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Study of Spectral Noise Emissions from Standard Turbulent Nonpremixed Flames

Kapil K. Singh,* Steven H. Frankel,† and Jay P. Gore‡
Purdue University, West Lafayette, Indiana 47907-1003

The occurrence of oscillating combustion and combustion instability has led to resurgence of interest in causes, mechanisms, suppression, and control of flame noise. Nonpremixed flame noise is low frequency and difficult to control using conventional acoustic liner and so significant noise reduction needs to be achieved by altering the source. Noise generated by enclosed flames is of greater practical interest but is more complicated than the noise generated by open flames, which itself is not clearly understood. Improved understanding of the noise generated by open flames is attempted by studying spectral content of the sound for flames for which detailed velocity, scalar property, and radiation measurements are available in the literature (International Turbulent Non-Premixed Workshop flames; http://www.ca.sandia.gov/TNF/abstract.html). Comparisons were made with the spectral content of sound generated by air jets at identical Reynolds numbers. The spectral sound pressure levels (SSPL) generated by the flames were higher than those generated by corresponding air jets at all frequencies. The differences between the SSPL were the highest in the relatively low-frequency range of 400–2000 Hz. The flames emanate a constant SSPL in this frequency range for locations near the axis. The width of this range decreases at larger radial locations. The effects of flow velocity are stronger at higher frequencies. The spectra show substantial reduction in high-frequency components away from the burner exit, especially in the axial direction. These observations can be used for designing combustors with lower noise and also in the evaluation of computational aeroacoustics codes.

Introduction

THE existence of combustion noise as distinct and separate from jet noise has long been established. In an ideal jet, noise is generated entirely by the turbulent mixing of the jet with the ambient fluid. The sound sources in jets extend over a considerable distance. The sources are usually regarded as quadrupoles,[1] whose strength and directivity are modified by nonuniform density (temperature) and convection.[2] One such phenomenon contributing to the noise especially at lower jet speeds is combustion.[3,4] The flame is a thin luminous region across which temperature and chemical species change very rapidly, the burnt products being of greatly elevated temperature and reduced density.

Combustion processes can produce noise following three different mechanisms.[5] First, the turbulence interaction with the reactions causes direct combustion noise. It arises when a volume of gas expands at constant pressure and is heated by combustion. Second, the combustion process changes the velocity field in the combustor, resulting in altered sound wave convection effects, known as indirect combustion noise. The third mechanism is the creation of noise by the convection of hot spots, generated by combustion process, through regions of mean velocity gradient, which is termed entropy noise and is also an indirect combustion noise.

Review of literature indicates that the phenomenon of combustion noise from open flames has been investigated to some extent. Many studies of the sound generated by turbulent premixed flames are available in the literature.[3,6–13] A few studies of the sound generated by nonpremixed turbulent flames, mostly with a coflow of air, have also been conducted.[6,9,14–17] Experimental data also exist for sound emitted by coflow partially premixed flames[18] and by industrial burner flames.[19] The sound produced by combustion appears to be primarily of monopole type,[6] though there are certain characteristics of dipole nature. Monopole sound is produced by unsteady heating, which causes volumetric expansion, and dipole sound is generated by the differential acceleration of hot spots, that is, by entropy inhomogeneities.

Because of fundamental differences in various modes of combustion, premixed (lean, stoichiometric, and rich) and nonpremixed (with and without coflow) differences in the noise generation mechanism are expected.[20,21] At same velocity and diameter, fuel-rich flames were found to be considerably noisier than fuel-lean flames.[10–12] Also, turbulent nonpremixed flames are noisier than premixed flames at similar velocity.[4] Combustion noise source is distributed mainly in the rear part of combustion region for fuel-lean premixed flames and in the forepart of this region for fuel-rich premixed flames.[12] For premixed flames the position of maximum volume per unit length, which occurs near the flame tip, is also the position of maximum acoustic output.[13] However, for turbulent nonpremixed flames, which are normally much longer than premixed flames,[6] the effective length of the predominant region of sound generation is notably less than the total flame length.[4,6]

