JOURNAL OF PROPULSION AND POWER
Vol. 10, No. 2, March–April 1994

Raman Measurements at the Exit of a Combustor Sector

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Spontaneous Raman diagnostics are applied to the exit plane of an aircraft engine combustor sector fueled with both natural gas and liquid fuel (kerosene). Profiles of temperature and major species are obtained at the sector exit. The Raman mean temperature data agrees well with thermocouple measurements at identical operating conditions. The rms profiles show up to 12 and 16% fluctuations in temperature at the centerline of the burner with natural gas and kerosene, respectively. The mean profiles of major species show the expected trends. Up to 6% unburnt oxygen is measured at the centerline with natural gas. The corresponding value with liquid fuel is 8%. Profiles of unburned hydrocarbons, carbon-monoxide, and hydrogen at the centerline indicate incomplete combustion at the measurement plane as also evidenced by the visible flame extending significantly beyond the sector exit. Profiles of normalized rms mole fractions of major species are also presented. Finally, the Raman system is applied to a room temperature cell at elevated pressures to extend the system to this regime. The Raman signals increase linearly with pressure as expected.

Introduction

AS the stoichiometry of advanced aircraft engine combustors is increased in response to the demand for increased engine efficiency, the temperature rise across such combustors increases correspondingly. This increase in temperature rise, besides challenging the turbine materials and cooling technology, presents a twofold challenge to conventional diagnostic techniques such as thermocouples and sampling probes used to measure the performance of these devices. These challenges are 1) physical survival of thermocouples and probes in the high-temperature environment of 2000 K and above, and 2) the need to provide temporal information about the flowfield. This information is necessary because increased unsteadiness in temperature and fuel-air ratios is believed to result in reduced combustion efficiency and increased heat transfer to turbine blades due to hot streaks. Unsteadiness in the temperature field could also lead to significantly larger NO_x emissions than estimated based on mean values because of the exponential dependence of thermal NO_x formation rates on temperature.[1,2] Quantification of the unsteadiness in temperature and scalar flowfields is therefore believed to be increasingly important as current combustors are pushed to their optimum performance levels. Conventional diagnostic tools have large time constants and provide only mean flow measurements. Good quality data is also needed to validate computational codes currently being developed for the full-scale combustors.

There are a number of laser-based diagnostic techniques capable of providing these measurements,[3,4] such as CARS, Spontaneous Raman, OH/NO-based LIF, etc. Spontaneous Raman Diagnostics is one of the more comprehensive of these techniques since it provides the means to measure the temperature and scalar flowfields simultaneously with excellent spatial and temporal resolution.[5–7] In the past, Spontaneous Raman spectroscopy has been used extensively in various laboratories[7–10] to obtain detailed profiles of temperature, major species, and mixture fraction to help understand turbulence chemistry interactions in jet flames and bluff-body stabilized flames of hydrogen,[9] $CO/H_2/N_2$ mixtures,[7,10] and more recently, dilute methane flames.[8] Making Raman measurements in these flames becomes increasingly difficult as the complexity of the fuel increases from pure hydrogen to $CO/H_2/N_2$ mixtures, and further to hydrocarbon flames due to increased interference from flame-generated incandescence, laser-induced fluorescence, and soot. Since the Raman signal is inherently weak it is susceptible to such interferences, and therefore, applications of Raman diagnostic technique to practical hardware have been limited in the past.[11] Great strides have recently been made in extending Raman diagnostics to hydrocarbon-based flames and correct for fluorescence interferences. With improved monitoring and calibration techniques such as those developed by Masri et al.[12–15] and in our laboratory,[16] and with the advent of advanced counter-rotating swirlers that result in relatively soot-free partially premixed flames of blue color, the use of Raman diagnostics for the study of practical hardware has become more realizable. In this article we successfully demonstrate such an application of the Raman diagnostic system by applying it to the relatively harsh environment of a combustor sector fueled with both natural gas and liquid fuel (kerosene), respectively. This is believed to be the first application of Raman scattering to obtain detailed scalar flowfield at the exit of a full-scale combustor sector.

To make these measurements possible, the Raman system has been modified and calibrated using a laminar CH_4/CO flame in controlled environment of a low-velocity tunnel. The system was then applied to a turbulent bluff-body stabilized pure methane flame with a sooty recirculation zone to demonstrate its capabilities. The approach developed in this manner to correct for laser-induced fluorescence is incorporated in the Raman system used in this study. As discussed later, minimal interference from laser-induced fluorescence was observed at the plane of the measurements in this application. The Raman system is rendered mobile by mounting it on a three-dimensional traversing table since the sector assembly could not be traversed for practical reasons. Profiles of mean and rms variation of temperature and mole fractions of all major species are obtained. The mean temperature data is compared with the corresponding thermocouple data obtained at the same operating conditions. Finally, the Raman system is applied to a high-pressure cell at room temperature to determine the potential of making Raman measurements at elevated pressures.

Presented as Paper 92-3350 at the AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference and Exhibit, Nashville, TN, July 6–8, 1992; received Oct. 8, 1992; revision received April 23, 1993; accepted for publication July 20, 1993.

