Evaluation of Combustion Noise Scaling Laws by an Optical Technique

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An investigation which was conducted to verify the existence of a one-to-one correspondence between the acoustic and optical emissions from open premixed turbulent flames is described. The sound pressure and the time derivative of the emission intensity of light radiation have been compared using a) direct time traces, b) a cross-correlation technique, and c) spectral analysis. Further substantiation to the existence of the correlation has been provided by evaluating combustion noise scaling laws using optical measurements. These laws have been compared with existing scaling laws obtained from sound pressure measurements. Important conclusions regarding the origin of combustion noise have been drawn from these results.

Introduction

COMBUSTION noise scaling laws have been deduced in the past by the measurement of sound pressures in the far field. Although this provides important scaling rules for the far-field noise radiation, there is a clear need for additional information to fully understand the mechanism of noise generation. The experimental findings of Hurle et al.[1] and Price et al.[2] appear to be an important step in this direction. Hurle et al.[1] showed that the sound pressure waveform could be deduced from the waveform of the time derivative of the emission intensity when the flame is viewed through a narrow-band optical filter. Open turbulent flames and spherically expanding flame fronts were considered in this work. Price et al.[2] extended the validity of such a correlation to include diffusion flames as well as liquid spray combustion. In both Refs. 1 and 2, the one-to-one correspondence between the optical and acoustic waveforms was established over a limited bandwidth of the signals. The limitation of bandwidth was primarily necessitated by the large amount of noise in the optical circuitry. Since the bandwidth considered included the predominant frequencies of combustion noise, the correlation could be considered significant. In an attempt to theoretically explain the results of Hurle et al.[1] and Price et al.,[2] Strahle[3] obtained an expression for the far-field acoustic density in the form

$$\rho \propto \int_V \omega_t\left[\mathbf{r}_o, t-(r/a_o)\right] dV(\mathbf{r}_o) \qquad (1)$$

where ω_t is the time derivative of the reaction rate referred to a retarded time corresponding to the distance r between the source and the far field location at which density is measured. This result supports the findings of Refs. 1 and 2 and states that the far-field acoustic density can be expressed as a volume integral of the time derivative of the time retarded reaction rate.

A good cross-correlation between the instantaneous sound pressure $p(t)$ and the time derivative of the emission intensity $\dot{I}(t)$ from zones of turbulent combustion would establish that the noise emitters are solely restricted to regions of active reaction thus isolating the origin of combustion noise. Further, the theoretical prediction of Ref. 3 would be verified. If in fact $p(t)$ and $\dot{I}(t)$ are correlated, it should be possible to deduce at least the general trends in the scaling laws on radiated sound power by the optical technique without the use of any sound measuring equipment.

The experiments on premixed turbulent flames in Refs. 1 and 2 used burner sizes varying from 0.17–0.67 in. diam with flow velocities up to about 100 fps. An equivalence ratio of 0.9–1.3 was covered. The experimental study described in this paper was conducted with an aim to determine if the correlation between the acoustic and optical emissions does exist for higher velocity flames also. A 100–600 fps velocity range was chosen. Burners up to 0.96 in. diam were used. The equivalence ratio was varied between 0.8 and 1.25. The comparison of $p(t)$ and $\dot{I}(t)$ was accomplished by the use of a) direct time traces and b) spectral analysis as was done by Hurle et al.[1] and Price et al.[2] In addition to these two methods, cross-correlation function analysis was also employed. Further, using $\dot{I}_{rms}$ values scaling laws of radiated acoustic power with respect to flow velocity and burner diameter were deduced.

The flames discussed in this paper were bunsen burner-type flames anchored at the end of tubes of circular cross section. The acoustic properties of these flames have been studied in detail in Ref. 4. The luminous zone of the turbulent flame is contained between fairly well defined inner and outer cones. A preliminary experiment, in which a microphone was traversed in a line parallel to the flame length at about 10 in. from the flame axis, showed that flames were loudest around the luminous zones.

