfs	Fuel U fps	Air Q 10^{-2}cfs	Oxygen Q 10^{-2}cfs	Total Oxidizer Q 10^{-2}cfs	Oxidizer, U fps	Total Flow, Q 10^{-2}cfs	Total Flow U fps	Oxidizer Composition Mole Fractions	$\frac{Q_{oxidizer}}{Q_{fuel}}$	$\frac{Q_o}{Q_f}$ for $\phi=1$	ϕ	Shear $\equiv \frac{2\Delta U}{U_o+U_f}$	$\bar{d}$ in.	P_{dB} ref. 0.0002μB
S1	NP	1.9	150	4.03	2.6	6.63	123	8.53	-	$0.52O_2+0.48N_2$	3.49	3.85	1.1	0.198	26	87
S2	P	1.9	-	4.03	2.6	6.63	-	8.53	128	$0.52O_2+0.48N_2$	3.49	3.85	1.1	-	26	93
S3	NP	2.53	200	5.35	3.5	8.85	162	11.38	-	$0.523O_2+0.477N_2$	3.50	3.82	1.09	0.21	26	93
S4	P	2.53	-	5.35	3.5	8.85	-	11.38	171	$0.523O_2+0.477N_2$	3.50	3.82	1.09	-	26	98
S5	NP	3.17	250	6.68	4.4	11.08	205	14.25	-	$0.525O_2+0.475N_2$	3.50	3.81	1.09	0.196	26	97
S6	P	3.17	-	6.68	4.4	11.08	-	14.25	214	$0.525O_2+0.475N_2$	3.50	3.81	1.09	-	26	99
S7	NP	3.8	300	8.05	5.26	13.31	246	17.11	-	$0.523O_2+0.477N_2$	3.50	3.82	1.09	0.198	26	100
S8	P	3.8	-	8.05	5.26	13.31	-	17.11	257	$0.523O_2+0.477N_2$	3.50	3.82	1.09	-	26	102
S9	NP	4.13	326	8.68	5.95	14.63	270	18.76	-	$0.532O_2+0.468N_2$	3.55	3.76	1.06	0.188	26	101
S10	P	4.13	-	8.68	5.95	14.63	-	18.76	281	$0.532O_2+0.468N_2$	3.55	3.76	1.06	-	26	103
S11	NP	1.9	150	4.03	2.6	6.63	123	8.53	-	$0.52O_2+0.48N_2$	3.49	3.85	1.1	0.198	55.7	86
S12	NP	2.53	200	5.35	3.5	8.85	162	11.38	-	$0.523O_2+0.477N_2$	3.50	3.82	1.09	0.21	55.7	90
S13	NP	3.17	250	6.68	4.4	11.08	205	14.25	-	$0.525O_2+0.475N_2$	3.50	3.81	1.09	0.196	55.7	93
S14	NP	3.8	300	8.05	5.26	13.31	246	17.11	-	$0.523O_2+0.477N_2$	3.50	3.82	1.09	0.198	55.7	95
S15	NP	4.13	326	8.68	5.95	14.63	270	18.76	-	$0.532O_2+0.468N_2$	3.55	3.76	1.06	0.188	55.7	96
S16	P	1.9	-	4.03	2.6	6.63	-	8.53	128	$0.52O_2+0.48N_2$	3.49	3.85	1.1	-	55.7	89
S17	P	2.53	-	5.35	3.5	8.85	-	11.38	171	$0.523O_2+0.477N_2$	3.50	3.82	1.09	-	55.7	94
C1	NP	1.89	150	5.475	2.625	8.1	150	9.99	-	$0.465O_2+0.535N_2$	4.3	4.3	1	zero	32.7	88
O2	P	1.89	-	5.475	2.625	8.1	-	9.99	150	$0.465O_2+0.535N_2$	4.3	4.3	1	-	32.7	94
O3	NP	2.52	200	6.475	3.75	10.225	189.5	12.745	-	$0.5O_2+0.5N_2$	4.06	4.0	0.986	.054	32.7	90
O4	P	2.52	-	6.475	3.75	10.225	-	12.745	191	$0.5O_2+0.5N_2$	4.06	4.0	0.986	-	32.7	96
O5	NP	3.15	250	8.05	4.92	12.97	240	16.12	-	$0.51O_2+0.49N_2$	4.12	3.92	0.952	.0408	32.7	96
O6	P	3.15	-	8.05	4.92	12.97	-	16.12	242	$0.51O_2+0.49N_2$	4.12	3.92	0.952	-	32.7	100
O7	NP	3.775	300	8.9	5.80	14.70	271	18.475	-	$0.521O_2+0.479N_2$	3.89	3.84	0.987	.084	32.7	99
O8	P	3.775	-	8.9	5.80	14.70	-	18.475	277	$0.521O_2+0.479N_2$	3.89	3.84	0.987	-	32.7	102
O9	NP	4.1	325	9.15	6.05	15.2	280	19.3	-	$0.525O_2+0.475N_2$	3.71	3.81	1.028	.149	32.7	100
O10	P	4.1	-	9.15	6.05	15.2	-	19.3	290	$0.525O_2+0.475N_2$	3.71	3.81	1.028	-	32.7	102
O11	P	4.1	-	11.9	5.7	17.6	-	21.7	325	$0.465O_2+0.535N_2$	4.3	4.3	1	-	32.7	105
O12	P	3.775	-	11.0	5.25	16.25	-	20.025	300	$0.465O_2+0.535N_2$	4.3	4.3	1	-	32.7	104

sweep rates that were used to expedite the data processing. The magnitude of the uncertainty introduced thereby can be estimated from the spectra of the single-frequency signals shown in figs. 2 and 3, which present all of the data graphically. In the acoustic spectra of the non-premixed flames (fig. 3), the high-amplitude peak near zero frequency is a manifestation of the electronics of the spectrum analyzer, as can be inferred from the calibration traces in the same figure.

The data on the premixed flames (fig. 2) and on the non-premixed flames (fig. 3) were obtained with the microphone at the same location relative to the

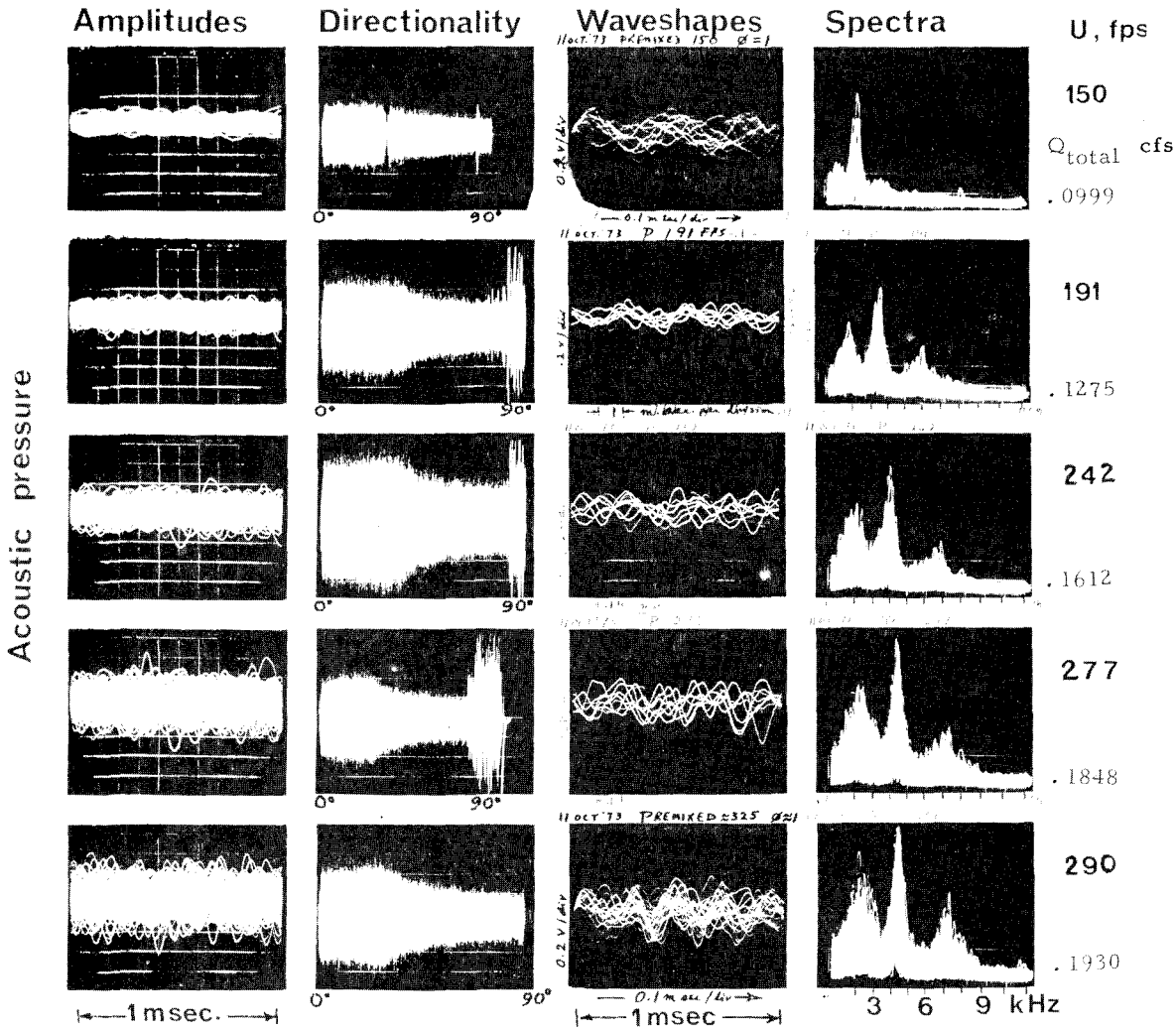
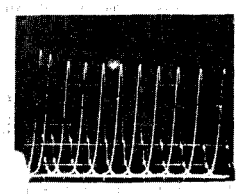