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Experimental Setup

The joint Raman/Rayleigh diagnostic system used in this study is similar to that used in the past,[7,10] except for the modifications made to allow measurements in the environment of a test cell where the sector assembly is located. The original Raman system consists of a Candela LFDL-20 flashlamp pumped dye laser that provides pulses of ~1 J in ~2 μs, within a 0.2-nm bandpass at 488.0 nm at 10 Hz. The laser has two 20-gal dye circulating systems to allow continuous operation. The laser beam is approximately 1 cm in diameter and is focused by a 200-mm lens forming the probe volume. The Raman scattered light is collected at right angles by an achromatic 250-mm f/2 lens, designed specifically for this application. It is then collimated and refocused onto the entrance slit of a $\frac{3}{4}$-m Spex polychrometer following a $\times 3$ magnification. The probe volume dimensions are approximately $0.3 \times 0.3 \times 0.6$ mm. The collected light is then dispersed for detection at the exit plane by numerous RCA 4526 photomultiplier tubes located at appropriate locations (Fig. 1) for detecting anti-Stokes Raman scattering from nitrogen, Stokes vibrational Raman scattering from N_2, O_2, H_2, H_2O, CO, CO_2, and unburnt hydrocarbons (C—H bond) and Rayleigh scattering. The data from the photomultiplier tubes is collected by custom-designed sample and hold circuitry, which integrates the signal over a 2-μs window before and after the firing of the laser with an 8-μs interval. The differential voltages corresponding to the Raman signal minus the background are recorded for all the channels simultaneously using a Data Translation 12-bit A/D board and Dell 333 IBM-AT compatible system. The signals are then corrected for electrical and other background errors corresponding to each channel, and after normalization are corrected for the relative sensitivities of the photomultiplier tubes. Typically, 200 measurements are made at every location, although 2000 data points are also collected at some locations for statistical purposes.

The Raman system described above has the inherent advantage of filtering any low-frequency (<125 kHz) flame generated incandescence due to the method used of subtracting the background signal recorded before the firing of the laser from the corresponding Raman signal on a shot-to-shot basis. Only the differential signal is recorded. This system cannot, however, correct for any laser-induced fluorescence interference such as that observed in the recirculation zone of a turbulent bluff-body stabilized pure methane flame. This is because laser-induced fluorescence accompanies the Raman signal and cannot be subtracted out. It is believed to be due to soot precursors in the flame.[12–14] An extensive calibration procedure has been developed to account for this laser-induced fluorescence in pure methane flames[16] using methodology similar to that described by Masri et al.[13,14] for dilute methane flames. Initial studies show that the fluorescence is fairly broadband and correlates well throughout the measured spectra. The extent of interference in pure methane flame is measured to be lower than that reported by Masri et al.[12–14] for dilute methane flames, probably because of the difference in the excitation wavelength used in the two studies. Two additional photomultiplier tubes termed "F_1" and "F_2" have been added to the exit plane of the polychrometer at Raman-free regions of the spectra at 535 and 578 nm between the oxygen and carbon-monoxide and methane and water vibrational bands, respectively, as shown in Fig. 1 to account for and monitor this fluorescence. The system was first applied to a laminar methane flame diluted with carbon-monoxide to obtain correction factors corresponding to all the major species. The details and results of the correction scheme developed based on this method are presented elsewhere.[16] For the application discussed here, the amount of interference in the Raman signals was found to be minimal, e.g., the peak activity in F_1 channel is less than 1% of that observed in the case of the laminar CH_4/CO flame. This is believed to be due to the following reasons:

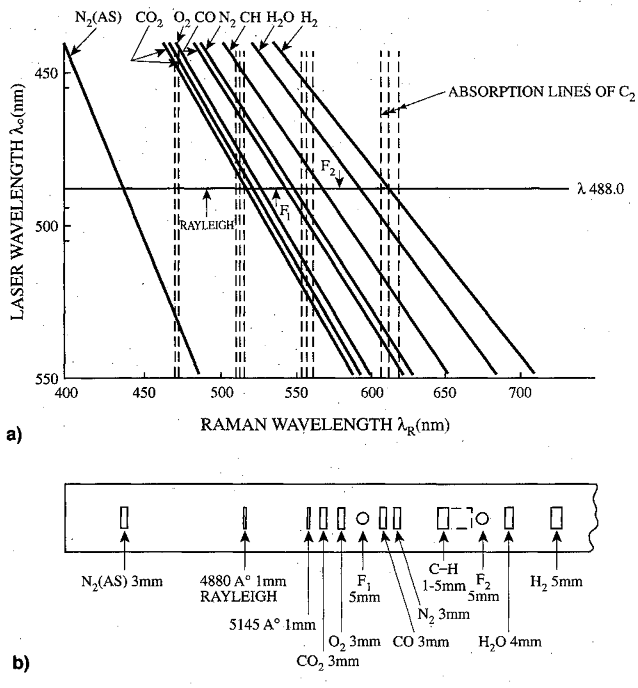


Fig. 1 Location of a) Raman vibrational bands and b) polychrometer exit slit maskings.