Noise production in turbulent flames is governed by the fluctuations in the local reaction rate in the combusting field and hence has been correlated to various flow properties and flame parameters. Price et al.[6] correlated sound generated by turbulent premixed and nonpremixed flames with the changes in the intensity of light emission by free radicals. Giammar and Putnam[8] presented sound-pressure-level data for three simple premixed burners of different sizes, individually and paired, as a function of the square of the firing rate as well as the product of pressure drop and heat release rate. Kilham and Kirmani[10] showed that combustion noise increased with turbulence intensity in premixed flames. Kotake and Takamoto[11] investigated the effects of burner nozzle shape and size on the noise of premixed flames by using rectangular, square, and circular nozzles of several sizes. They also investigated the effects of turbulence in the unburned mixture on the acoustic characteristics.[12] Ohiwa et al.[14] studied the relationship between flame structure and noise characteristics for coflow nonpremixed turbulent flames. They showed that fluctuations in sound pressure, ion current, temperature, and CH emission corresponded to organized eddy formation.

There have been a few spectral measurements of sound generated by premixed[3,7,9,11–13] and nonpremixed[9,15–17] flames. Measurements over a wide range of burner diameter (6–176 mm) and with

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*Ph.D. Student, School of Mechanical Engineering. Member AIAA.
†Associate Professor, School of Mechanical Engineering. Member AIAA.
‡Vincent P. Reilly Professor, School of Mechanical Engineering, Engineering Administration Building, Room 101, 400 Centennial Mall Drive; gore@ecn.purdue.edu. Associate Fellow AIAA.

hydrocarbon fuels have found combustion noise to be a broadband noise with peak in the range of 250–700 Hz for various modes of combustion.[3,11,13,17,18] However, Hurle et al.[7] found the stoichiometric premixed ethylene-air flame to peak at about 1200 Hz with a 4.4-mm burner. Also, studying a coflow premixed flame, Kumar[9] observed well-defined peaks in the frequency range 2–4.5 kHz in hard-walled bay and 1.5–3 kHz in anechoic chamber. Nevertheless, he found broadband spectra for coflow nonpremixed flame with only a broad peak in the range 750–1000 Hz in anechoic chamber.

A power-type scaling law for the frequency of maximum radiated acoustic power of premixed flames was developed by Shivashankara et al.[3] This frequency was found to be dependent on flow velocity, burner diameter, laminar flame speed, and fuel mass fraction. The indices of dependence were modified as the data for more fuels and larger range of burner diameter became available.[22,23] These laws are primarily based on experimental data, but theoretical developments have confirmed the correctness of physics in these scaling laws.[22]

The primary reason for no such extensive and detailed scaling law for nonpremixed flames is lack of exhaustive experiments on these flames. Strahle[23] commented that there had been no work at all on perhaps the simplest—that of a fuel exhausting into a quiescent air atmosphere. This situation appears to have changed little since. Also, there are no theoretical scaling laws for nonpremixed flames because of nonavailability of data for comparison.[21,23,24]

Earlier works on nonpremixed combustion noise lack standardization and availability of measurements of other parameters and properties, which are needed in thorough understanding of combustion generated noise. Past studies of sound generation from nonpremixed flames involved a wide range of burner dimensions with a coflow, a pilot flame or a flame holder. None of the past measurements are for flames for which detailed velocity, temperature, and species concentration statistics, necessary for a description of the aerothermoacoustic phenomena, are available. A complete set of measurements including velocity and scalar statistics in addition to the sound pressure, power, and spectral measurements is necessary for validation of aeroacoustic and thermoacoustic computational models.