Experimental Set-Up

The experimental facility used for these experiments was the same as the one used for the noise measurements of Ref. 4. The burner sizes were 0.402 in., 0.652 in., and 0.96 in. diam. Gaseous fuels propane and ethylene were used with air as the oxidizer. The open, premixed turbulent flames were stabilized using a pilot flame of hydrogen. The anechoic chamber provided a satisfactory dark enclosure for the light measurements to be made. The image of the flame was focused on the cathode of a photomultiplier tube using a lens fixed to the front end of the photomultiplier tube housing. The photomultiplier tube was placed with its axis in the same horizontal plane as the burner axis and at 90° to the flow direction. In the experiments conducted, the distance between the burner and the front of the lens was 53.5–75 in. At this distance, it was determined that the lens would capture the light from the

Presented as Paper 74-47 at the AIAA 12th Aerospace Sciences Meeting, Washington, D.C., January 30–February 1, 1974; submitted February 7, 1974; revision received September 23, 1974. This work was supported by the National Science Foundation and the Air Force Office of Scientific Research under Grants GK 32544 and AFOSR-72-2365. The support is gratefully acknowledged.

Index category: Aircraft Noise, Aerodynamics (Including Sonic Boom).

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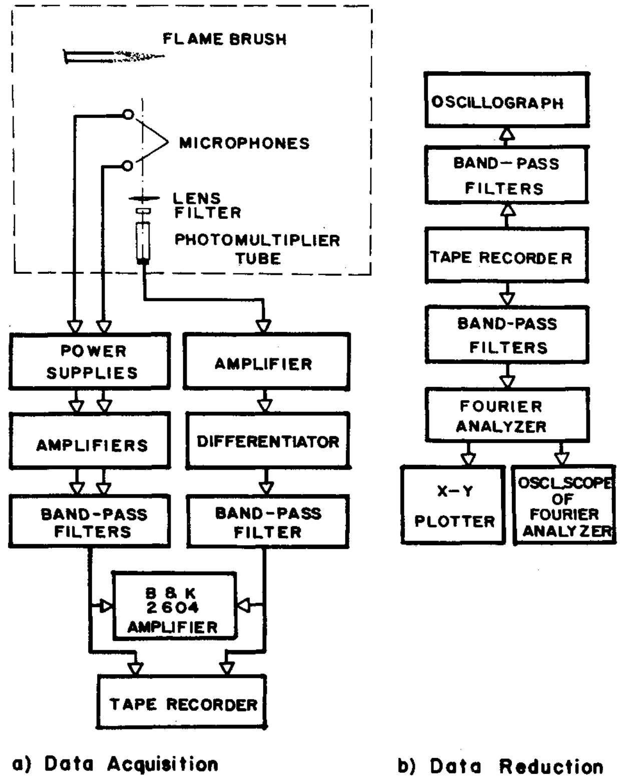

Fig. 1 Instrumentation schematic.

entire flame brush over the complete range of experimental conditions. The light collected by the lens was filtered through a narrow band optical filter centered on C_2 radiation (5165 Å). The peak transmission of the filter was at 5155 Å with a half-peak transmittance bandwidth of 50 Å. The selection of the filter was based on the recomendations of Refs. 1 and 2. It is known from spectroscopic studies[5] that the radicals like CH, C_2, and OH exist only in the zone of reaction. The mean intensity of emission of any one of these active radicals should be proportional to the global reaction rate in the flame, while the time derivative of the emission intensity should be proportional to the time derivative of the global reaction rate. Thus, by focusing the entire flame onto the photomultiplier tube an effective volume integration is performed over the reacting volume. Figure 1 shows the instrumentation used in this study. The output of the photomultiplier tube is amplified and the mean intensity I is measured. The amplified signal is differentiated and recorded on a magnetic tape recorder after passing it through a band-pass filter.

Two Brüel and Kjaer-type 4134 half-inch condenser microphones, stationed at 90° to the flow direction with reference to the burner exit, were used for sound pressure measurement. The microphones were placed at 14 in. and 25 in. from the burner port. The microphones have a flat response in the frequency range of 20–10,000 Hz. The outputs from the microphones were also filtered by band-pass filters identical to the one used to filter $\dot{I}(t)$. The sound pressure waveforms were recorded simultaneously with $\dot{I}(t)$ on two other channels of the tape recorder. The spectra of $p(t)$ and $\dot{I}(t)$ as well as the cross-correlation functions between them were obtained on a digital Fourier analyzer. To obtain stable results, a 100 sample averaging process was used.