Fig. 2. Premixed Flames -- Acoustic Data.



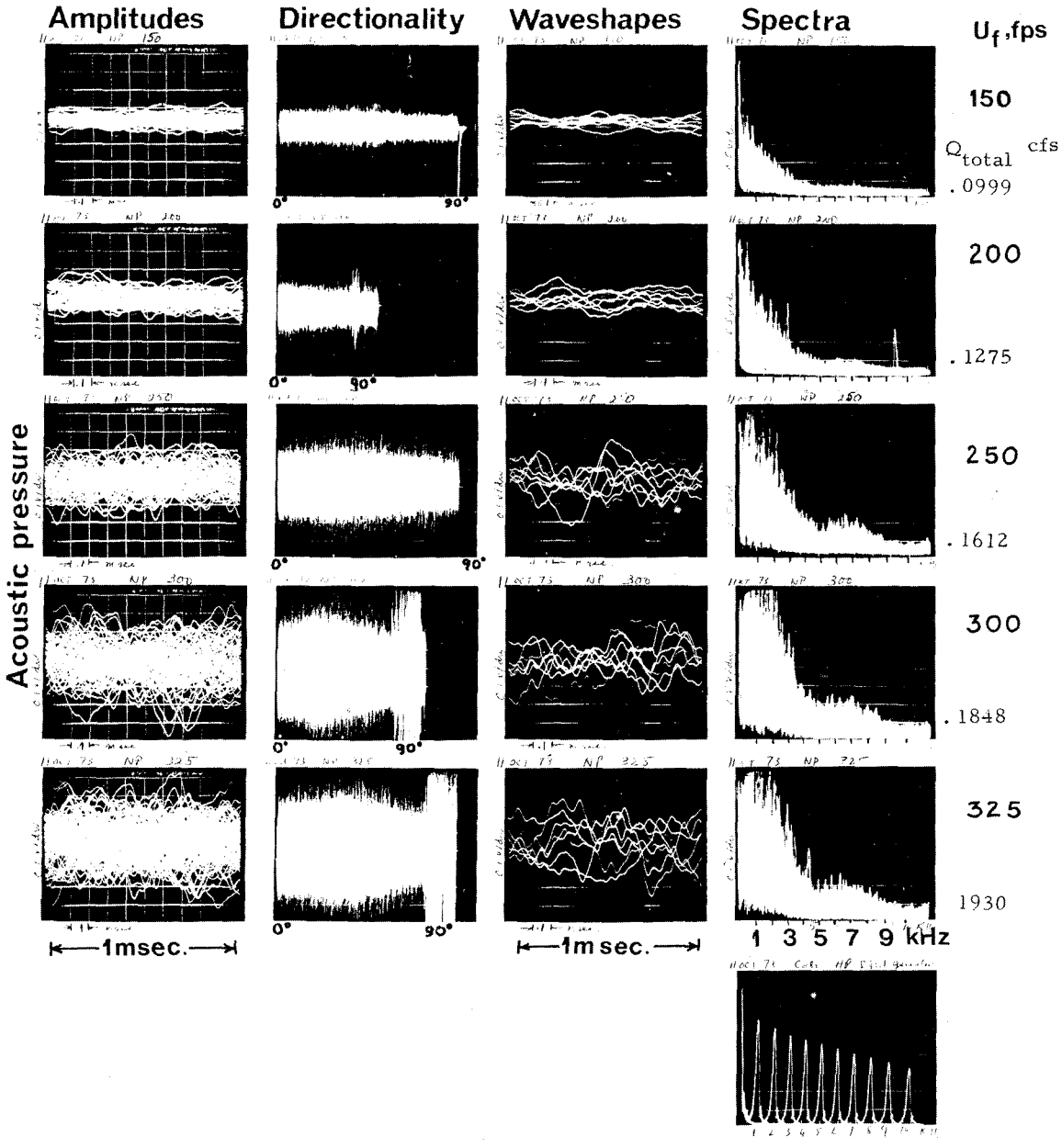
burner. The microphone signals were calibrated with a standard B&K 124 dB piston calibrator.

The circumstances under which the results were obtained in the anechoic chamber were such that, for the premixed case, only the first, second, and last velocities were valid data (fig. 6); and for the non-premixed case, the first four velocities were valid data (fig. 7). The range of the spectrum analyzer was extended considerably into the lower range in this case, and this extra set of data can be seen in fig. 7.

Examples of still photographs of the visible flames are shown in fig. 8. These photographs were obtained on Kodak Ektachrome transparencies at 1/60 sec exposures. The examples in fig. 5 are of the lowest and the highest velocities employed. The photographs of the intermediate velocities are also available.

In order to compare the results of the combusting jets with those of the non-combusting jets, cold-flow noise measurements were attempted, with nitrogen substituted for the fuel. The sensitivity of the 1/2" microphone was not sufficient to obtain the noise output of the cold jets, which was usually comparable to the electronic noise in the instrumentation system. The least obscure record obtained for the cold jet noise is shown in fig. 9. The main point of presenting this spectrum is to indicate the general noise pattern of a jet in the present apparatus geometry. As discussed in the next section, the three peaks seen in fig. 4 are believed to be caused by the three discrete dimensions of importance to flow exit in the apparatus used. These are: the inner diameter of the outer tube, the outer diameter of the inner tube, and the inner diameter of the inner tube.

The acoustic spectra were processed to yield the Strouhal Numbers at the peaks, figs. 10(a) and (b), and the acoustic amplitudes, as a function of



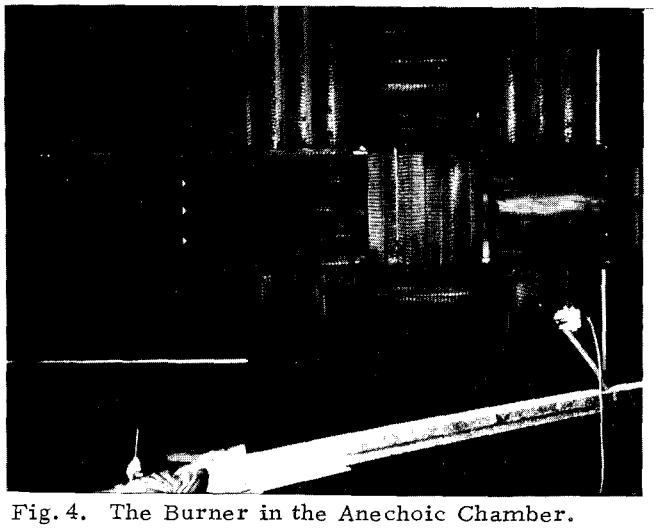


Fig. 4. The Burner in the Anechoic Chamber.

