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Effects of Combustion on the Sound Pressure Generated by Circular Jet Flows

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Introduction

MANY studies of the sound generated by premixed turbulent jet flames are available in the literature.[1–7] Some studies of the sound generated by nonpremixed turbulent flames with a coflow of air also exist.[1,4,8,9] Experimental data also exist for sound emitted by a coflow partially premixed flame[10] and by industrial burner flames.[11] Efforts have been made to correlate the sound generation of the flames to various flow properties and flame parameters. Price et al.[1] correlated sound generated by turbulent premixed and diffusion flames with the changes in the intensity of light emission by free radicals. Giammar and Putnam[2] presented sound pressure level data as a function of the square of the firing rate and also as a function of the product of pressure drop and heat release rate. Kilham and Kirmani[5] showed that combustion noise increased with turbulence intensity in premixed jet flames. Kotake and Takamoto[6,7] investigated the effects of the shape and the size of the burner nozzle on the combustion noise of premixed flames. They also investigated the effects of the turbulence in the unburned mixture on the acoustic characteristics. Ohiwa et al.[8] studied the relationship between flame structure and noise characteristics for coflow nonpremixed turbulent flames. They were able to show that fluctuations in sound pressure, ion current, temperature, and CH emission corresponded to organized eddy formation.

Shivashankara et al.[3] compared flame-generated noise for premixed turbulent flames with the corresponding cold-jet noise. They showed that the sound generated by the premixed flames differs from that generated by the cold jets in terms of scaling, directionality, and spectral content. Kumar[4] studied the sound generated by both premixed and coflow nonpremixed turbulent flames and found significant differences in their characteristics. Recently, for a nonreacting jet, Narayanan et al.[12] found a downstream low-frequency source ($5 \le x/D \le 10$) and an upstream high-frequency source ($0 \le x/D \le 3$). The contributions from farther downstream ($x/D \ge 10$) were found to be small. The data for heated jets indicated that the sources are distributed farther downstream compared to those in the cold jets. Narayanan et al.[12] showed that for a fixed exit velocity a cold jet is noisier than the corresponding heated jet. The present work involves jets that are at much lower exit Mach numbers compared to those studied by Narayanan et al.[12] The acoustic characteristics of the present low-Mach-number jets and flames are of interest in combustion instability studies, where acoustic fluctuations of the low-Mach-number jets serve as the perturbations that can grow by coupling with the combustor modes.

The specific objectives of the present work are to obtain sound pressure level (SPL) data for turbulent nonpremixed flames, with fuel issuing into quiescent surrounding air. Review of literature shows that sound generation phenomena from this simple configuration of nonpremixed combustion have not been studied in detail. 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 aerothermo-acoustic phenomena, are available. A complete set of measurements including velocity and scalar statistics, in addition to the sound pressure measurements, is necessary for validation of aeroacoustic and thermoacoustic computational models. We have selected two turbulent nonpremixed flame (TNF) workshop standard flames, German Aerospace Center DLR-A and DLR-B, because of the availability of the extensive experimental data for velocities, species concentrations, and thermal radiation properties[13,14] (also private communication from A. Dreizler, 2000), as well as the simplicity of the configuration. The SPL produced by the flames are compared with those produced by nonreacting air jets with identical exit Reynolds numbers *Re*. Note that the Mach number *M* rather than the Reynolds number *Re* is the appropriate nondimensional parameter for studies of aeroacoustics. However, for identical tube diameters, the exit velocity and the exit Mach number are linearly proportional to the exit Reynolds number. Therefore, the Reynolds number, which is the appropriate parameter for studying inertial and diffusive effects and turbulence, is used simply as the designator of the jets in the present study. SPL measurements were also performed for four flames (for which velocity and scalar field data do not exist) and corresponding six air jets to study the velocity and exit Mach number scaling.