Comparison of Instantaneous Waveforms

The instantaneous time traces of sound pressure $p(t)$ and the time derivative of the emission intensity $\dot{I}(t)$ are compared in Fig. 2. Three typical cases are presented. The following notation is used to identify the tests: P-100–0.8–0.40 where the first letter "P" is equal to fuel (P = Propane; E = Ethylene); the second number is equal to flow velocity (fps); the third number is equal to equivalence ratio; and the final number is equal to burner diameter (inches).

The waveforms shown are oscillograph recordings redrawn incorporating a time shift $\tau^* \cdot \tau^* = r/a_o$ is the amount of time by which the $p(t)$ waveform is moved in the $-t$ direction to account for the time taken by sound to travel the distance between the source (the flame) and the receiver (the microphone). The optical radiation from the flame reaches the photomultiplier almost instantaneously in comparison with τ^*. The tape recorder used is known to introduce phase differences between signals recorded on different channels. The maximum phase difference is about 20° for a signal of frequency 1000 Hz. Also, the phase difference is directly proportional to the frequency. It is possible that an error of the order of 5% (of τ^*) is introduced in the time shift τ^* on Fig. 2, which is quite small since only qualitative comparisons are being made because of this phase difference. Some similarities exist between the $p(t)$ and $\dot{I}(t)$ waveforms over a wide range of experimental conditions. Thus, it has been demonstrated that the results of Refs. 1 and 2 can be extended to include high velocity flames. Further, one-to-one correspondence between $p(t)$ and $\dot{I}(t)$ has been shown to exist for different burners and mixture ratios. The most important conclusion of this correlation between optical and acoustic emissions is that sources of combustion noise are primarily located in the visible flame brush. This can be considered to support the theory of Ref. 3 which recognized the value of evaluating the flame volume in studying combustion noise scaling laws.

Although comparing the instantaneous $p(t)$ and $\dot{I}(t)$ would establish a one-to-one correspondence directly, certain experimental difficulties are involved. These difficulties arise mainly because of spurious electronic noise in the instrumentation. The $p(t)$ is relatively free from spurious noise. However, the differentiator in the optical circuitry tends to magnify the relative importance of noise making the signal to noise ratio in $\dot{I}(t)$ rather low. In many cases (e.g., P-100–0.8–0.4) it was very difficult to compare the two waveforms and decide whether or not a reasonable similarity existed between them. Further discussion on the spurious noise has been presented later in this paper.

The foregoing discussion clearly demonstrates that more definite evidence than what was presented in Fig. 2 is required before a one-to-one correspondence between optical and acoustical emissions from turbulent flames can be accepted. Therefore, further experiments aimed at obtaining cross-correlation and spectral distributions were conducted.

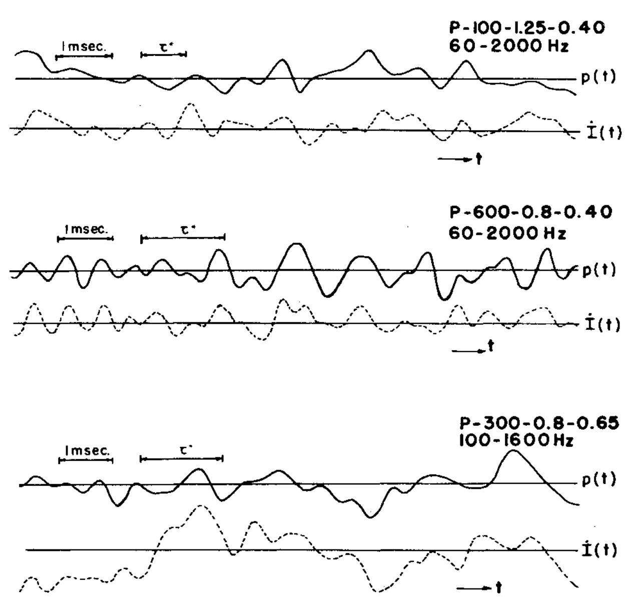

Fig. 2 Comparison between $\dot{I}(t)$ and $p(t)$ waveforms. $p(t)$ waveforms are shifted to left by τ^*.