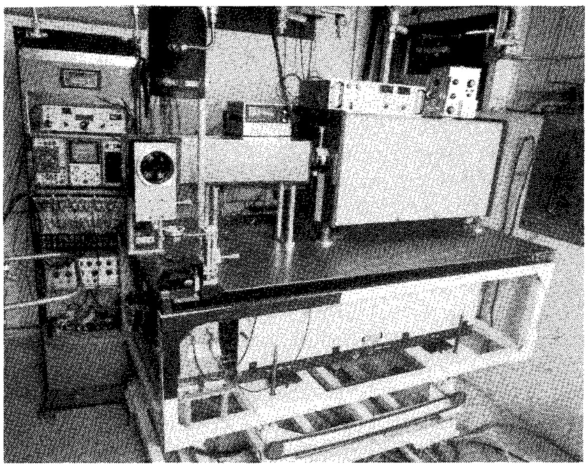
1) The counter-rotating swirlers in the various swirl cups provide an intensely turbulent region in the vicinity of the cups where the fuel is introduced into the high-speed swirling air. The result is that the flame is sustained only downstream of the swirl cup in the region of partially premixed fuel and air. The fuel-rich zone embedded in the intense turbulent zone is unable to sustain any flame, and therefore, the flame is not sooty but appears bluish-white to the eye with a few streaks of yellow in contrast to the bluff-body stabilized pure methane flame which appears intensely yellow to the eye.

2) The measurement location is 76 mm downstream of the sector exit, which itself is approximately 225 mm from the swirl cups. Any soot precursors and polycyclic aromatic hydrocarbon (PAH) compounds potentially responsible for laser-induced fluorescence therefore probably get diluted and consumed upstream of the measurement location, resulting in contamination of less than 5% shots with laser-induced interference in the worst case (with kerosene). These shots were corrected for the fluorescence interference (which was typically less than 1% of that measured in CH_4/CO flame), using the calibration procedure described in Ref. 16 on a shot-to-shot basis. The overall effect on the measured temperature and mole fraction data of major species is estimated to be less than 1% at the conditions examined in this study. Fuel-rich operation can result in much higher levels of fluorescence interference.

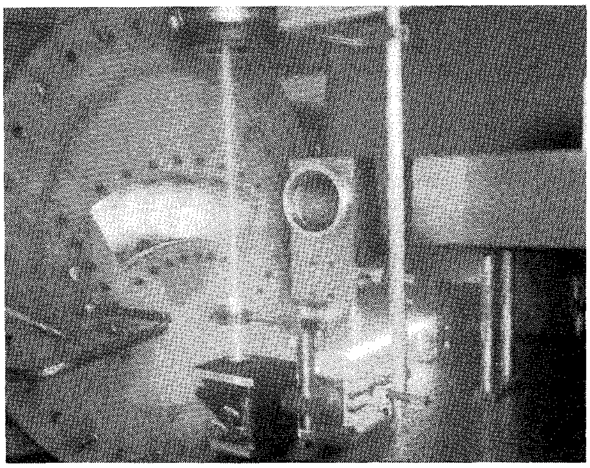
The joint Raman/Rayleigh system is used to obtain the temperature and major species as follows: The Raman signals are collected on a shot-to-shot basis for all the major species including N_2, H_2, O_2, CO, CO_2, H_2O, and the CH band. After correcting these signals for electrical noise and background luminosity the mole fractions of major species are obtained using calibration factors obtained with 100% pure gases and well-calibrated gas mixtures. Next, the correction factors described above are used to correct for laser-induced interference, if any. The temperature is obtained using any of the following two methods: In the first method the temperature is initially guessed, based on which the mole fractions of all major species are calculated using their measured vibrational intensities. The mole fractions are then corrected using high temperature correction factors to account for changes in the fraction of the Raman band falling in the fixed exit slits of the respective photomultiplier tubes. The process is repeated until the sum of the mole fractions is unity. This iterative procedure converges typically in two to three iterations since the correction factors are relatively weak functions of temperature. The second method is based on using the Rayleigh signal. Since the reactants are not perfectly premixed, additional information regarding Rayleigh cross section of the mixture is necessary. This is obtained from the accompanying Raman signal and an iterative process which again converges in two/three iterations is used to obtain the temperature. Comparison between mean temperature values obtained using the two methods is presented in the Results section.

Application to Sector

In the past, in general, the Raman system has been mounted rigidly and the test-section traversed. In this study it was not feasible to traverse the sector assembly because of its large size and the requirement for preheated high-temperature air. The Raman system was therefore mounted on a three-dimensional traversing table built specifically for this purpose, which allowed sufficient motion in all three directions and could be remotely positioned. The laser is mounted at the bottom of the table and the optics and the polychrometer are mounted on the top as shown in the photograph of Fig. 2a. The sector used in this study is a 75-deg section of a triple-annular research combustor with the central pilot stage consisting of five swirler/fuel-nozzle cup assemblies, and the outer and inner main stages consisting of four each. The sector is capable of operating with both gaseous and liquid fuel and is operated at atmospheric pressure. Figure 2b shows a photograph of the sector assembly and the laser beam traversing the flame-front. The sector is operated with preheated air of up to 600 K with liquid fuel. The airflow rate varied from 0.4 to 0.7 kg/s, and the overall stoichiometry of the combustor varied between 0.2–0.3. Only the middle pilot stage is fueled for these tests. Efforts are under way to fuel all the three stages of the sector. At higher operating conditions, the flame is fairly long at atmospheric pressure and the visual flame-zone extends up to 20 cm from the exit plane. To protect the Raman collection lens from the flame-front, it is shielded in an air-cooled box. A sheath of nitrogen is laid on top of the window protecting the collection lens, and on the focusing lens to avoid buildup of residue from kerosene. This layer of nitrogen had no effect on the measured Raman signals. Routine monitoring of the Stokes vibrational signal from nitrogen in room air also showed no misalignment of the system during the operation of the sector and the traversing of the Raman setup. Figure 3 shows a schematic diagram of the Raman system as applied to the sector exit. Raman measurements are obtained 76 mm from the exit plane of the sector due to physical constraints imposed by the 800-mm-diam faceplate used to mount the sector in the plenum. Efforts are under way to modify the faceplate to allow Raman access to within 5 mm of the exit plane. The airflow rate is measured using a standard orifice meter and the liquid fuel flow rate using a turbine flow meter. Delavan peanut nozzles (smaller versions of the regular hollow cone Delavan pressure blast swirl nozzles) are used to introduce kerosene in the swirlers producing good atomization even at low fuel supply pressures.