The specific objective of the present work was to measure the spectra of sound generated by standardized turbulent nonpremixed flames in quiescent atmosphere. We have selected two Turbulent Non-Premixed Flame (TNF) Workshop standard flames DLR-A (Deutschen Zentrum für Luft- und Raumfahrt or German Aerospace Center) and DLR-B because of the availability of the extensive experimental data for velocities, species concentrations, and thermal radiation properties[25,26] (also private communication from A. Dreizler, 2000), as well as the simplicity of the configuration. The sound-pressure-level data for these flames were reported in an earlier study.[4] The corresponding frequency spectra of the radiated sound at the same locations were measured and are reported here. The flame spectra are also compared with those of air jets with identical exit Reynolds number. Mach number M rather than the Reynolds number Re is the appropriate nondimensional parameter for studies of aeroacoustics. However, for identical tube diameters, exit velocity and exit Mach number are linearly proportional to exit Reynolds number. Therefore, Reynolds number, which is the appropriate parameter for studying inertial and diffusive effects and turbulence, is used simply as the designator of air jets in the present study.

The acoustic characteristics of the present low-Mach-number flames and air jets are of interest in combustion instability studies, where acoustic fluctuations of the low-Mach-number flames and jets serve as the perturbations that can grow by coupling with the combustor modes. In addition, the frequency spectra will allow a detailed evaluation of time dependent computational models.

Experimental Apparatus

TNF standard flames DLR-A and DLR-B were stabilized in the laboratory. The fuel stream of the DLR-A and DLR-B flames contains CH_4–22.1%, H_2–33.2%, and N_2–44.7% by mole. The flames were stabilized on a standard 0.8-cm internal diameter burner, with a sharp exit, obtained from Sandia National Laboratories. This burner is a replica of original burner used at DLR. The burner had a length of 350 mm and was press fitted, using outer shield, to another tube making the total length 500 mm. The exit Reynolds number for the two flames based on injected gas properties at room temperature are 1.52×10^4 for DLR-A ($M = 0.12$) and 2.28×10^4 for DLR-B ($M = 0.18$). Air at room temperature was used for studying the sound emission from jets with the same burner and at same Reynolds number; 1.52×10^4 ($M = 0.08$) and 2.28×10^4 ($M = 0.12$). The exit Mach number M is based on the sound speed at room temperature and is low in all cases. The three fuel stream constituents were supplied from bottled sources and measured using calibrated sonic orifices. A pipe length of more than 500 length-to-diameter ratio ensured proper mixing before the flow reached the burner exit. The burner was placed with its exit 76 cm above the floor, firing vertically upwards and 160 cm away from the nearest wall. Figure 1 shows a schematic diagram of experimental arrangement. The composition

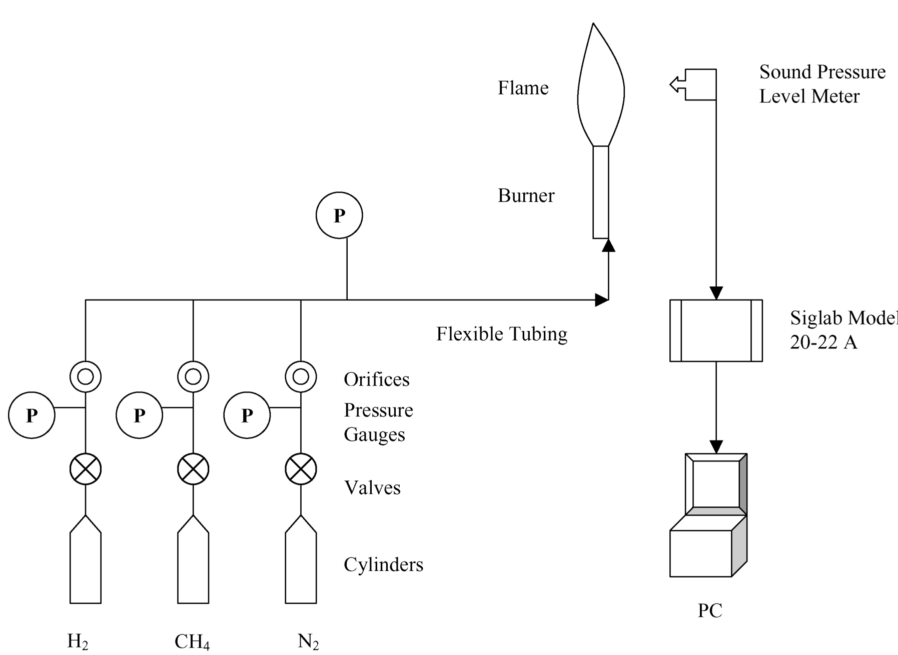

Fig. 1 Schematic diagram of the experimental arrangement.

of the mixture was checked using sampling and gas chromatography. The velocity measurements obtained using particle imaging velocimetry in our laboratory agree well with the velocity data from DLR. In addition, spectral radiation intensities from these flames has also been studied in our lab as well at Sandia National Laboratory and the results agree with each other within 5% (Refs. 26 and 27).