Experimental Arrangement

TNF standard flames DLR-A and DLR-B were stabilized in the laboratory. The fuel stream of these 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. The exit Reynolds numbers for the two flames based on injected gas properties at room temperature are 1.52×10^4 (DLR-A) and 2.28×10^4 (DLR-B). Air was used for studying the sound emission from equivalent nonreacting jets with the same burner. The flow in each case has very low exit Mach numbers ($M = 0.04$–0.18) based on the sound speed at room temperature. The three fuel stream constituents were supplied from bottled sources and measured using calibrated sonic orifices. A pipe length of more than $500L/D$ ensured proper mixing before the flow reached the burner exit. The burner was placed with its exit 76 cm above the floor, firing vertically upward and 160 cm away from the nearest wall. Acoustic measurements were made using a Realistic Sound Level Meter (Model 33-2050). The SPL was read in terms of A-weighted decibels (dBA referenced to 0.0002 μbar) and recorded using a National Instrument ADC board and a personal computer. The meter has an accuracy of ± 2 dB at 114 dB. This meter was checked using a B&K 4230 sound level calibrator producing 94 dB at 1 kHz and also with a B&K 4231 sound level meter producing 94 dB and 114 dB SPL at 1 kHz. The Realistic Sound Level Meter returned accurate measurements in all cases, well within 2 dB. The maximum spherical solid angle for the sound level 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 sound level meter has less than 2-dB systematic variations 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

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directional sensitivity on the present data to within the other experimental uncertainties.

Flexible tubing was used to minimize the sound generated by the flow in the pipes and bends. Also, the orifices and the tubing downstream of the orifices were covered with acoustic absorbent material (glass-wool and foam), and the flow metering arrangement was separated from the burner by wooden panels and located more than 3 m away. The exhaust fan in the room was kept off for the duration of the measurement. As a result, the ambient sound pressure levels were less than 50 dBA.

Both axial and radial variations in sound from reacting and nonreacting jets were studied. For studying the axial variations, the SPL meter was located 40 cm away from burner axis and started from the level of the burner exit up to 50 cm above. The visible flame length was approximately 60 cm. To study 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.

Results and Discussion

Figure 1 shows the axial variation in sound pressure in pascal and sound pressure level in A-weighted decibels for flames (top panel) and air jets (bottom panel) as a function of axial distance from burner exit, normalized by the burner diameter (0.8 cm). In view of the SPL meter accuracy of ±2 dB at 114 dB, the measurements were repeated six times. The average values were taken as the data points and the error bars determined based on the maximum spread of the data at a particular location. The sound pressure in pascal was computed from the A-weighted decibel measurements and reference pressure. Clearly, the nonpremixed turbulent flames are much noisier than the cold jets. Also, the sound generated by the flames remains almost constant between x/D values of 10 and 30, whereas the nonreacting jet sound exhibits a monotonous decrease in this region. The scalar data for the flames show that significant chemical reactions occur in this region of the flames. Therefore, a combustion generated sound source is expected. The data show the existence of larger sound sources in the flames compared to those in the nonreacting jets. The sound sources in the flames are located farther away from the exit compared to those in the air jets. This is in agreement with the observations in the literature for premixed turbulent flames and coflow nonpremixed turbulent flames. Also, the differences between SPL for nonpremixed flames and for the air jets observed in the present experiments are higher than those reported by Shivashankara et al.[3] for 0.8 equivalence ratio propane–air premixed flames and air jets.