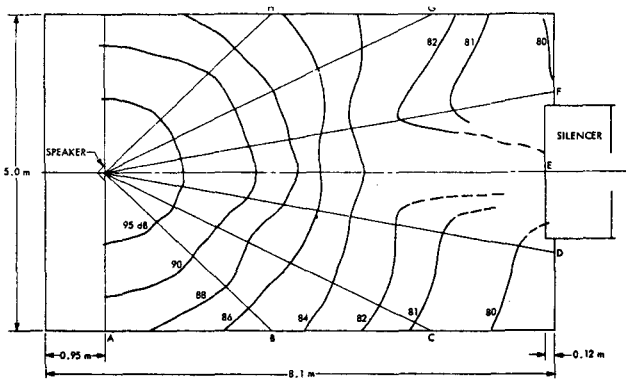
the mean flow rate, as presented in fig. 11.

Four representative frames from the high-speed ($\approx$ 2500 frames/sec) motion picture of a non-premixed flame is shown in fig. 12. Kodak 2475 recording film [ESTAR-AH Base (16 mm)] was used in a FASTAX movie camera. The motion pictures were taken from approximately the same relative position as the still photographs. The movie of the premixed flame under identical conditions of flow did not reveal as many details, mainly because of limitations on the framing rate. (The principal frequencies are much higher in the premixed mode of burning.) Nevertheless, the visible flame surface showed well-defined oscillations in the movie.

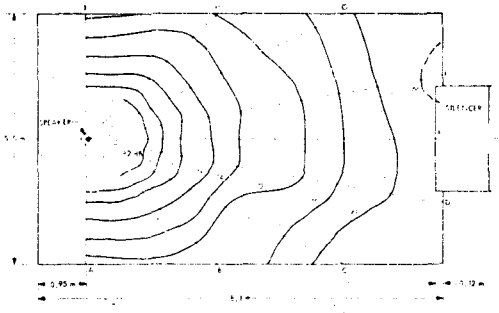
IV. Interpretation and Discussion

It should be remembered that in all of the present experiments, no external flameholder was necessary to anchor the flames to the tip of the

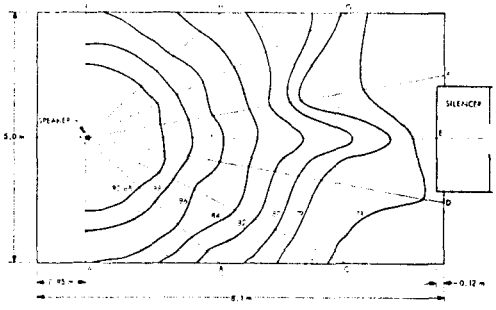
Fig. 5. The Acoustics Characteristics of the Anechoic Chamber.



(a) overall sound



(b) 500 Hz



(c) 2000 Hz

tubes. (In one case during preliminary testing of the apparatus, the measured acoustic amplitude was twice with an external flameholding compared with natural flameholding.) The total noise outputs of premixed flames have been systematically investigated as a function of pilot mass flow rate by Smith and Kilham (1963). The noise amplitude of the cold flow, flow with pilot flame, and the fully stabilized flame have been systematically investigated by Shivashankara, et al. (1973) for premixed flames. Aside from the total noise output that has been investigated as mentioned, it is possible that many other important features (such as the frequency spectrum) may also be influenced by pilot flames, as discussed in greater detail below. Unless the noise data are accompanied by supplementary data on the role of the pilot flame, there exists room for doubts.

In the present experiments, the nature of turbulence generated by the "bluff body" thick wall influences the acoustic character of the flames studied. It would certainly seem desirable to investigate the influences of different types of flameholders (i.e., with different exit conditions).

The rest of the discussion is about the acoustic power, directionality, and the frequency spectra which are compared in the two cases of anechoic chamber and hard-walled bay data.

The Acoustic Power

The measured amplitudes of the noise output are plotted in fig. 11 as functions of the mean velocity. In a simple acoustic wave, the power is proportional to the square of the acoustic pressure. Hence, in the present experiments, the acoustic power of the open jet flames is proportional to the third power of the mean flow velocity in the premixed case and to the fourth power of the fuel flow velocity in the non-premixed case in the hard-walled bay. The premixed flame has indeed been observed to yield the cubic law in previous investigations also (Strahle and Shivashankara 1973). The case of the less explored non-premixed flame is not so certain, and many different indices have been reported in the literature (Kotake and Hatta 1965, Giammar and Putnam 1970, Knott 1971).

In the anechoic chamber the premixed flames have yielded a slightly lower exponent of 2.7, which is also much closer to the regression analysis generated by Shivashankara, et al. (1973). But the non-premixed flames continue to yield an unmistakable fourth power.

Although the mean flow velocity is not the directly relevant parameter in noise production, it is frequently used as a ready means of comparing data. The noise production depends on the fluctuating components which may bear a one-to-one reproducible relation to the mean flow velocity. In fact, the existence of such a relation is tacitly assumed in all correlations of the noise with mean flow variables.

The U^3 or the $U^{2.7}$ law obtained in the present experiments is consistent with the premixed flame data of Strahle, et al. The fact that this law is not universally obtained is evidence of the complex nature of the variables involved. The existence of an external pilot flame does not appear to be of crucial importance to this question, since the present experiments and those of Knott obtained different exponents, although neither used a pilot flame. Similarly, the experiments of Strahle and Shivashankara (1973) and of Smith and Kilham (1963) have yielded different exponents, although both of these investigations used very similar pilot flames.

The data scatter in fig. 11 is attributed to the small variations in the stoichiometry. In the O-series experiments, there occurred a greater variation in the stoichiometry, and the data scatter is also somewhat higher than for the S-series experiments plotted in fig. 11.

Directionality

The rather pronounced directionality of the premixed flame noise (seen in fig. 2) can be explained on the basis of mutual cancellations of acoustic signals emitted by different regions of the combustion zone. When the wavelength of emitted sound gets comparable to or smaller than the source