a)



b)

Fig. 2 Photographs of a) Raman setup and b) sector exit.

Results

Combustor Sector—Natural Gas

The Raman system is first applied to the combustor sector with natural gas as the fuel. The operating conditions are an airflow of 0.68 kg/s and an overall equivalence ratio of 0.21. Only the center annulus is fueled. With natural gas as the fuel, the flame is blue, it is fairly long at these conditions, and extends beyond the sector exit by approximately 150 mm. Minimal amount of flame-generated incandescence and laser-induced fluorescence are subtracted from the Raman signal on a shot-to-shot basis as discussed earlier. The data is obtained over a 125-mm-wide region which spans the sector exit of 108 mm. Figure 4a shows a profile of mean temperature measured across the sector exit at these conditions. The temperature values have been obtained using the sum of mole fraction method. Thermocouple data obtained with a Pt/Pt-10%Rh thermocouple of 1.3-mm bead diameter is also shown in Fig. 4a. The thermocouple data has been corrected for radiation losses using standard procedure. It has not been corrected for conduction losses through the lead wires and convective cooling. The two profiles have a similar shape and show fairly good agreement between the two values. The temperature profile shows a typical rise and fall through the flame-front as expected, with the maximum values being slightly above the centerline of the burner exit due to buoyancy effects. The peak value of mean temperature of 2000 K is approaching the practical limit for application of conventional thermocouples.

The rms temperature profile at this location is shown in Fig. 4b. This profile is double peaked with a minimum value of 12% at the centerline. The high peak values at the edges of the flame are due to turbulence in the shear layers caused by entrainment of cold air in the inner and outer annuli of the sector into the hot combustion products of the center annulus. The centerline value of 12% is larger than the design value. It is, however, close to the value inferred from probe-sampling data obtained at similar operating conditions. Asymmetry in the profile is believed to be due to different widths of the inner and outer annuli of the combustor. The edges of the profile lie in cool unburnt airstream, and therefore, have