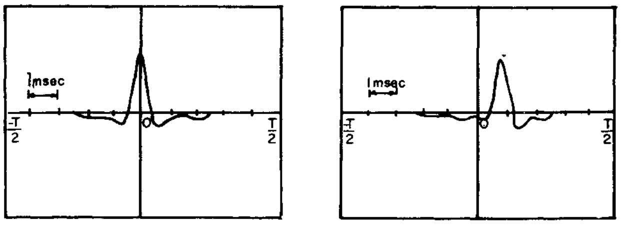

Fig. 3 Cross-correlation function between a) $p(t)$ waveform at 14 in. microphone with itself and b) with $p(t)$ at 24 in. microphone. Band-width 60–1600 Hz; P-600–0.8–0.4 case.

Cross-Correlation

The correlation functions are obtained using the Fourier Analyzer. The cross-correlation function displayed on the Fourier Analyzer system oscilloscope screen is photographed. The traces shown in Figs. 3 and 4 are redrawn using these photographs. Figure 3 essentially illustrates how cross-correlation works. Figure 3a shows an auto-correlation function for the $p(t)$ of the P-600–0.8–0.40 case. Figure 3b is a display of the cross-correlation function between $p(t)$ as measured by the microphones at 14 in. and 24 in. from the flame. Notice that the cross-correlation maximizes at $\tau \approx 0.8$ msec which corresponds to the time taken by sound waves to travel the distance between the two microphones. In Fig. 3, as well as in Fig. 4, trace lengths of $T/4$ have been cleared at both ends of the time axis. This is required to eliminate wrap around errors.[6] Cross-correlation functions between $\dot{I}(t)$ and $p(t)$ waveforms over various experimental conditions are presented in Fig. 4. Figure 4a shows the cases for which $p(t)$'s from the microphone at 14 in. have been used. The cross-correlations maximize for $\tau \approx 1.0$ msec in these cases. Figure 4b is for $p(t)$'s from microphone at 24 in. The time delay at which maxima occur is $\approx$1.8 msec. In Fig. 4 the experiments include a flow velocity range of 100–600 fps. The fuels propane and ethylene are used and both fuel-lean and fuel-rich mixtures are included. Thus, over a wide range of parameters a good cross-correlation between $p(t)$ and $\dot{I}(t)$ exists.

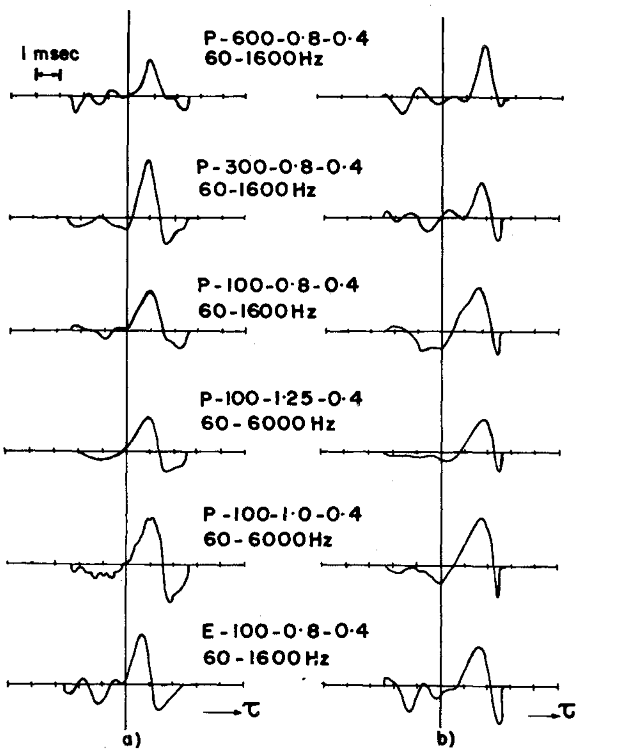

Fig. 4 Cross-correlation between $p(t)$ and $\dot{I}(t)$ waveforms. a) $p(t)$ from microphone at 14 in. b) $p(t)$ from microphone at 24 in.

Frequency Spectra of Optical Emission

After having established that a good cross-correlation exists between the acoustic and optical emissions, the spectra of $\dot{I}(t)$ and $p(t)$ were compared. These spectra should show identical frequency distributions if a one-to-one correspondence exists.