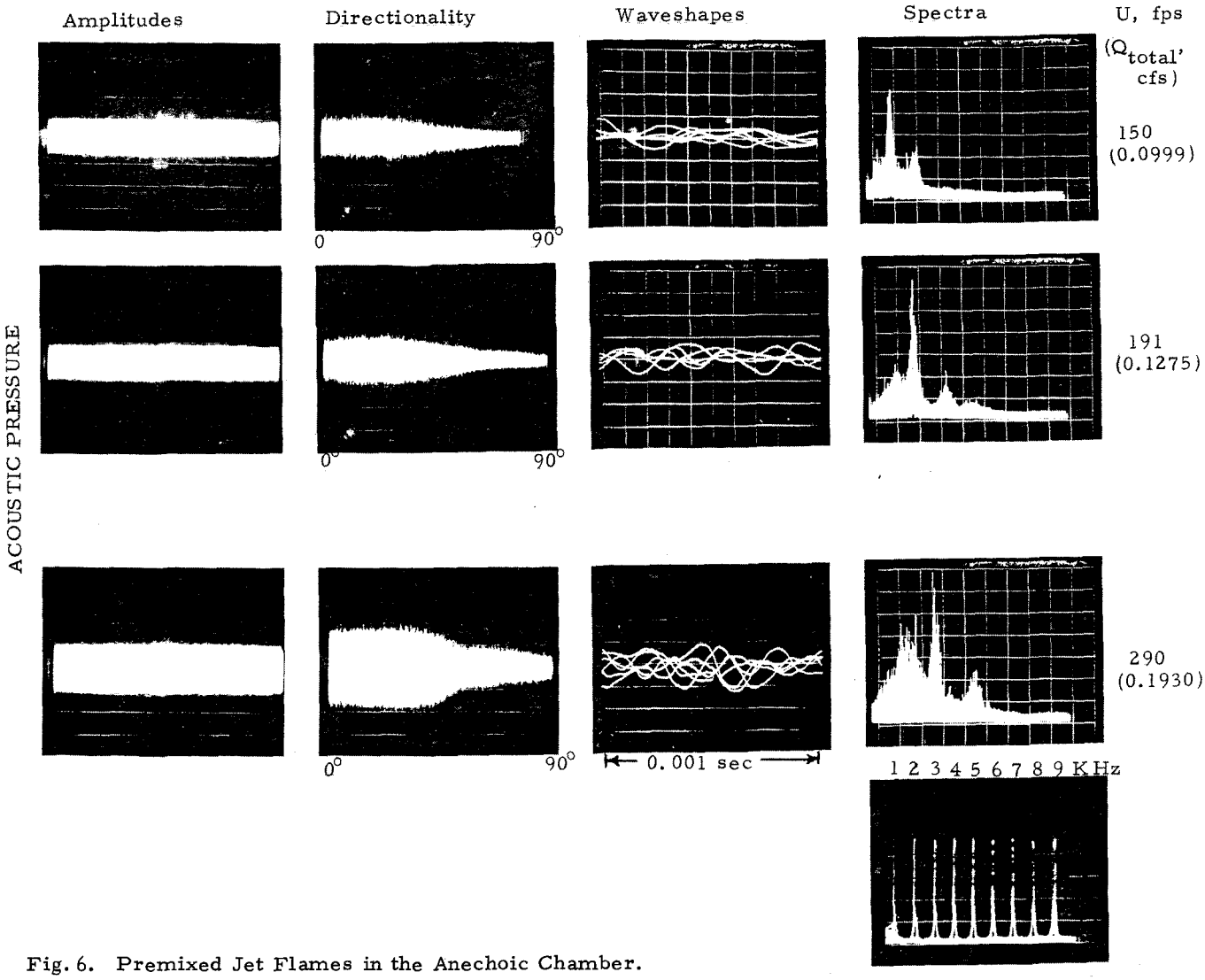


Fig. 6. Premixed Jet Flames in the Anechoic Chamber.

region of interest, such cancellations may be expected. In the premixed situation, the principal wavelengths are as small as a few inches, as deduced from the acoustic spectra (fig. 2). The physical extent of the source (combustion zone) in the axial direction is of the order of a few inches (fig. 8), and hence comparable to the wavelengths. This could reduce the acoustic amplitudes in the axial direction. However, the maximum physical extent of the source region in the lateral direction is about one inch, and may not attenuate signals in this direction. The rather marked change in the amplitude around 45° seems to lend credence to such a speculation. Incidentally, on a (more meaningful) dB scale, the directionality would appear much smaller than on the linear scale presented in fig. 2.

On the other hand, the non-premixed flames are reasonably free of directionality in their noise output. This lack of directionality may be taken to imply a source region of random character. The directionality of the fluid dynamic variables (that is present, at least in the non-combusting case) does not seem to influence the combustion region. The directionality of the premixed flame implies some influence of the mean fluid dynamics. With the additional information of a nearly constant Strouhal Number (see later), it would appear that the premixed flame is strongly influenced by the jet dynamics.

The changes in the directionalities of both the premixed and non-premixed flames between the hard-walled bay (figs. 2 and 3) and the anechoic chamber (figs. 6 and 7) appear to be essentially insignificant.

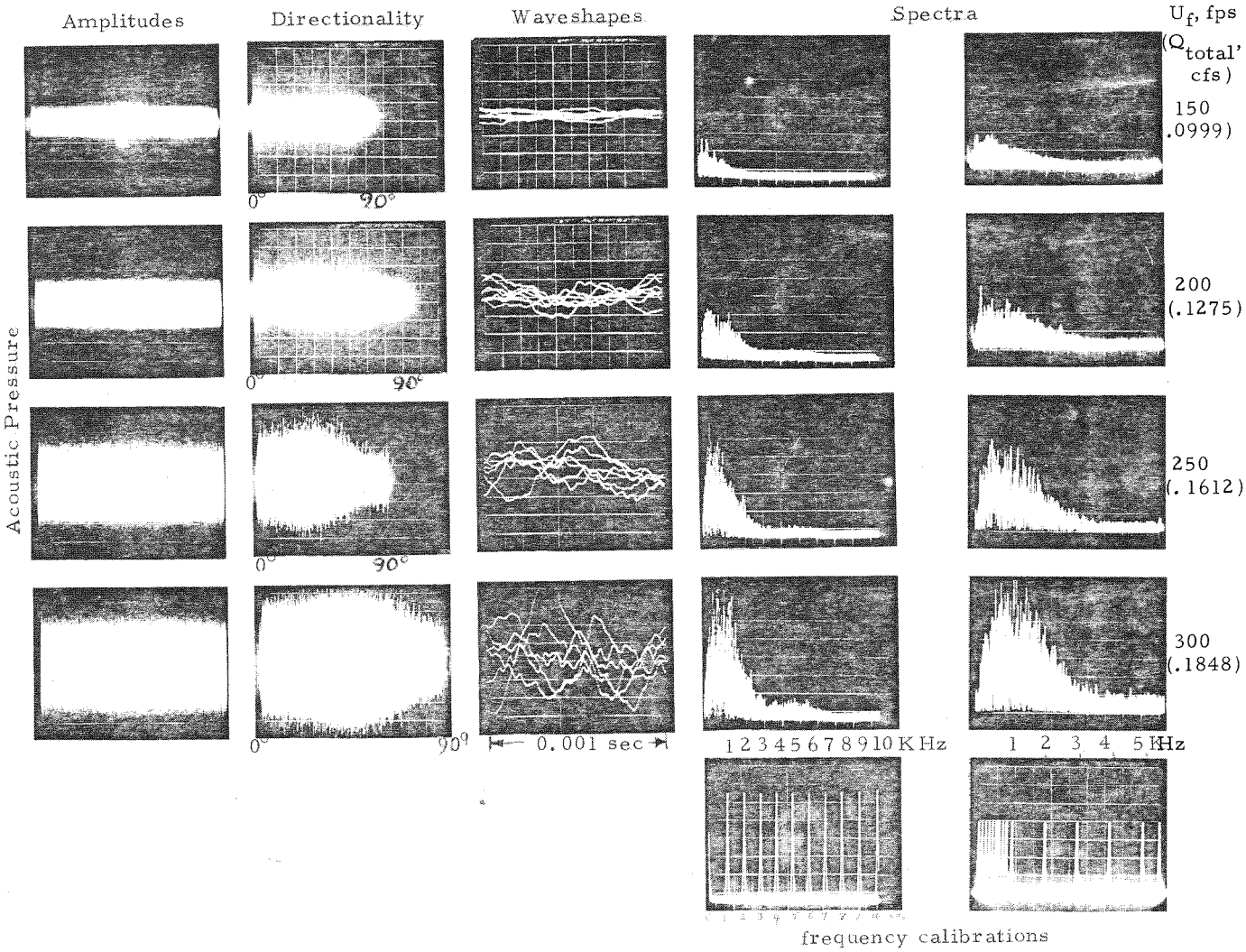


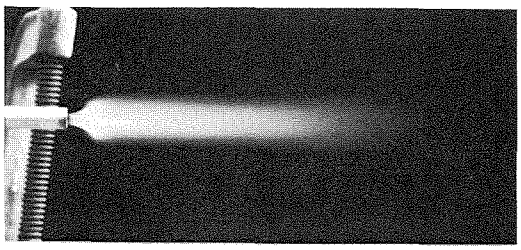
Fig. 7. Non-premixed Jet Flames in the Anechoic Chamber.

Waveshapes and Spectra

The most significant result of the present experiments is the revelation of the differences between premixed and non-premixed flames. The waveforms ofthe non-premixed flames (figs. 3, 7) are highly distorted and contrast with the smooth (if not sinusoidal) waveforms of the premixed case (figs. 2, 6). These high-frequency components are clearly seen in the acoustic spectra also.