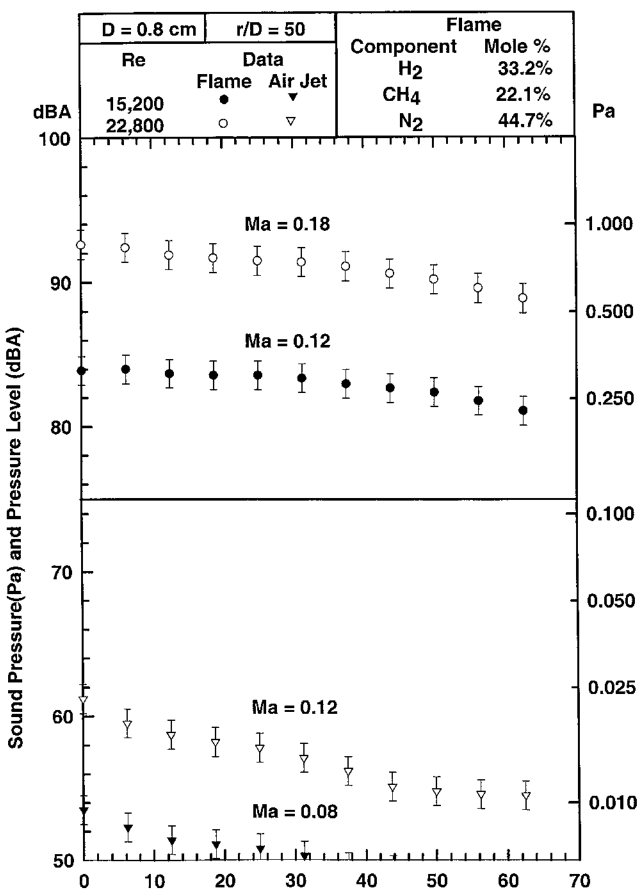

Fig. 1 Axial variation of sound pressure and pressure level for flames and jets.

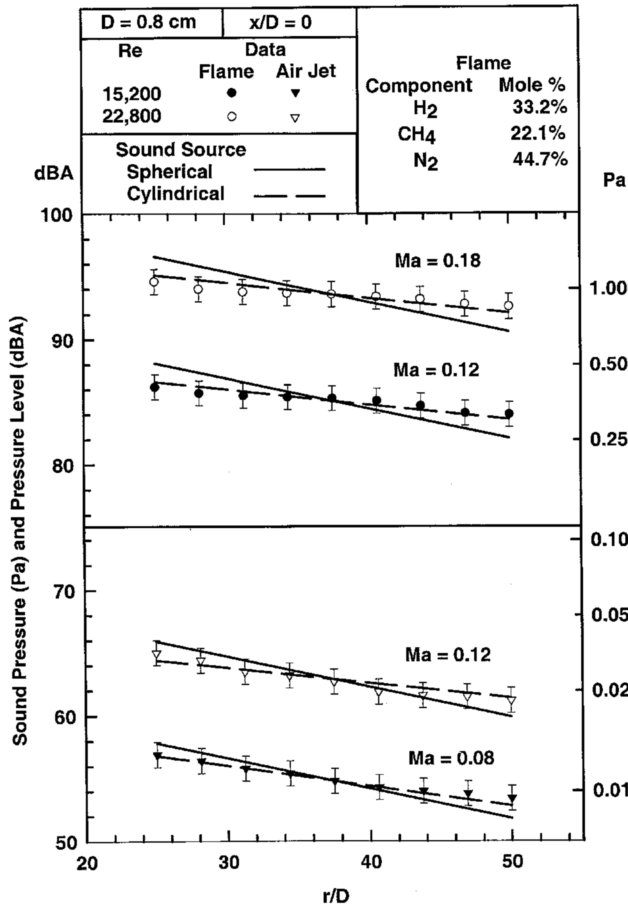

Fig. 2 Radial variation of sound pressure and pressure level for flames and jets compared with idealized source spreading.

Figure 2 shows the radial variation in sound pressure (pascal) and SPL (A-weighted decibel) for flames (top panel) and air jets (bottom panel) as a function of radial distance from the burner exit, normalized by the burner diameter. Clearly, the flames produce much higher levels of sound compared to the nonreacting jets, and the decay with radial distance is much slower for the flames compared to the nonreacting jets. Under free-field conditions, the sound pressure of a point source with spherical sound radiation is inversely proportional to the distance from the source. Similarly, for a cylindrical source, the sound pressure is inversely proportional to the square root of distance away from the source. Therefore, under such conditions, it is expected that the SPL for a spherical source will drop by 6 dBA and that for a cylindrical source will drop by 3 dBA per doubling of the distance. Figure 2 also shows the expected drops from spherical and cylindrical sources for reference. The flames exhibit acoustic characteristics closer to a cylindrical source than those of the cold jets.