Acoustic measurements were made using a Realistic Sound Level Meter Cat. No. 33-2050. The signal from the meter was fed to a 2-channel Siglab, Model 20-22A, a PC-based data-acquisition and analysis system. The output from sound pressure level (SPL) meter was A-weighted decibel (dBA) referenced to 0.0002 mibar. True rms sound pressure level would be different and more precise representation of the combustion sound generated under idealized conditions for sound generation and propagation. However, the present measurements were conducted in a laboratory environment and hence A-weighted. The A-weighting is a filter for very low-frequency environment noise inherent in laboratory arrangement. The A-weighting filter rolls off below 1 kHz, by about 4 dB at 400 Hz and features a slight gain above 1 kHz, about 4 dB at 5 kHz. The impact of A-weighting at the frequencies of interest is limited and has been taken into consideration while analyzing the results.

Modifying and interfering external sound sources were minimized in the arrangement. Flexible tubing was used in order to minimize structural sound generated by the flow in the pipes and bends. Also, the orifices and the tubing downstream of the orifices were covered with sound-absorbing material (mineral wool and foam). The flow-metering arrangement was located more than 3 m away and isolated from the burner using a partial wooden enclosure.

The measurement system was calibrated using a B & K 4231 Sound Level Calibrator generating 94 and 114 dB SPL at 1 kHz with an accuracy of ± 0.2 dB. The Realistic Sound Level Meter has an accuracy of ± 2 dB at 114 dB. The SPL meter accurately measured the calibrator sound, well within stated accuracy of ± 2 dB (within 94 ± 2 dB and 114 ± 2 dB, respectively). The maximum spherical solid angle for SPL meter in present measurements, with the assumption that the sources are distributed along the full observed length of flames, is about 71.5 deg. As per the manufacturer's catalog, the SPL meter has less than 2-dB systematic variation in directional sensitivity for frequencies less than 8 kHz within this spherical solid angle. Spectral measurements show that for the flows considered here most of the energy is below 8 kHz limiting the effects of directional sensitivity on the present data to within the other experimental uncertainties.

Both axial and radial variations in frequency spectra of sound from flames and air jets were studied. For studying the axial variations, the SPL meter was located 40 cm away from burner axis and