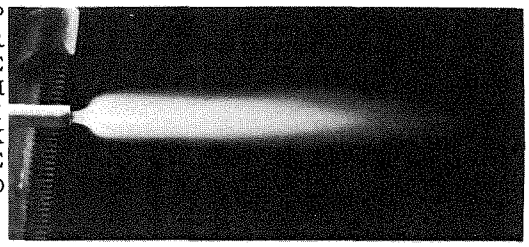
The appearance of well-defined peaks in the broad band spectra of premixed flames (figs. 2, 6) is at variance with the earlier findings of Smith and Kilham (1963), Strahle and Shivashankara (1973), Hurle, et al. (1968), all of whom reported broad peaks. (On a dB scale, the peaks seen in fig. 2 would be broader than on the linear scale, but the perceptible variance with earlier results would still persist.) It would appear that the acoustic amplitudes near the natural frequencies in the system (namely, mean velocity ÷ a characteristic length scale) are greatly accentuated by combustion. The well-defined peaks may be associated with the rigidly determined dimension of the flames, because of the natural flameholding by the tubes. With external pilot flames, the flame dimensions are uncertain by an amount determined by the fluid dynamics of the pilot-flame/main-flame interactions and could spread out the peaks. If we picture the noise production as arising from the distortions of the flame surface by the turbulence eddies, the principal frequencies may be anticipated to be governed by principal length scales governing the sizes of the eddies. In the present apparatus geometry, three distinct dimensions of relevance to eddies are present. These are the three diameters associated with the flow, namely, inner and outer diameters of the inner tube and the inner diameter of the outer tube, in increasing order. Hence, if we believe that the discrete frequency noise production is associated with these scales, the three peaks

Fig. 8. Time-averaged Appearance of the Jet Flames.

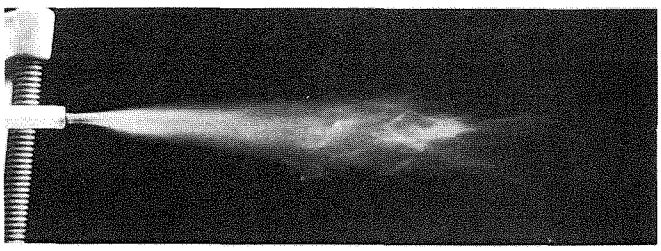


Q_{total} = .0999 cfs; U = 150 fps

PREMIXED

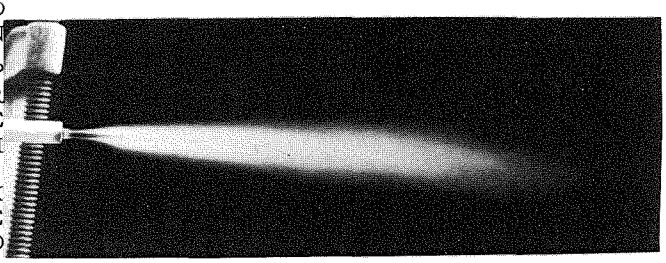


Q_{total} = .193 cfs; U = 290 fps



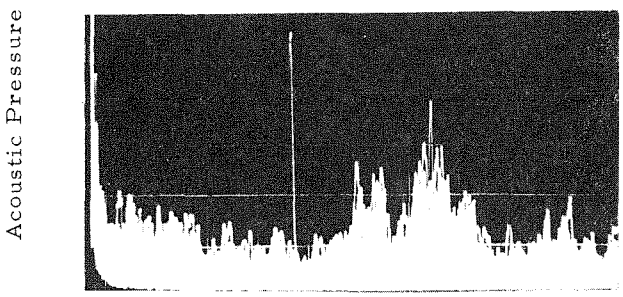
Q_{total} = 0.0999 cfs; U_f = 150 fps

NON PREMIXED



Q_{total} = 0.193 cfs; U_f = 325 fps

Fig. 9. An Acoustic Spectrum of the Cold Flow.
Nitrogen flow central tube - 232 fps
Enriched air flow - outer tube - 280 fps



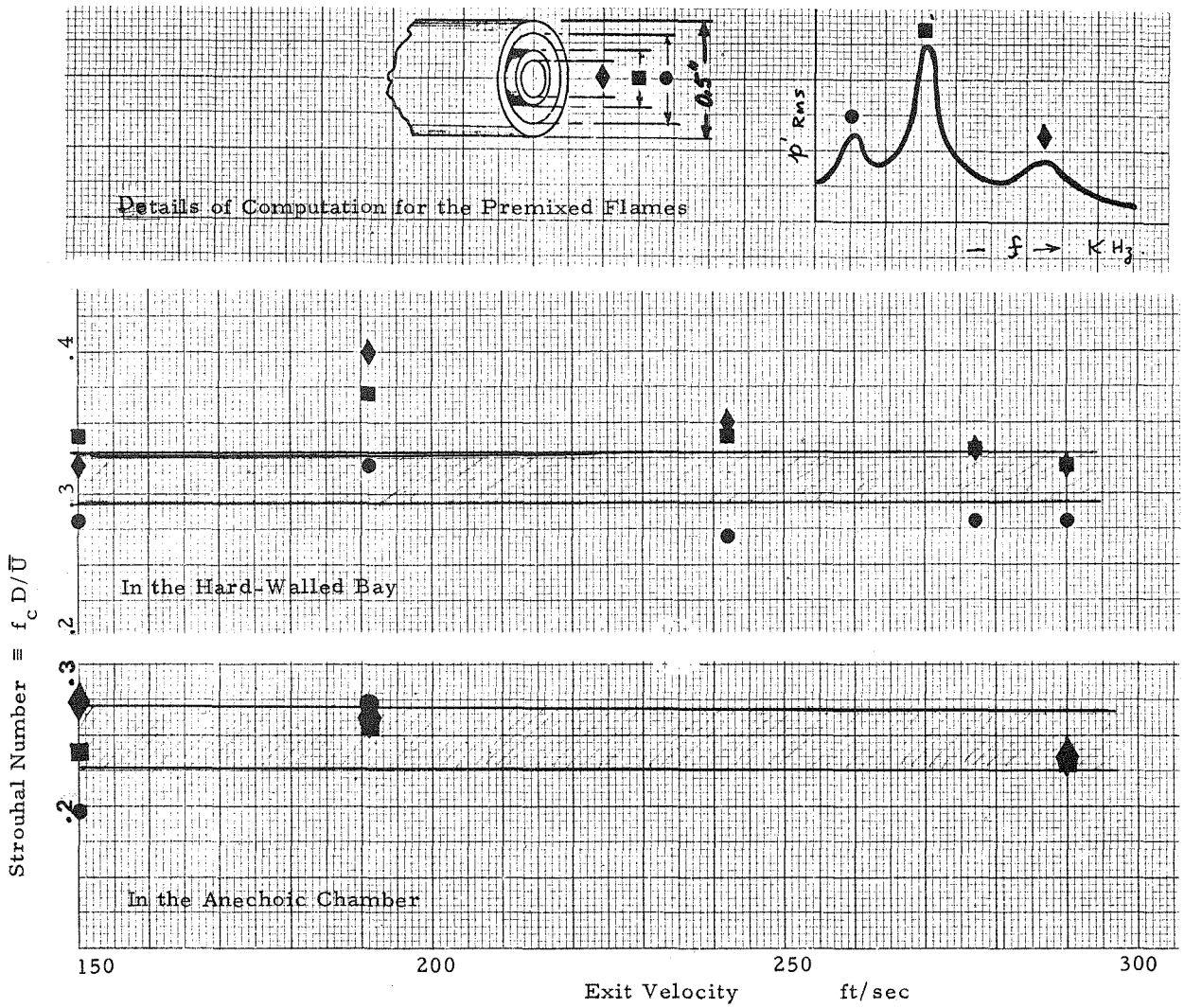
seen in the acoustic spectra must correspond to the above dimensions in the reverse order. The computed Strouhal Numbers based on such an assumption are plotted in fig. 10. As can be seen, the Strouhal Numbers are reasonably constant around 0.3 in the bay and slightly lower in the anechoic chamber, indicating that the basic reasoning behind the plot may be valid. At any rate, the near constancy of the Strouhal Numbers at the peaks strongly indicates a simple mechanism of noise production.