Figure 3 shows the sound pressure (pascal) and SPL (A-weighted decibel) at a radial location of 25 diameters in the nozzle exit plane, generated by the present turbulent nonpremixed flames and air jets as a function of the exit Reynolds number. The corresponding exit

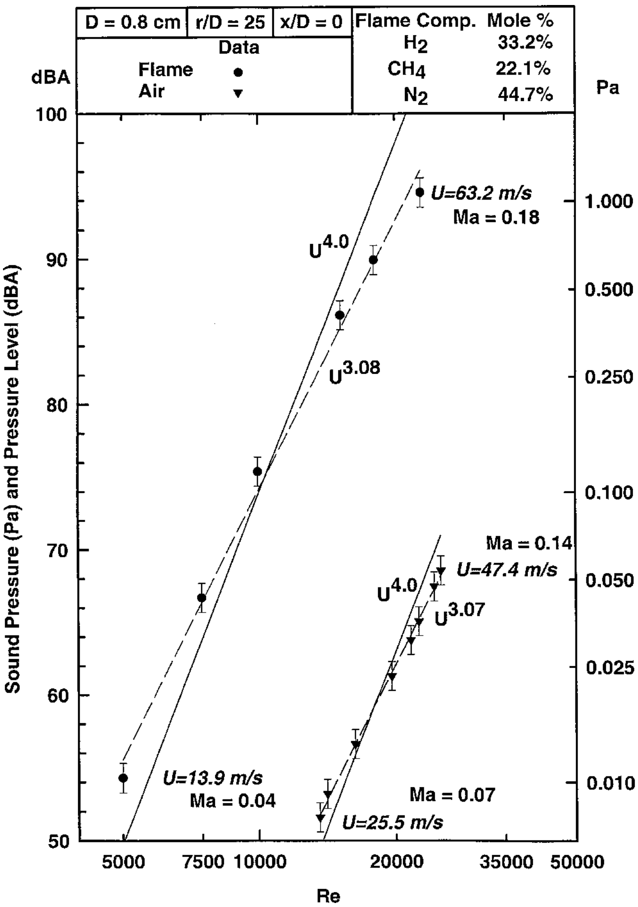

Fig. 3 Reynolds number dependence of sound pressure and pressure level for flames and jets and linear regression analysis for velocity dependence.

velocity and Mach number, which are the appropriate scaling variables, are also noted in Fig. 3. The TNF sound decreases rapidly with decreasing Reynolds number, and at $Re = 5 \times 10^3$ ($M = 0.04$), the TNF sound levels are comparable to those of the nonreacting air jets at $Re = 1.52 \times 10^4$ ($M = 0.08$). The results indicate that the combustion process is a stronger contributor to sound generation at lower exit velocities. Figure 3 shows a linear regression on the data for flames and air jets resulting in velocity scaling exponents close to three for both the flames and the air jets. Figure 3 also shows a line corresponding to the U^4 scaling expected for nonreacting air jets as per Lighthill.[15] The linear regression lines for flames and air jets are almost parallel to each other, suggesting similar velocity scaling. However, Shivashankara et al.[3] indicated a lower velocity exponent for premixed combustion noise compared to the air jet noise.

Under free-field assumptions the results indicate that the sound power (which scales as the square of the SPL under the free-field assumptions) of TNFs issuing into quiescent air varies as $U^{6.16}$. Shivashankara et al.[3] reported a much lower sound power scaling ($U^{2.7}$ for fuel lean and U^3 for fuel rich) for premixed flames. Kumar[4] also found the scaling for premixed flames to be $U^{2.7}$ in an anechoic chamber and $U^{3.0}$ in a hard-walled bay. For coflow nonpremixed flames, Kumar[4] reported a scaling of U^4 under both anechoic chamber and hard-walled bay conditions. Therefore, our results for the sound power scaling are clearly not in agreement with the past data. However, the most recent data for nonreacting jets[12] from the literature show an overall sound power scaling of $U^{6.14}$, and our results with the free-field assumptions are in agreement with these. The reasons for the lower and widely varying scaling reported for combustion noise in the past works are unknown.

Conclusions

1) TNFs with fuel issuing in a quiescent air environment produce several orders of magnitude higher sound pressure compared to corresponding air jets with identical exit velocities.

2) The effective sound source in the TNFs is farther downstream from the burner exit compared to that in the cold jet.

3) The decrease in SPL with increasing radial distance from the burner axis for the flame-generated sound is less pronounced than that for the nonreacting jet sound. This suggests that the combustion noise source is distributed over a wider spatial region than the air jet noise source.

4) The difference between the reacting and the nonreacting jet SPLs decreases with increasing exit velocity and Mach numbers.

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