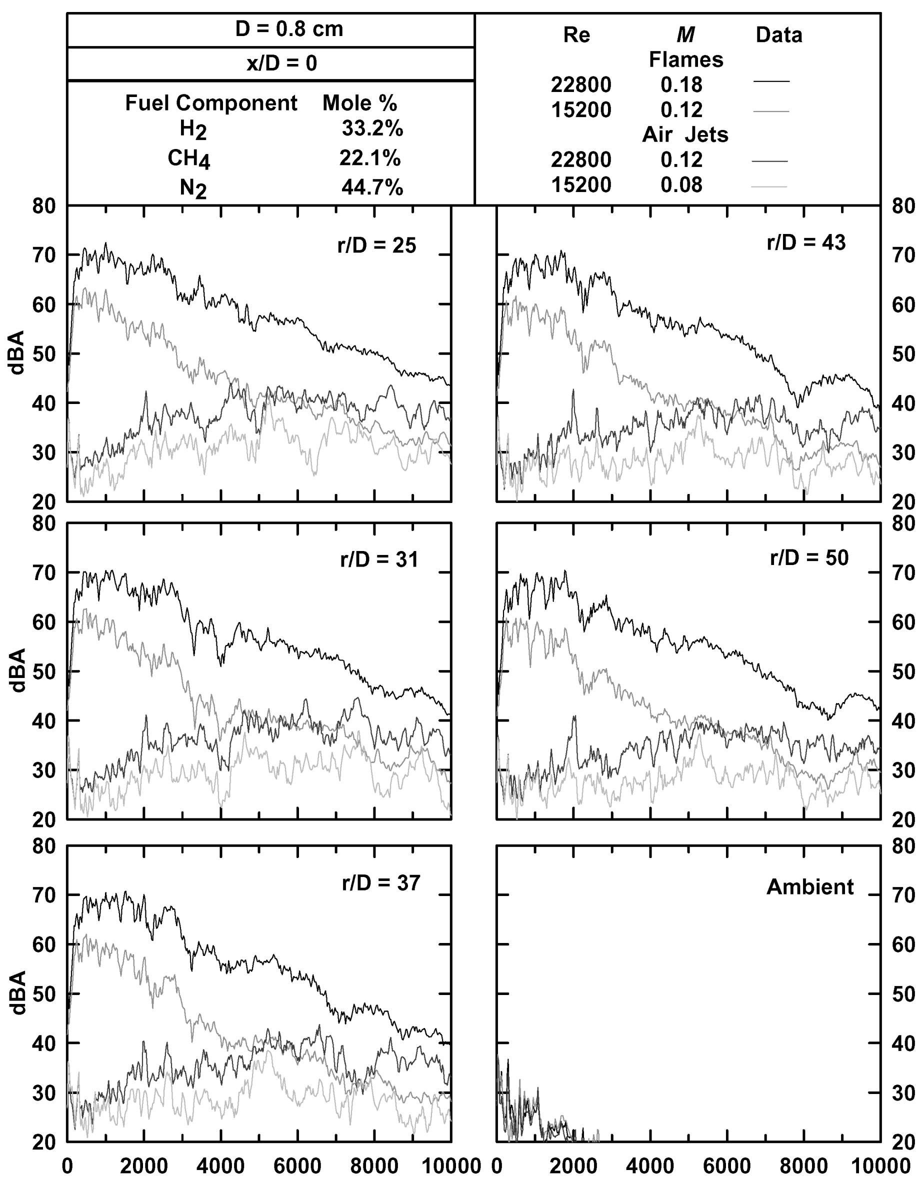

Fig. 2 Radial variation in sound spectra for two flames and corresponding air jets: $x/D = 0$ and $r/D = 25$–50.

starting from the level of the burner exit up to 50 cm above. The visible flame length was approximately 60 cm. For studying the radial variations, the measurements were taken at the burner exit level from a distance of 20–40 cm from the burner center. The temperature limitations of the SPL meter and the possibility of near-field errors restricted the minimum radius at which the measurements could be obtained. Narrowband spectra were obtained for all cases with a frequency resolution of 25 Hz and using a Hanning window in time with a bandwidth of 10 kHz, corresponding to a sampling rate of 25.6 kHz. A record length of 1024 and 500 averages was used for all measurements.

The background acoustics including reflection characteristics of the walls and possible wave interference effects influence all measurements of sound.[24] In measurements of sound generated by strong sources, the background influences can often be minimal.[5,9] In the present work background (ambient) measurements were completed after each experiment to utilize only data that are minimally impacted.

Results and Discussion

Figure 2 shows sound pressure level in A-weighted decibels plotted as a function of frequency for the two flames and two air jets at the burner exit level ($x/D = 0$) and at various radial locations ($r/D = 25$–50) from the burner exit. Background (ambient) noise spectra are also shown for comparison. Both flames DLR-A and DLR-B exhibit constant sound-pressure amplitude plateau in the low-frequency region and then monotonous decrease with increasing frequency. Also the width of the constant pressure amplitude plateau increases with increasing radial distance from burner axis. For flame DLR-B ($Re = 2.28 \times 10^4$, $M = 0.18$) this constant plateau extends from 400 to 2000 Hz at 73 dBA and then decreases in almost linear fashion to 44–48 dBA at 10 kHz, depending on the location in agreement with Strahle.[5] For flame DLR-A ($Re = 1.52 \times 10^4$, $M = 0.12$) the plateau extends from 400 to 1200 Hz at 67 dBA and then decreases to 34–39 dBA at 10 kHz, depending on the location. In contrast, the sound pressure level for the air jets is very close to the background up to 1200 Hz and then increases, reaches a peak, and starts decreasing. The sound pressure level for air jet at $Re = 2.28 \times 10^4$ ($M = 0.12$) reaches peak around 6.5 kHz attaining 40 dBA, whereas for the air jet at $Re = 1.52 \times 10^4$ ($M = 0.08$) it reaches peak around 5 kHz attaining about 34 dBA. The observation that there is a constant pressure for a range of frequencies below 2000 Hz for combustion noise is in agreement with past studies.[14] The frequency at which the sound pressure begins its decline is higher for present flames compared to values in the literature. The