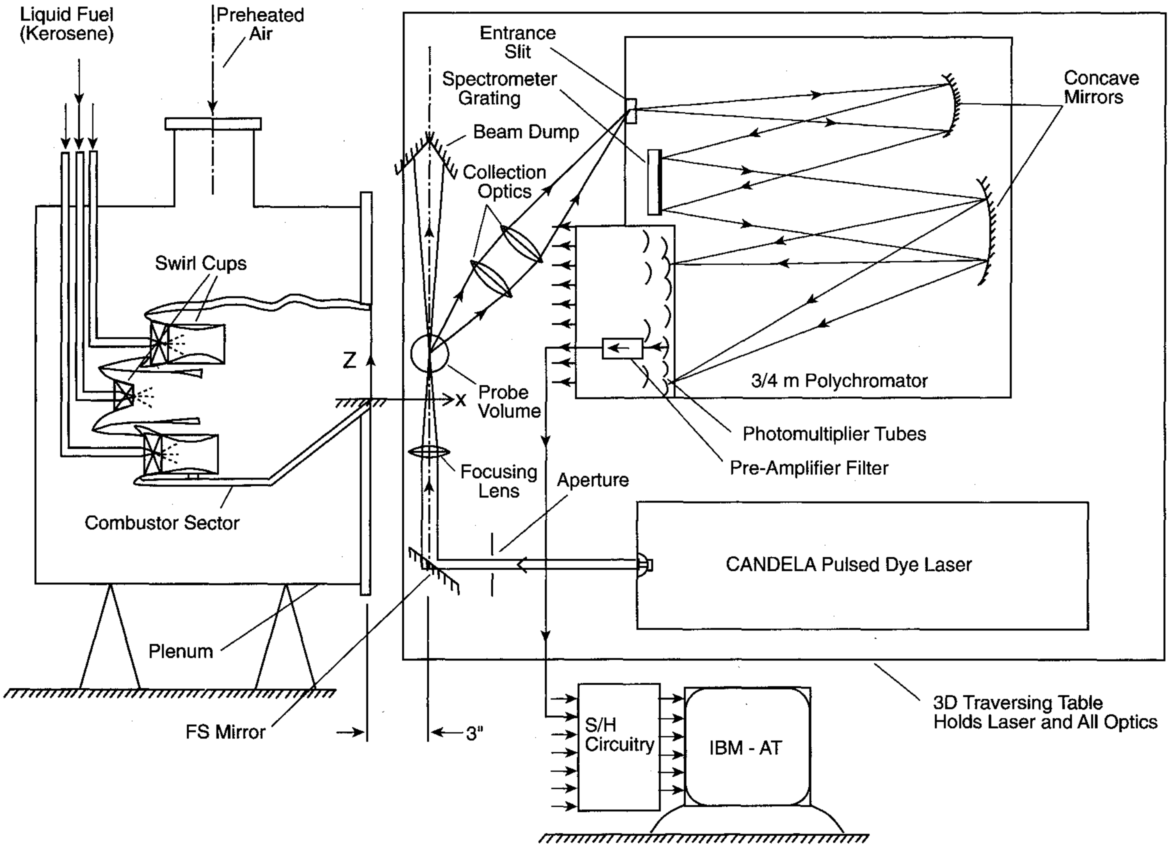


Fig. 3 Schematic of the Raman setup.

relatively low rms values. This information cannot be obtained using standard thermocouples and represents a significant advantage of the Raman diagnostic system. The rms values plotted in Fig. 4b are the measured values. True rms values are estimated to be lower by 1–2%, based on location due to the estimated inherent shot-to-shot rms variation of up to 5% in the Raman measurements. Figure 5 shows the shot-to-shot variation of the temperature at three typical locations in the exit plane: 1) at the centerline ($Z = 54$ mm), 2) in the mixing region ($Z = 81$ mm), and 3) in the outer cold air region ($Z = 96$ mm). The temperature data shows significant shot-to-shot variations caused by the turbulent mixing of the hot reaction products with cold unburnt air in the mixing layer. Figure 5a shows minimal fluctuations at the centerline since the data point is fully immersed in the combustion region at this location.

The profiles of mole fractions of the major species are shown in Figs. 6a and 6b. The data shows expected trends with nitrogen remaining fairly constant throughout the flame-front, and oxygen dropping to a minimum value of 6% at the location corresponding to the peak in the temperature profile. Unburnt oxygen at the centerline is indicative of incomplete combustion and overall lean stoichiometry of the burner. In a stoichiometric combustor, any unburnt oxygen is expected to result in losses in combustion efficiency and is a quantity of great interest. Figure 6 shows the profile of the product species carbon-dioxide and water to peak at values of 6 and 14%, respectively, at the centerline, and fall at the edges of the flame-front as expected. The profiles of hydrogen and carbon-monoxide are also interesting and show unburnt fuel at the centerline of up to 1%, which agrees with the visual observation of the flame extending beyond the measurement plane. The amount of unburned hydrocarbons (lumped together as C—H band) are measured to be less than 1% throughout the flame-front. Unburned fuel at the sector exit is undesirable since it represents incomplete combustion and a drop in combustion efficiency. These results show that the Raman system can help identify such losses. Figure 7 shows profiles of normalized (by local mean) rms mole fractions of major species. The profiles show expected trends with nitrogen having very low rms values throughout the flame-front, oxygen and water showing double peaks, and the carbon-dioxide profile tending to very large values at the outside shear layers. The Raman system quantifies unsteadiness in both temperature and scalar flowfields since the data is obtained in a temporally resolved manner. These results, besides helping evaluate combustor performance, also provide good quality data base to help validate computational codes being developed for such configurations. A program is currently underway to make detailed comparison of Raman data with model predictions at various operating conditions.

Combustor Sector with Kerosene

The primary fuel used in commercial aircraft engine applications is Jet-A. In this study kerosene was used as the liquid fuel since it is relatively safer to handle and use in laboratory-type applications, and since its characteristics closely resemble Jet-A. For liquid fuel application the air was preheated by an indirect gas-fired heat exchanger at temperatures of up to 620 K. At a flow rate of 0.45 kg/s and an overall equivalence ratio of 0.21 (only middle annulus fired), the flame extends further beyond the exit of the sector than with natural gas (250 mm), is bluish-white in color, and is relatively brighter. In the vicinity of the swirl cups where kerosene is introduced using pressure atomized Delavan peanut nozzles, the flame contains some streaks of yellow on an unsteady basis. Some activity was also recorded on the F_1 and F_2 monitoring channels at the sector exit in this flame. Less than 5% of the shots indicated contamination of the signal, as discussed earlier. This is believed to be due to the partially premixed mode of operation of the combustor, even though the configuration suggests diffusion operation. Raman measurements in the immediate vicinity of the swirl cup region are required to determine the exact mode of operation of the burner.