First, the P-100–1.25–0.40 case is considered. The comparison between the instantaneous $p(t)$ and $\dot{I}(t)$ traces was shown to be quite reasonable in Fig. 2a for this case. Figure 5a shows that the spectra of $\dot{I}$ and p are in excellent agreement up to 1000 Hz. The correspondence between the spectra grows progressively worse due to electronic noise at higher frequencies. Since in Fig. 2a the waveforms were restricted to 2000 Hz, it was possible to observe a reasonable similarity.

Figure 5b shows the spectra for the case P-100–0.8–0.40. It has been stated earlier that an instantaneous waveform comparison was found to be extremely difficult for this case. The spectra for optical emission is almost flat over the entire frequency range showing that the $I(t)$ signal is dominated by spurious noise. The reason for the difference in behavior between the two cases shown in Fig. 5 can be explained to some extent by their mean intensities. It will be shown later, in Fig. 7, that electronic noise dominates for flames with low mean intensity. The P-100–1.25–0.40 flame, being much brighter than the P-100–0.8–0.40 flame, has a better signal-to-noise ratio and, therefore, shows a reasonable spectral comparison.

Similar spectral comparisons were made at various other experimental conditions. In general, it was observed that above about 1000–2000 Hz frequency electronic noise dominates $\dot{I}(t)$. Thus, any study using optical emissions from flames should exclude frequency components above 1000–2000 Hz unless better electronics are available. Since, in Ref. 4, it has been established that for hydrocarbon-air flames the combustion noise peaks in the 250–700 Hz range, this should not be a major restriction. Nevertheless, electronic noise appears to be a major problem to guard against in optical emission studies. Hurle et al.[1] presented the spectra of both total $\dot{I}$ signal as well as the electronic noise. The signal to noise ratio was found to be very close to unity for frequencies below 200 Hz and above about 4000 Hz. In the range of 200–4000 Hz the signal to noise ratio was found to be about two at best. The spectrum of $\dot{I}$ corrected was compared with the spectrum for the sound pressure and moderate correspondence was observed by the authors in Ref. 1. Price et al.[2] state that the overall $\dot{I}_{rms}$ values were corrected for electronic

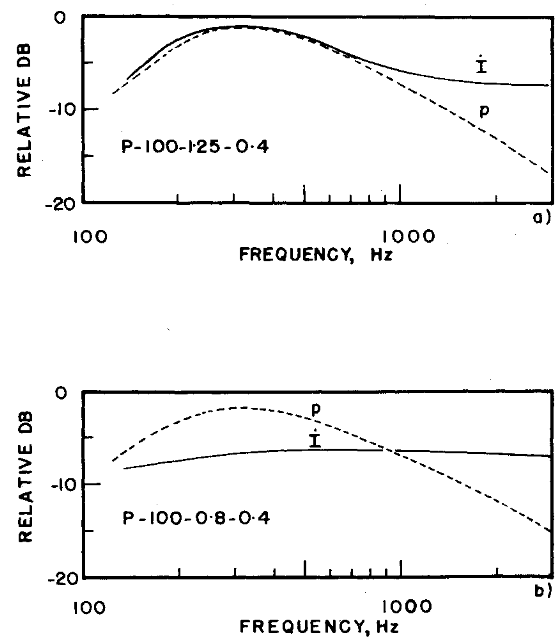

Fig. 5 Frequency spectra of $\dot{I}$ and P a) for P-100–1.25–0.40 case and b) P-100–0.8–0.40 case.

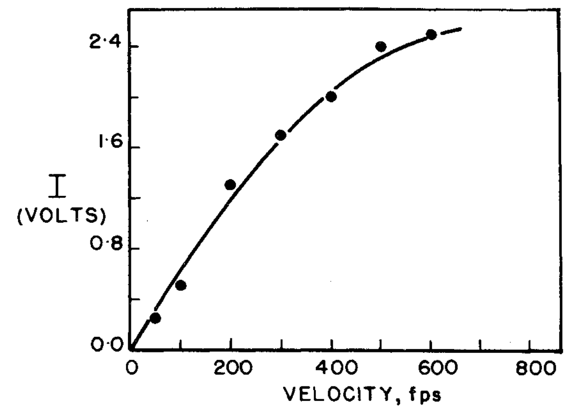

Fig. 6 Mean intensity as a function of flow velocity.