The high-speed motion pictures (not presented here) show well-defined oscillations of the visible flame surface, as also evident from the acoustic waveshapes that are smooth. The visible flame region (high luminosity flame surface) is seen in fig. 8 to expand with increases in the mean flow rate, consistent with previous observations (Hurle, et al. 1968; Strahle and Shivashankara 1973; Shivashankara, et al. 1973). All of the above observations conform to the general idea that noise generation in premixed flames is due to simple oscillations (wrinkling) of the flame surface. This wrinkling process leads to fluctuations in the local volumetric reaction rate, and noise is generated in accordance with the monopole model.

In non-premixed combustion, the highly distorted waveforms (sharp gradients) suggest some form of abrupt volume expansion, in the source region, randomly distributed in space and time. These high-frequency components are clearly seen in the acoustic spectra also. The broad band spectra with higher energies in the lower frequencies (larger scales) suggest a true turbulent field with no preferred frequencies. However, the only discrete frequency in the system (mean velocity ÷ the diameter of this interfacial mixing region) near the burner mouth (fig. 8) is revealed as a mild peak in the spectra. (Ex. at U = 300 fps the mixing zone diameter ≈ 1/2", f = 7200 Hz, which is close to the observed frequency at that mild peak.) High-speed motion pictures (fig. 12) clearly reveal the discrete eddy structure in the combustion zone which appears as a diffuse luminous jet in the time-averaged photograph.

The anechoic chamber data on non-premixed flames have been analyzed in the low-frequency regime as shown in fig. 7. It is seen that even the non-premixed flames show a peak in the spectrum, however broad. This needs careful interpretation. The lowest frequency associated with the flames, it would seem, cannot be lower than the ratio of the mean flow velocity to the length of the flame.

When the chemical kinetic time scale is far less than the molecular mixing time scale, the dynamics of the flame is essentially controlled by the turbulence characteristics. It is known that the turbulence level in the open jet increases linearly with the Reynolds number and hence with the velocity (for a fixed tube geometry). For such cases, the length of the flame is nearly invariant with the jet velocity, as has been discussed at length in the classic paper of Hottel and Hawthorne (1949). In



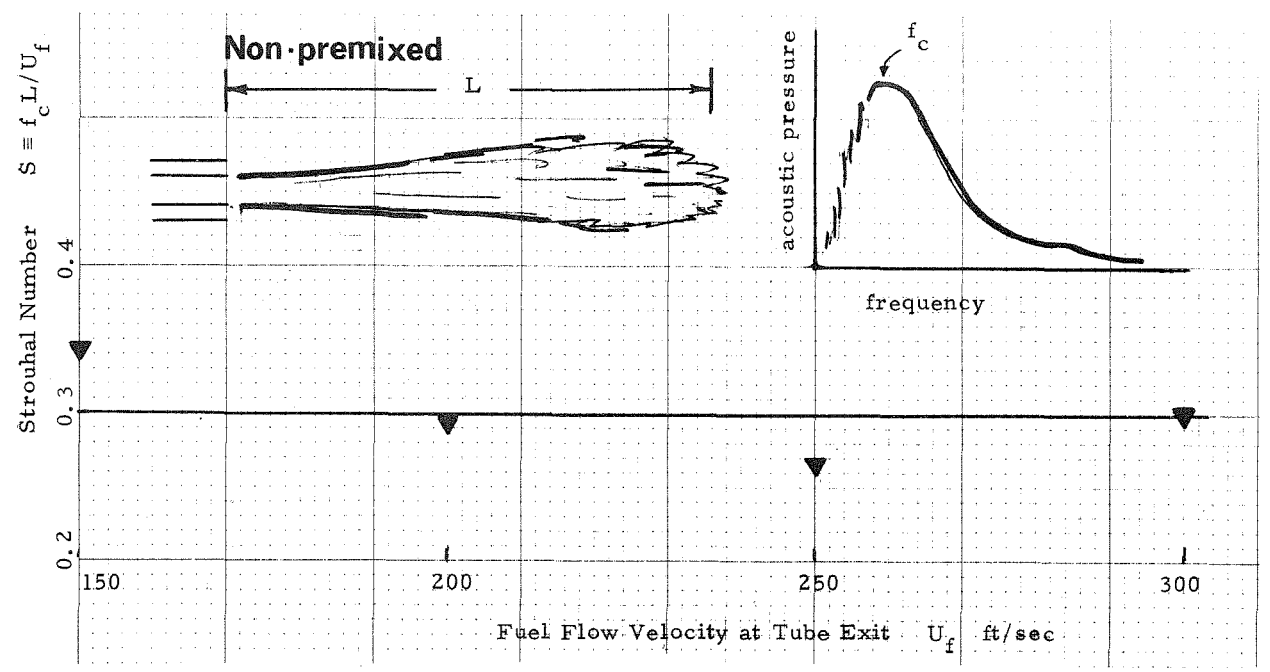


Fig. 10. The Strouhal Numbers.

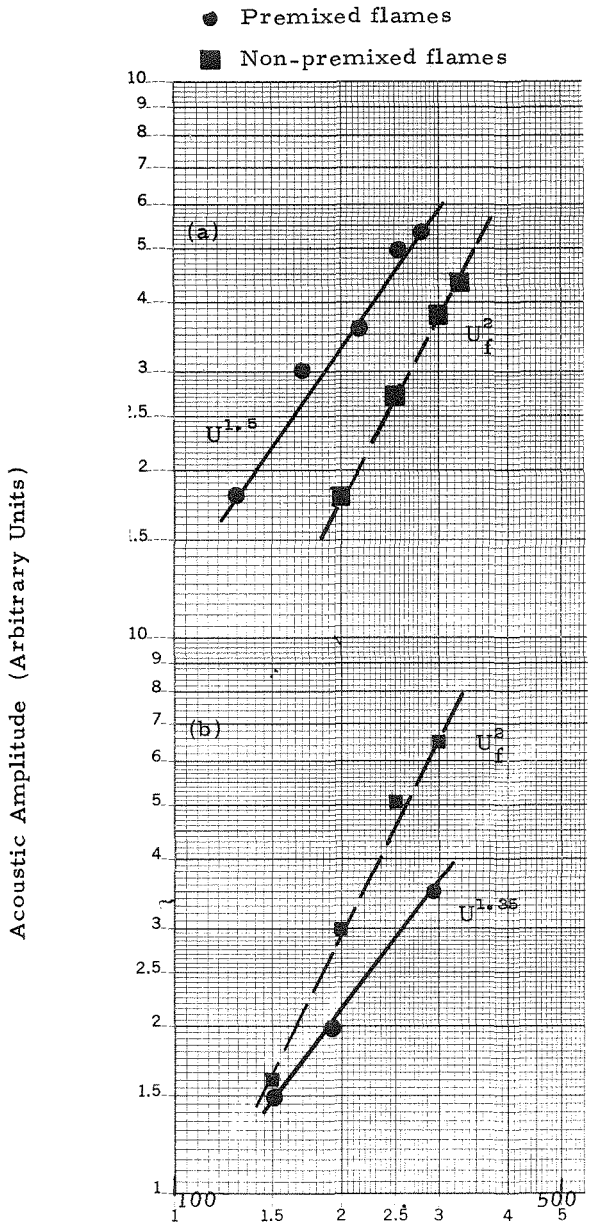


Fig. 11. The Acoustic Amplitudes as a Function of Velocity.
(a) in the hard-walled bay
(b) in the anechoic chamber

the present experiments also, the length of the turbulent flames has remained constant, as seen in fig. 8. (In a related set of experiments, the stoichiometry was also varied from the lean to the rich side with variations in the flow velocities. This resulted in profound color changes in the flames -- blue → yellow -- and yet the length remained constant.) This is a clear indication that the details of turbulence are far more important than the details of chemistry.