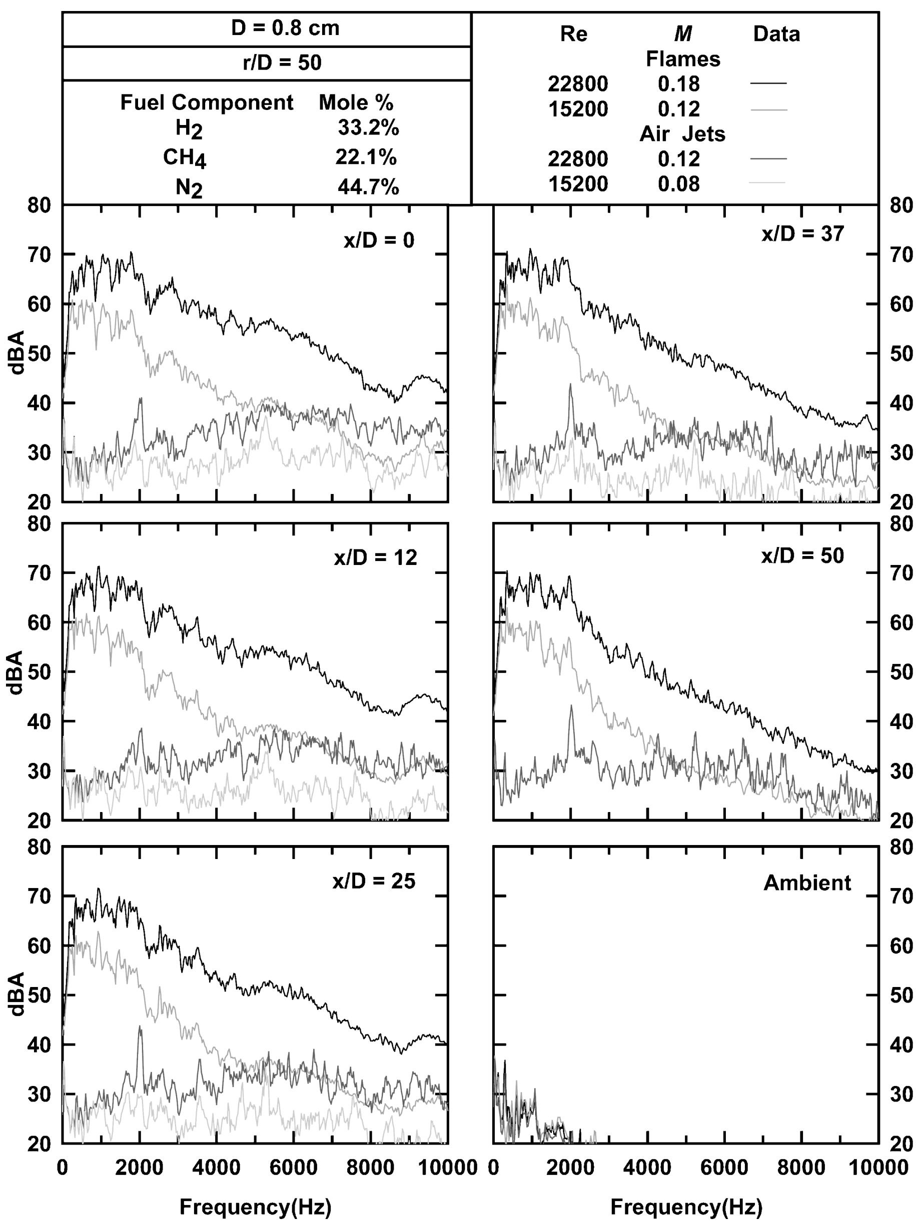

Fig. 3 Axial variation in sound spectra for flames and air jets: $r/D = 50$ and $x/D = 0$–50.