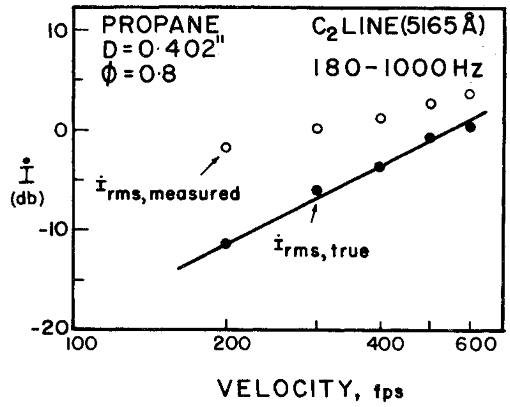

Fig. 8 Acoustic power law with flow velocity by optical technique.

noise. In the present experiments the corrections applied on the overall $\dot{I}_{rms}$ were between about 2–10 db (see Fig. 8). Although these corrections are rather high there is reason to believe that the corrections applied for the data of Refs. 1 and 2 must also have been of comparable magnitude.

In Fig. 5 the contribution of electronic noise has not been subtracted from $\dot{I}$ spectra because of the low signal to noise ratios which made it very difficult to apply corrections at individual frequencies. Such a procedure was tried, as has been explained in the previous paragraph, with marginal success by Hurle et al.[1] It thus appears that cross-correlation analysis is the most meaningful test for one-to-one correspondence out of all the three methods used in this study.

Scaling Laws for Acoustic Power from Optical Emission Measurements

The investigation discussed in this section arises as a natural consequence of the results presented so far in this paper. If, in fact, there is a one-to-one correspondence between $p(t)$ and $\dot{I}(t)$, then it should be possible to obtain at least the scaling laws on the flow velocity U and burner diameter D for the radiated acoustic power from the optical experiments, The scaling laws with respect to laminar flame speed S_L and fuel mass fraction F would require the use of more than one fuel. Since the line intensities in the optical spectra for various fuels differ, there are bound to be additional corrections required for mean intensities. Because of the presence of substantial amounts of spurious noise in the $\dot{I}$ measurements, the scaling laws by the optical technique should be considered more as a substantiation to the existence of the correlation rather than as a method for generating combustion noise scaling laws. The following paragraphs describe experiments using propane as the fuel designed to recover the velocity and diameter scaling on the radiated acoustic power.

The photomultiplier tube output was amplified and differentiated. The differentiated signal was passed through a band-pass filter set to allow frequencies between 180–1000 Hz. This restriction on frequency was decided by the results of the spectral analysis. The $\dot{I}_{rms}$ measured would be due to both the true signal and the electronic noise. Since it had been determined that electric noise is appreciable it was necessary to correct the measured $\dot{I}_{rms}$ for electronic noise.

Electronic noise in $\dot{I}$ is known to be a function of the mean intensity I received by the photomultiplier tube. Figure 6 shows the variation of mean intensity of the particular flame under consideration with flow velocity. Using a standard lamp supplied with ripple-free d.c. current, a light source with negligible light flickering was obtained. The $\dot{I}_{rms}$ measured for this case should be indicative of the electric noise. Figure 7 shows the $(\dot{I}_{rms})_{\text{elec. noise}}$ as a function of mean intensity I. Using Figs. 6 and 7 together the values of electronic noise at various flow velocities for the particular flame could be determined. Now,

$$\underset{\text{in db}}{(\dot{I}_{rms})_{true}} = \underset{\text{in db}}{(\dot{I}_{rms})_{measured}} - \text{db correction}$$

The values of db correction were obtained from standard background noise correction graphs.[7] Hurle et al.[1] and Price et al.[2] also found that corrections such as these were needed for their measurements.

Figure 8 shows $(\dot{I}_{rms})_{true}$ as a function of flow velocity U. Also, values of $(\dot{I}_{rms})_{total}$ have been shown on Fig. 8 to indicate that corrections applied are quite heavy. $(\dot{I})^2{}_{rms}$ appears to scale as $U^{2.7}$. This implies that radiated acoustic power P has a $P \propto U^{2.7}$ scaling which is in agreement with the $U^{2.7}$ law of Ref. 4. However, it should be cautioned against considering the optical method to be accurate based on the $\dot{I}^2{}_{rms} \propto U^{2.7}$ result. Below 200 fps, the signal to noise ratio was so low as to make it impossible to get $(\dot{I}_{rms})_{true}$. Also, recall that a rather restricted frequency range of 180–1000 Hz has been used for these experiments.