The "length" referred to above is of course the time-averaged length of the luminous brush

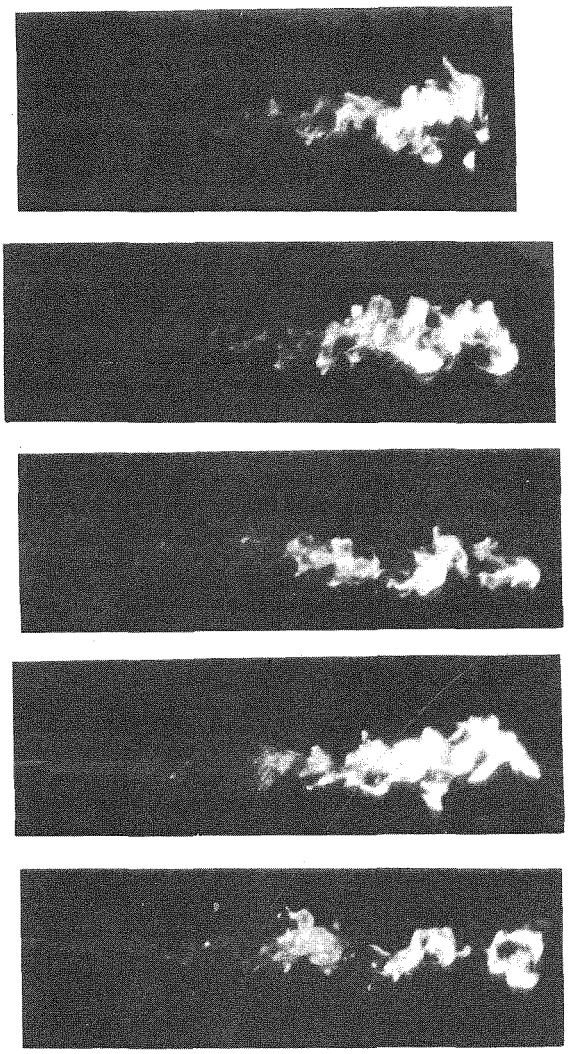


Fig. 12. Examples of Frames from the High-Speed Movie on a Non-premixed Flame. (Exposure of each frame ≈ 1/7500 sec.)

seen in fig. 8. In actuality, the "length" varies as a function of time, as seen in the high-speed pictures (fig. 12). What we really have is a random field dictated by the statistical nature of the large-scale eddies. These eddies get dissipated at different distances from the tube exit, but always within a band of lengths, the mean of which is the "length" of the flame. Thus, frequencies lower than the lowest can indeed occur when one of the large eddies travels a larger distance before dissipation. However, these occurrences become rarer and rarer as we depart farther and farther from the ratio of the mean velocity to the time-averaged length. This is also seen in the spectra as lower density peaks (fig. 7). That is, in the 30 seconds of data reduction, these very low frequencies occurred only a few times. When we do not encounter a large number of events, the averages are not meaningful and hence the lowest frequency, for all practical purposes, appears to be the one at the peak. Hence, it seemed worthwhile to compute the Strouhal Numbers based on the time-averaged length of the flame brush and the frequency at the peak. The values (plotted in fig. 10) are surpris-

ingly close to 0.3, indicating that the basic reasoning behind this argument may be valid.

The frequency thus bears a simple relation to the jet dynamics which was seen to be unrelated to the chemistry. Considering the rather strong decay in the radiated acoustic power at the higher frequencies, it may be said that the frequency of maximum radiated power in the non-premixed flame is independent of the chemistry. This result is in agreement with the theory of Strahle (1973).

V. Concluding Remarks

These qualitative experiments have yielded data that support the following general statements. The noise outputs of combusting jets are much higher than those of non-combusting jets under otherwise identical conditions. It is possible to conduct experiments without external flameholders (at least up to velocities of 325 fps), so that uncertainties are kept to a minimum. Premixed and non-premixed flames are significantly different both in their structure and in their acoustics.

An attempt has been made to keep the conditions as similar as possible between the premixed and non-premixed flames. For the same total flow rate of the reactants and the same exit velocities, the exit areas have to be the same. Hence, the same concentric-tubes configuration was used in both cases. This leads in the premixed case to combustion zones in both the outer and inner jets; hence, the external configurations of the premixed flames are not identical with those of single jet flames. It is believed that this is a distinction which is unlikely to alter the conclusions of this work. (In fact, the U^3 power law obtained here is the same as that obtained by Strahle and Shivashankara on single jet flames.) If an attempt is made to maintain the same flow velocity for the same total flow rate of the reactants in a single tube, the diameter will have to be less than that of the outer tube used in the present experiments. The tube diameter directly controls the scale of turbulence in the jet. Alterations in the turbulence scale are likely to have an important influence on the noise output, which is controlled by jet turbulence. Thus, one of the meaningful standards of comparison maintained in the present study would be lost with the use of a single tube.

The results in the hard-walled bay and in the anechoic chamber (under these conditions of flow and microphone distance) have indicated the following similarities and dissimilarities.

The Similarities

(a) The premixed flame noise output shows sharply defined peaks that scale well with the concept of a constant Strouhal Number.

(b) The acoustic power in the non-premixed flames scales very well with the fourth power of the mean velocity.

(c) The directionalities appear to be hardly affected.

(d) The non-premixed flames show a broad frequency spectrum with most of the energy in the lower frequencies.

The Dissimilarities

(a) The principal frequencies are somewhat lower in the anechoic chamber for the premixed flames, so that the Strouhal Numbers are lower in value (by about 25 per cent).

(b) The exponent in the velocity scaling of power in the premixed case is 2.7 in the anechoic chamber and 3.0 in the hard-walled bay.

The judgement on whether the similarities are more profound or whether the dissimilarities are more profound is left to the competent reader, who should also evaluate the earlier statement "... comparison between results for the premixed and non-premixed flames should be valid..." in the hard-walled bay (Kumar 1974).

Several improvements are possible in the experimental technique. Measurements of velocity (mean and fluctuating) profiles in the jet, choice of a fuel like hydrogen (so that its wide flammability limits in air enable us to gradually vary the combustion conditions from those of an isothermal jet), spark Schlieren photographs, all seem desirable. On the theoretical front, the results reported here may prove useful in the analytical modeling of the reaction rate term in the conservation equations. It is recalled that the uncertainty in the theoretical treatments is associated with the local reaction rate in the combustion zone. Simple treatments, such as that of Bragg (1963); rigorous treatments, such as that of Kotake and Hatta (1965); and even the more recent treatments of Strahle (1971), all leave the acoustic field as a function of the local reaction rate, for which an expression is not yet available as a function of the experimentally-determined variables of composition, flow, and geometry. It is believed that these results will also aid in solving the basic problems of turbulent mixing and combustion which have been the subject of two excellent summaries recently (Williams 1974).

Acknowledgments

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Nomenclature

A^*	throat area of the metering orifices
c	sonic velocity
C^*	characteristic velocity of the gas under consideration
D	diameter of the burner
E	expansion ratio ($\equiv \rho_u/\rho_b$)
f	frequency
L	characteristic physical extent of the noise source
ℓ	length of flow in the tube
$\dot{m}$	mass flow rate

N	number of elementary sources in a collection that constitutes the combustion zone
P	acoustic power
p	acoustic pressure in dB (ref. 0.0002 μbar)
P_o	stagnation pressure
q	volumetric combustion rate of gases
$\mathcal{R}$	Reynolds number ($\equiv UD/\nu$) based on cold gas ν
S_b	laminar flame speed of combustible mixture relative to the unburned gas
S	Strouhal Number ($\equiv fD/U$)
U	characteristic mean velocity in the noise source
u	characteristic fluctuating velocity in the noise source
δ	characteristic laminar flame thickness
λ	wavelength ($= c_o/f$)
ν	kinematic viscosity
ρ	density
ϕ	stoichiometric coefficient
$(\ )_o$	medium of propagation
$(\ )_u$	unburned condition
$(\ )_b$	burned condition
$(\ )_F$	finite source

References

Bilger, R. W. and Beck, R. E. "Further Experiments on Turbulent Jet Diffusion Flames," Charles Kolling Research Laboratory Technical Note F-67, The University of Sydney (April 1974).

Bragg, S. L. "Combustion Noise," J. Inst. Fuel 36 (1963), p. 12.

Burke, S. P. and Schumann, T. E. W. "Diffusion Flames," First Symposium on Combustion (1928), p. 1, The Combustion Institute (1965).