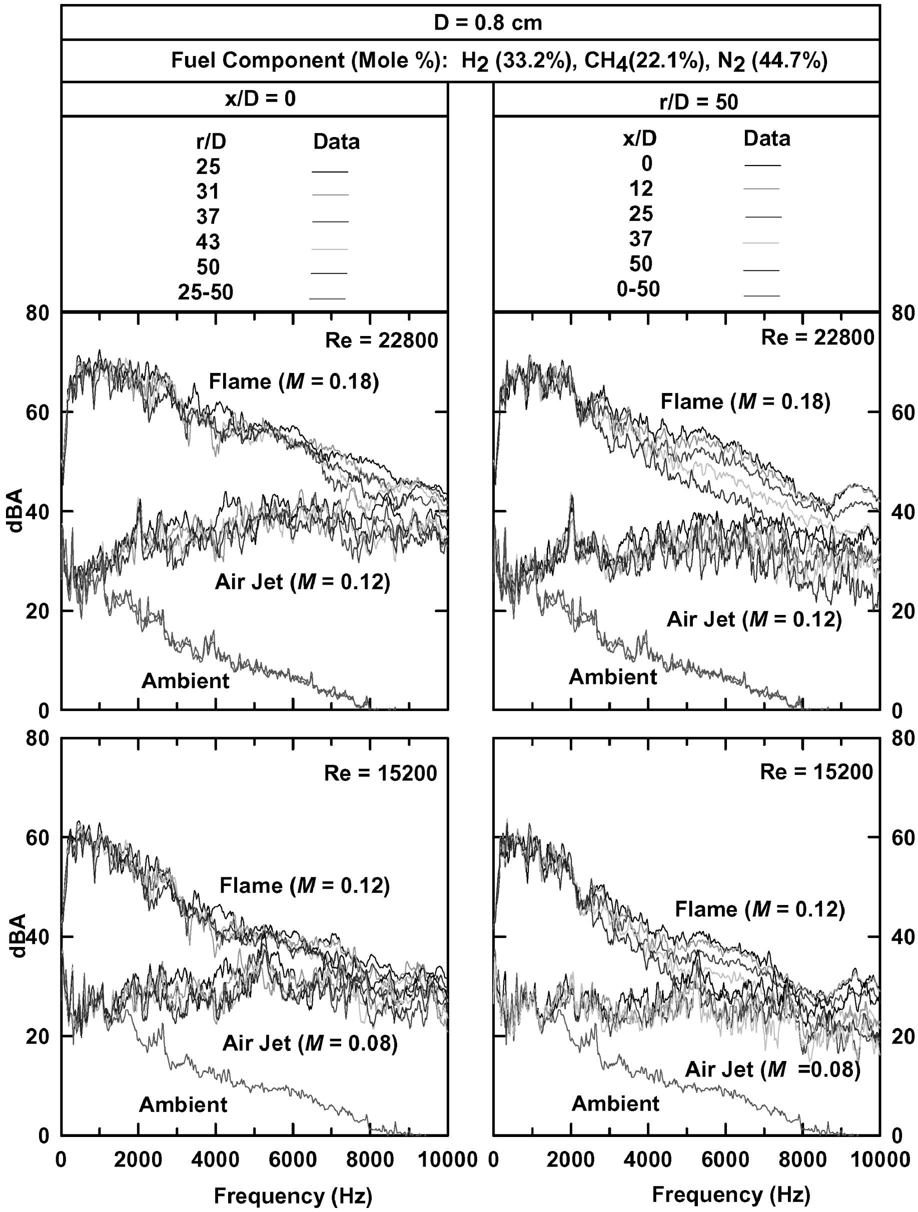

Fig. 4 Combined radial and axial variation in sound spectra for flames and air jets: *x/D* = 0, *r/D* = 25–50; *r/D* = 50, *x/D* = 0–50, and ambient.

difference in the fuel type[16,22,28] and a small diameter[3,11] and long burner[12] is a possible reason for this dissimilarity.