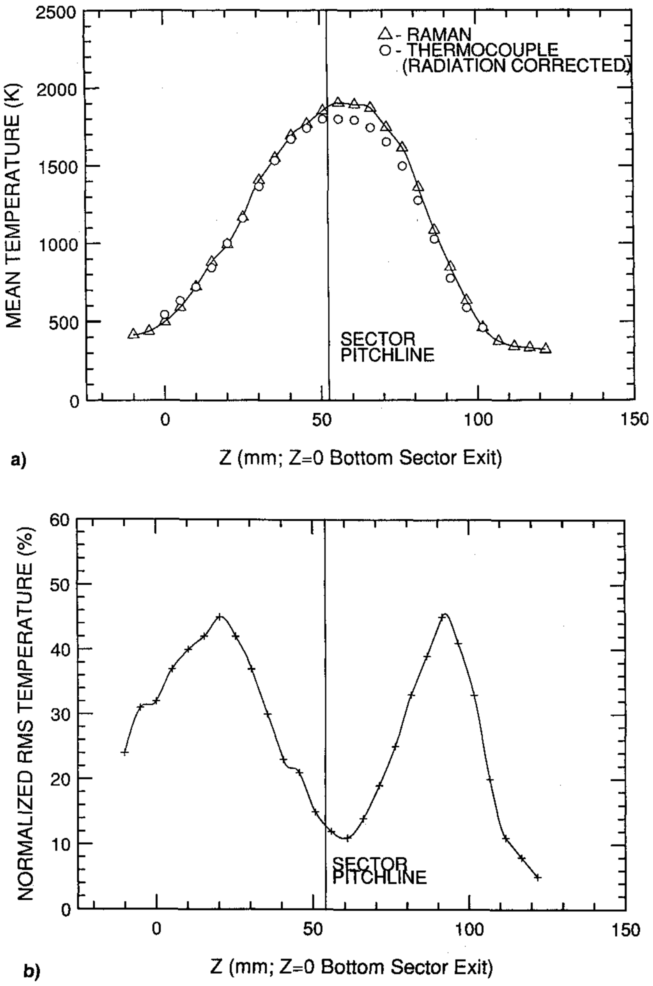


Fig. 4 Profile of a) measured mean temperature at sector exit: airflow = 0.68 kg/s, fuel = natural gas, overall equivalence ratio = 0.21 and b) normalized rms temperature profile obtained using Raman diagnostics. Data normalized by local mean values.

Figure 8 shows the profile of mean temperature in the lower half of the sector exit. The temperature profile shows a sharp rise to values as high as 2100 K at the centerline. Temperature data obtained by the two methods of sum-of-mole fractions and Rayleigh scattering shows very good agreement, except at the centerline where the temperature obtained by the Rayleigh technique is slightly lower. The rms profile of temperature (Fig. 8) shows the expected profile with a peak in the shear region and low values on both sides. The rms level at the centerline of 16% is higher than that with natural gas. This is probably due to the unburnt air in the outer and inner annuli penetrating the fueled middle annulus to a larger extent. As was the case with natural gas, air in the region between the measurement plane and the sector exit is also entrained, resulting in high rms levels. Future plans call for obtaining data with all three annuli fueled and the plenum sector assembly modified to allow optical access to within 5 mm of the sector exit to determine the true extent of centerline rms temperature fluctuations.

Figure 9 shows the mean profile of all the major species at the sector exit with kerosene. All the profiles exhibit expected trends with nitrogen and oxygen dropping in the center of the exit as expected, and the combustion products carbon-dioxide and water increasing there. Larger amounts of unburned fuel species i.e., carbon-monoxide (2.5%), hydrogen (1%), and unburned hydrocarbons (<1%) are measured in this flame than was the case with natural gas. The longer length of the flame is also indicative of this. It is probably due to the additional processes of atomization and vaporization associated with liquid fuel. At the centerline, the amount of oxygen is measured to be 8%. Centerline profiles obtained further downstream of the sector exit show this value to increase because of entrainment of surrounding unburnt air. A more rigorous comparison of the major species profile with probe-sampling measurements needs to be done to further qualify the technique. These results, however, show Raman diagnostics to have the potential to yield reasonable results in full-scale hardware at realistic operating conditions.