Giammar, R. D. and Putnam, A. A. "Combustion Roar of Turbulent Diffusion Flames," J. Eng. for Power 92A (1970), p. 157.

Hottel, H. C. and Hawthorne, W. R. "Diffusion in Laminar Flame Jets," Third Symposium (International) on Combustion, p. 254, Williams and Wilkins (1949).

Hurle, I. R., et al. "Sound Emission from Open Turbulent Premixed Flames," Proc. Roy. Soc. A303 (1968), p. 409.

Kent, J. H. and Bilger, R. W. "Turbulent Diffusion Flames," Fourteenth Symposium (International) on Combustion, p. 615, The Combustion Institute (1973).

Kent, J. H. and Bilger, R. W. "The Prediction of Turbulent Jet Diffusion Flames," Charles Kolling Research Laboratory Technical Note F-47, The University of Sydney (Dec. 1972).

Knott, P. R. "Noise Generated by Turbulent Non-Premixed Flames," AIAA Paper 71-732 (1971).

Kotake, S. and Hatta, K. "On the Noise of Diffusion Flames," JSME 8, 30 (1965), p. 211.

Kumar, R. N. "Some Experiments on the Structure and Acoustics of Turbulent Jet Flames," WSS/CI Paper 74-25 (October 1974).

Massier, P. F. and Parthasarathy, S. P. "An Anechoic Chamber Facility for Investigating Aerodynamic Noise," JPL Technical Report No. 32-1564.

Shivashankara, B. N., et al. "Combustion Noise Radiation by Open Turbulent Flames," AIAA Paper No. 73-1025 (1973).

Shivashankara, B. N., et al. "An Evaluation of Combustion Noise Scaling Laws by an Optical Technique," AIAA Paper No. 74-47 (1974).

Smith, T. B. J. and Kilham, J. K. "Noise Generated by Open Turbulent Flames," J. Acous. Soc. Amer. 35 (1963), p. 715.

Strahle, W. C. "On Combustion Generated Noise," J. Fluid Mech. 49 (1971), p. 399.

Strahle, W. C. "Refraction, Convection, and Diffusion Flame Effects in Combustion-Generated Noise," Fourteenth Symposium (International) on Combustion, p. 527, The Combustion Institute (1973).

Strahle, W. C. and Shivashankara, B. N. "Experiments on Combustion Generated Noise," Interagency Symposium on University Research in Transportation Noise, Vol. III, p. 536, Stanford University (1973).

Strahle, W. C. "A Review of Combustion Generated Noise," AIAA Paper No. 73-1023 (1973).

Williams, F. A. "A Review of Some Theoretical Considerations of Turbulent Flame Structure," to appear in the Proceedings of the April 1974 meeting of the Propulsion and Energetics Panel of AGARD entitled "Analytical and Numerical Methods for Investigation of Flow Fields with Chemical Reactions Especially Related to Combustion.

Williams, F. A. "Recent Advances in Theoretical Descriptions of Turbulent Diffusion Flames," Proceedings of the Workshop on Turbulent Mixing, Purdue University (May 20-21, 1974).

SUMMARY OF THE RELEVANT EXPERIMENTAL PAPERS IN THE FIELD OF COMBUSTION ACOUSTICS. (MAY 1973)

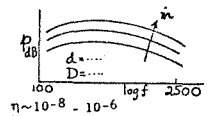
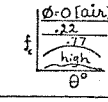
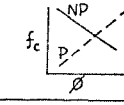
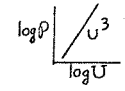
Work: Author(s) Source (Year)	Geometry: Co-flow Non-Premixed	Geometry: Impinging Jets	Geometry: Premixed	Figures: Dia. (relevant)	Figures: m (relevant)	Figures: U (relevant)	Gases: Oxidizer	Gases: Fuel	Gases: Stoich. ϕ	Measurements: r	Measurements: θ	Measurements: ϕ	Open Anechoic Field	Flame-holder Arrangement	Other Observations	Principal Findings
Thomas & Williams, PRS, A294, p. 449 (1966)	-	-	inside a soap bubble	-	-	-	various [O_2]	ethylene propane hydrogen	various				A		0.5μsec spark schlieren. Streak photographs. 16000 frames/sec movie.	p_{max} (in the acoustic field) $\propto S_b^2$; $p_{max} \propto$ (initial radius) up to $\bar{r}$. Central ignition: $\eta \approx 10^{-6}$. Eccentric ignition: $\eta \approx 10^{-7}$.
Hurle, et al., PRS, A303, p. 409 (1968)	-	-	√	.44 cm .95 cm	~0.001 lbm/sec	10-100 fps	N_2+O_2 (i.e., air?)	ethylene	0.9 1.1 1.3	≈1'(?)	-	-	A	annular H_2+Air pilot flame	Intensity of light emission from C_2 and CH bands in the reaction zone.	Excellent correlation between (instantaneous) time histories of pressure and the rate of change of volumetric reaction rate; wrinkled laminar flame model is supported. Flame may be regarded as a collection of monopoles.
Smith & Kilham, J. Acoust. Soc. Amer. 35, 3, p. 715 (1963)	-	-	√	0.25" 0.375" 0.5" (I. D.)	R - 5000 - 2000		air	propane ethylene methane	various	a good range		-	6'X6'X9' A	annular pilot flame of H_2	$\dot{m}_{pilot}/\dot{m}_{main}$ was thoroughly investigated.	Noise field is very similar to that of a noncombusting jet. $p_{dB} \propto (UD)^{\bar{m}}$ with $\bar{m} \approx 1$ [≈4 for cold flow] r > 30D gave $p_{dB} \propto 1/r^2$ $\rho \propto (UDS_b)^2$ for $\phi = 1$, C_3H_8, C_2H_4, CH_4 Off center "effect" due to convection and refraction Broad peak, $f_{max\,dB} = fn(U, D, fuel)$
Glammar & Putnam J. Eng. for Power, Apr. 1970, p. 157	-	√ 2 & 8	-	0.04" 0.0635" 0.116- 0.04	0.2 - 10 SCFM		air	natural gas (i.e., methane + ethane)	self determined	30"	90° in one of the experiments		A semi-A	They do not need one: it is a stirred reactor	A neat survey of previous work in the field is also included. They feel that the work of Hurle, et al. simply amplified the cold turbulence noise with no original "combustion noise" as such.	$p_{dB} \propto \dot{m}^2$ [generally; exceptions do exist] $\dot{m}/d\uparrow \Rightarrow$ index < 2; $\frac{\dot{m}}{d}\downarrow \Rightarrow$ index > 2 OJDF: $D/d\uparrow \Rightarrow p_{dB}\downarrow$  $\eta \sim 10^{-8} - 10^{-6}$ Frequency spectrum simply moves up in (p') without change in slope with and without combustion (natural gas)
Knott, AIAA Paper No. 71-732 (June 1971)	√	√	√	co-flow 1.835 cm oxidizer 0.813 cm and 0.391 cm impinging jet 1.1303 cm 0.8079 cm 0.4981 cm	oxidizer flow ≈ 5 to 20 gm/sec	200 to 1000 (!!) fps	air oxygen	ethylene hydrogen	various	95.098 cm always	90° to ≈160°		F	None whatever (seems to check with JPL work). Hydrogen-Air premixed flame needed the spark to be left continuously ON!!	Qualitative features of various flames. No spectroscopic or schlieren photos. He says he took 2 photos (plates I, II) but does not present them here.	Simple monopole picture is good; but not for non-premixed co-flow cases, i.e., the directionality is not that of a collection of monopoles. Premixed: $\eta_{acoustic} \propto (UA)^3_{fuel}$ Non-premixed: $\eta_{acoustic} \propto (UA)^4_{fuel}$ $\rho/\rho_{cold\ jet}$ = 10 to 550  
Strahle & Shivashankara ISURTN, Stanford, Mar. 1973, p. 536	-	-	√	0.402"		50-600 fps	air	propane ethylene propylene	0.8	60D	15° to 120°	-	A	Annular pilot flame of H_2	Direct flame photography through a blue filter.	 

Table A