Figure 9 shows the variation of $\dot{I}_{rms}$ with diameter. The data points have been corrected for electronic noise. It can be seen that $\dot{I}^2_{rms}$ scales with diameter to an exponent roughly between

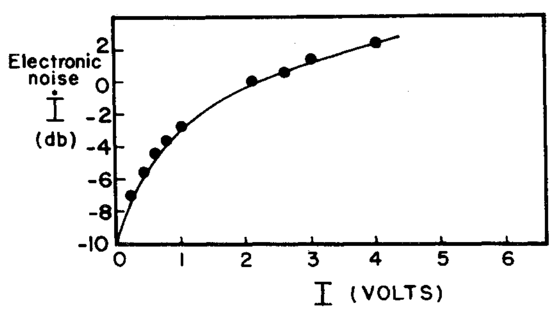

Fig. 7 Electronic noise $\dot{I}$ as a function of mean intensity.

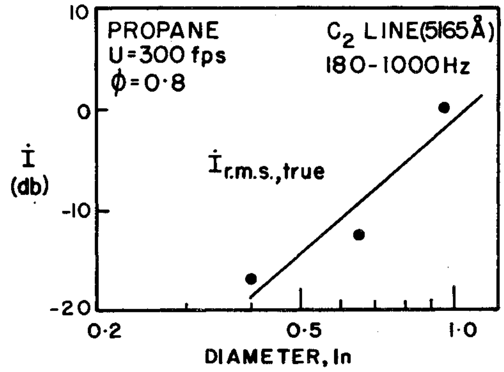

Fig. 9 Acoustic power laws with burner diameter by optical technique.

2 and 4.5. A least square fit preferred a $\dot{I}^2_{rms} \propto D^{4.5}$ law. However, improved data are required before one can conclusively determine the scaling law. $\dot{I}^2_{rms} \propto D^{2-4.5}$ implies that radiated acoustic power P would also scale to $D^{2-4.5}$. Sound pressure measurements of these flames, in Ref. 4, gave a $P \propto D^{2.9}$ scaling. In any case, the results presented in Figs. 8 and 9 do show that scaling laws obtained by optical measurements reflect the proper trend as compared with those obtained from sound pressure measurements, considering the very poor signal to noise ratios encountered in $\dot{I}$ signals. This strongly supports the theoretical deduction of Ref. 3 shown in Eq. (1) which states that the far-field sound density (or pressure) is proportional to the global integration over the reacting volume of the first Eulerian time derivative of the time retarded reaction rate.

Conclusions

The intimate relation observed between the optical and acoustic emissions raises one important question: Is the correlation obtained because the noise generated outside the flame zone in the hot efflux, travels through the region of reaction and creates light fluctuations? This possibility can be ruled out because if a presssure wave $p(t)$ passes through a flame, it creates changes in the reaction rate ω. Since $I(t) \propto \omega(t)$, this implies that $p(t) \propto I(t)$, thus contradicting the experimental result $p(t) \propto \dot{I}(t)$.

The experiments described in this paper have shown, despite the experimental difficulties due to electronic noise in the differentiated photomultiplier output, it is possible to observe one-to-one correspondence between the acoustic pressure and the time derivative of emission intensity from turbulent flames. This work supports the experimental findings of Refs. 1 and 2 and the theoretical prediction of Ref. 3 [see Eq. (1)]. The range of validity of the correlation has been extended to include flow velocities as high as 600 fps. Whereas, Hurle et al.[1] and Price et al.[2] compared $p(t)$ and $\dot{I}(t)$ directly, the present study employed a cross-correlation technique in addition to direct time-trace comparisons. Further, scaling laws for radiated acoustic power were developed with respect to the flow velocity and the burner diameter. These laws had the same general trend as the ones obtained by sound pressure measurements when the band-width of the optical signals was limited to 180–1000 Hz and necessary corrections were applied for electronic noise. This result again supports the existence of a correlation between optical and acoustic emissions. Poor signal-to-noise ratios, however, restrict the use of this method unless better electronics are available. The most important conclusion from this study is that the sources of combustion noise are primarily located in the luminous flame brush and that the noise generation mechanism can be attributed to the time derivatives of the chemical reaction rate.

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