Figure 3 shows sound pressure level in A-weighted decibels plotted as a function of frequency for the two flames and two air jets at a fixed radial location ($r/D = 50$) and at various axial locations from the burner exit ($x/D = 0$–50). Background noise spectra are also shown for comparison. Both flames DLR-A and DLR-B maintain the level of constant amplitude plateau in axial direction. However, both flames exhibit substantial reduction in high-frequency components with increasing distance from burner exit level. The SPL obtained after integrating the spectra in the frequency domain shows that at $r/D = 50$ and in the range $x/D = 0$–50 the SPL for both flames reduces by about 3 dBA away from burner exit. Therefore, reduction in high-frequency component accounts for reduction in earlier reported[4] axial variations of overall SPL. It is believed that the downstream suppression of high-frequency radiation is a refraction effect caused by the temperature gradients.

Figure 4 combines radial and axial locations spectra and presents them as categorized in terms of Reynolds number Re. Comparison of frequency spectra of flames DLR-A and DLR-B shows that the spectra of these flames are similar in shape and differ only in amplitude with less difference towards the low-frequency side and larger difference toward the high-frequency side. The spectral shape independence with respect to flow velocity is a property of nonpremixed combustion in agreement with Kumar's findings.[9] Although the DLR-A and DLR-B flame spectra are qualitatively similar, there is velocity dependence quantitatively. As the flow velocity is decreased, the width of the plateau in the TNF spectra is reduced from the high-frequency side, similar to premixed flames.[3,11]

At identical Reynolds numbers, the TNF spectra for both flame DLR-A (1.52×10^4) and DLR-B (2.28×10^4) have higher amplitudes compared to the identical Reynolds number cold air jets at all frequencies up to 10 kHz. If Mach number based on the speed of sound in air is considered as the relevant parameter, then the air jet at $Re = 2.28 \times 10^4$ and the flame DLR-A, which has $Re = 1.52 \times 10^4$, both have identical exit Mach numbers of 0.12. A comparison of the spectra for DLR-A with those for the air jet at $M = 0.12$ shows that the air jet has higher amplitudes for frequencies >5 kHz.

The substantial differences in the spectra of combustion noise from the TNF and the jet noise from air jets suggest significant differences in the nature of the sound sources. Jet noise is generated by turbulent mixing of fluid with ambient. However, the combustion noise from TNF is believed to be caused primarily by unsteady heating, which causes volumetric expansion. The unsteady heat-release process clearly leads to significantly higher level of noise at lower frequencies compared to the unsteady mixing process.

Conclusions

The following can be inferred from this study;

1) The frequency spectra of noise generated by turbulent nonpremixed flames (TNF) with fuel issuing in a quiescent air environment are predominantly low frequency with a constant pressure level plateau in the range 400–2000 Hz unlike those of noise from air jets at same Reynolds number. At the same Reynolds number, TNF spectra have higher amplitudes than air jets spectra at all frequencies up to 10 kHz, and most of the sound energy for TNF is located in low frequency unlike the sound energy of air jets.

2) The spectra for the TNF were found to be qualitatively similar with variation in flow velocity. However, quantitatively the differences in the spectra on the high-frequency side are more compared to differences in low-frequency side.

3) The width of constant pressure level plateau in TNF spectra is reduced from high-frequency side with reduction in flow velocity.

4) The TNF spectra depend on location of measurement, and the high-frequency components in the spectra drop significantly as the distance from the burner exit increases, especially in axial direction.

The present data for standard flames and the parametric variations with exit conditions are of value in the evaluation of computational aeroacoustics codes and their extensions to combustion applications.

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W. Devenport
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