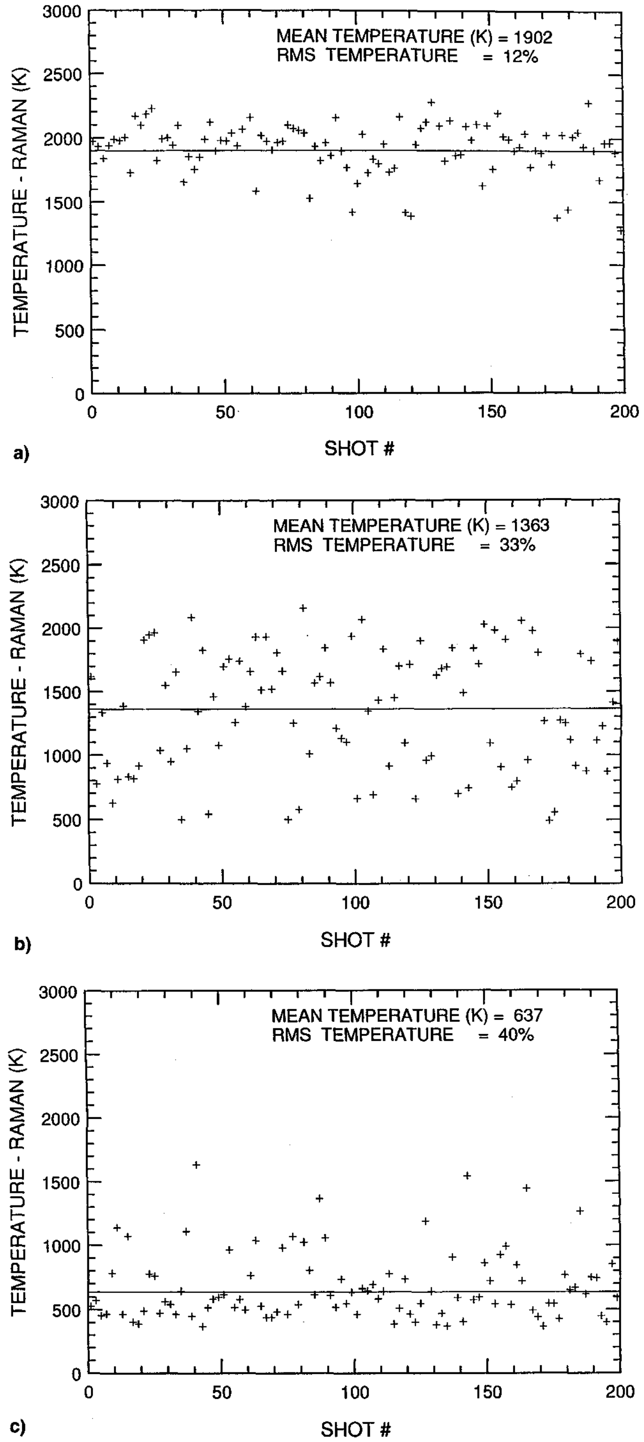


Fig. 5 Instantaneous Raman temperature vs shot number at a) $Z = 54$ mm, b) $Z = 81$ mm, and c) $Z = 96$ mm. Operating conditions are the same as in Fig. 4.

Raman Measurements at Pressure

All the above data were obtained at atmospheric pressure. Most practical combustors operate at elevated pressures, and therefore, Raman measurements need to be extended to this

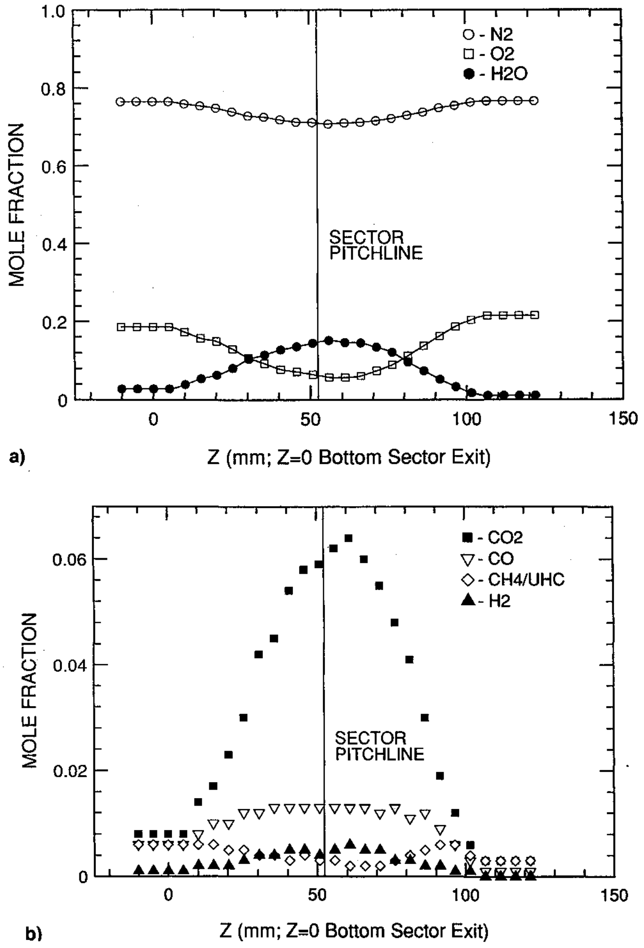


Fig. 6 Mean mole fraction profiles of major species. Operating conditions are the same as in Fig. 4: a) N_2, O_2, H_2O and b) CO_2, CO, H_2 and unburned hydrocarbons.

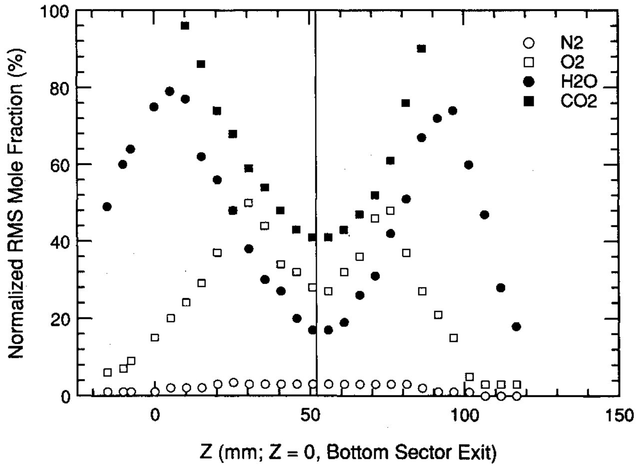


Fig. 7 Normalized rms mole fraction profiles of selected major species. Operating conditions are the same as in Fig. 4.

regime. As a first step, a room temperature cell has been built with quartz windows to allow optical access at pressures of up to 10 atm. Raman signal is expected to increase linearly with pressure since the signal is proportional to the number density of the molecules of the species probed. Figure 10 shows the measured Stokes Raman signal of nitrogen and oxygen in room air in the cell at pressures of up to 8 atm. The signal increases linearly and suggests that the Raman diagnostics should have an improved signal-to-noise ratio at elevated pressures. Anticipated increase in the amount of soot at elevated pressures could adversely affect this signal-to-noise ratio. A high-pressure rig with optical access is currently being built to allow Raman measurements at elevated pressures with combustion.

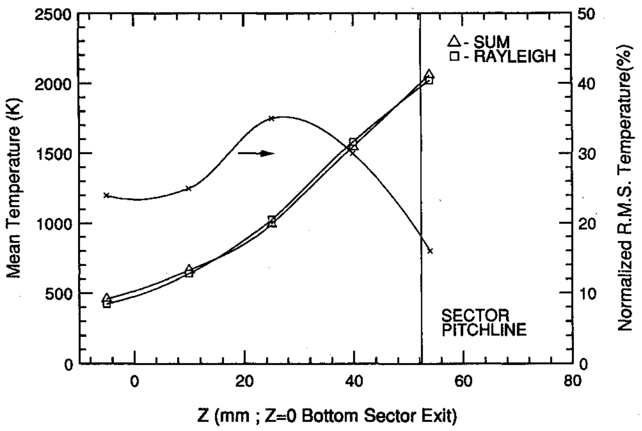


Fig. 8 Mean and rms temperature profiles at sector exit. Airflow = 0.45 kg/s; fuel = kerosene; overall equivalence ratio = 0.21, air preheat temperature = 620 K.

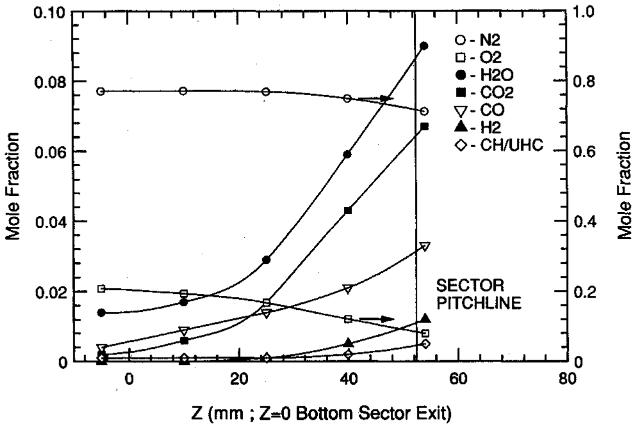


Fig. 9 Mean mole fraction profiles of major species. Operating conditions are the same as in Fig. 8.

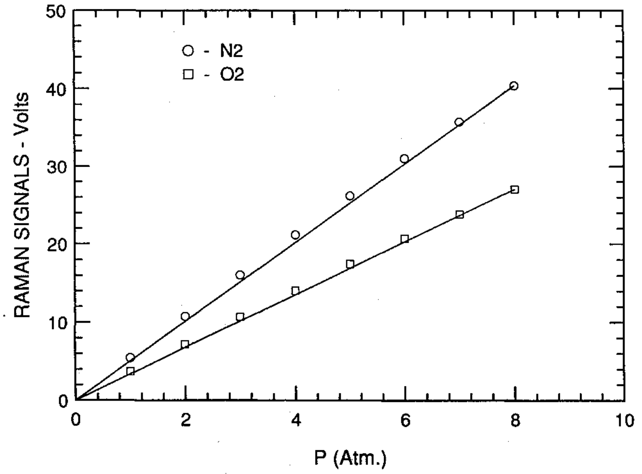


Fig. 10 Raw Raman signals as a function of pressure in a high-pressure cell at room temperature.

Conclusions

The Raman system has been successfully applied to the exit plane of a combustor sector to make temperature and scalar flowfield measurements with both natural gas and liquid fuel (kerosene). Minimal interference from flame-generated incandescence and laser-induced fluorescence was observed. This interference was corrected for using the procedure developed with laminar CH_4/CO flame in an earlier study.[16] The mean temperature measurements agree well with corrected thermocouple data in the flame at the same operating conditions. The temperature data obtained by the two different methods of the sum of mole fractions and Rayleigh scattering also agree reasonably well. The rms temperature profiles show significant temperature fluctuations of up to 12 and 16% at the centerline in the natural gas and kerosene flames, respectively. This information cannot be obtained by thermocouples. These fluctuations are larger than expected and are believed to have an adverse effect on the overall efficiency of the system and on turbine heat transfer due to the hot streaks.

Measured mean profiles of major species at the sector exit with both natural gas and kerosene show expected trends with the reaction products peaking in the center of the flame at values of 6 and 14% for carbon-dioxide and water, respectively. Up to 6% of unburned oxygen and total unburned hydrocarbons of less than 2% consisting of carbon-monoxide and hydrogen and minimal amounts of unburned hydrocarbons are detected in the center of the flame with natural gas. Higher values are measured in the kerosene flame which has a longer flame brush. Normalized rms profiles of the major species show the expected trends. The data is useful in helping quantify the performance of the combustor and providing good quality data base for computational code validations at realistic operating conditions.

Preliminary results obtained in a room temperature cell show that the Raman signal increases linearly with pressure, as expected. Further work is required to make Raman measurements applicable at more practical operating conditions.

Acknowledgments

The technical expertise of Frank Haller made this work possible. The author is grateful to Robert W. Dibble for consultations on the Raman system. Support provided by Ramani Mani and Will Dodds (GEAE) and helpful technical discussions with Jayesh Mehta, Paul Heberling, and Dave Burrus of GE Aircraft Engines are also gratefully acknowledged.

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