Title
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Publication Date
2005-10-27

Western States Section/Combustion Institute 2005 Fall Meeting
Stanford University (Palo Alto, California)
Paper 05F-2

A Comparison of Infrared Light Emitting Diodes (IR-LED) versus Infrared Helium-Neon (HeNe) Lasers for Tomographic Reconstruction of Mean and RMS Fuel Concentration in Combustors

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ABSTRACT

In lean premixed combustion systems, inadequate mixing of the fuel and air, prior to combustion can cause unnecessarily large pollutant emissions. Measuring the extent of mixing of fuel into air is often difficult, since combustion in lean premixed gas turbines takes place at high pressures, often making optical access to the combustion area limited. In addition, the pressure broadening of the molecular absorption lines renders the spectrally narrow line associated with a laser light source less useful. This paper studies some of the problems in determining the extent of mixing of the fuel into air in these lean premixed combustion systems. The focus of this paper is the use of an infrared light emitting diode (IR-LED) to quantitatively measure fuel concentration in a lean premixed gas turbine. The IR-LED emits radiation over a wide wavelength range compared to a laser, meaning that the development of an absorption coefficient to relate the fuel concentration to the absorption of the IR-LED radiation is not as direct as developing the absorption coefficient for the absorption of laser light. Controlled experiments were performed where the pressure, path length and fuel concentration were varied and the effects of these three parameters on the absorption of radiation from the IR-LED were studied. A broad band absorption coefficient was developed relating the absorption of light from the IR-LED to the fuel concentration. This broad band absorption coefficient was found to be in good agreement with calculated coefficient values. Experiments were performed on a lean premixed gas turbine combustor modified for line-of-sight optical access. The concentration profile of this high pressure combustor was found by tomographic reconstruction from line-of-sight absorption measurements using the IR-LED. We demonstrated that the IR-LED can be used for quantitative measurements of the fuel concentration for high pressure systems.

INTRODUCTION

Visible light emitting diodes (LEDs) are very common, but LEDs have only recently become available in the infrared (IR). These IR-LEDs are available in various IR bands for CO2, CO, and including a band centered at a wavelength of 3.3 μm, where hydrocarbons have absorption features. UC Berkeley has had success in quantifying hydrocarbon concentration by using a 3.392 μm He-Ne laser as an optical probe. It may be possible to replace the glass tube laser with a solid state 3.3 μm IR-LED. Previous experiments using broad band sources for determining gaseous fuel concentration from IR absorption measurements include the work of Beckendorf

(1997), and Koenig and Hall (1997), who used a broadband IR source (a glowing wire in a quartz tube) with a bandpass (BP) filter. The advantages of IR-LEDs over use of the IR He-Ne laser are increased ruggedness, reduced size, the ability to modulate the LED at approximately 100 kHz, and lower cost (currently IR-LEDs are about $400 each versus $1500 each for the IR He-Ne Laser; the price of the IR-LED could come down as visible LEDs are less than a dollar). Experiments were carried out using a 3.3 μm IR-LED. The test setup for these experiments is given in Figure 1, and the experiments are described in the next section of the paper. Disadvantages of the IR-LED will be discussed below, including lower power (200micro-Watts) and beam divergence.

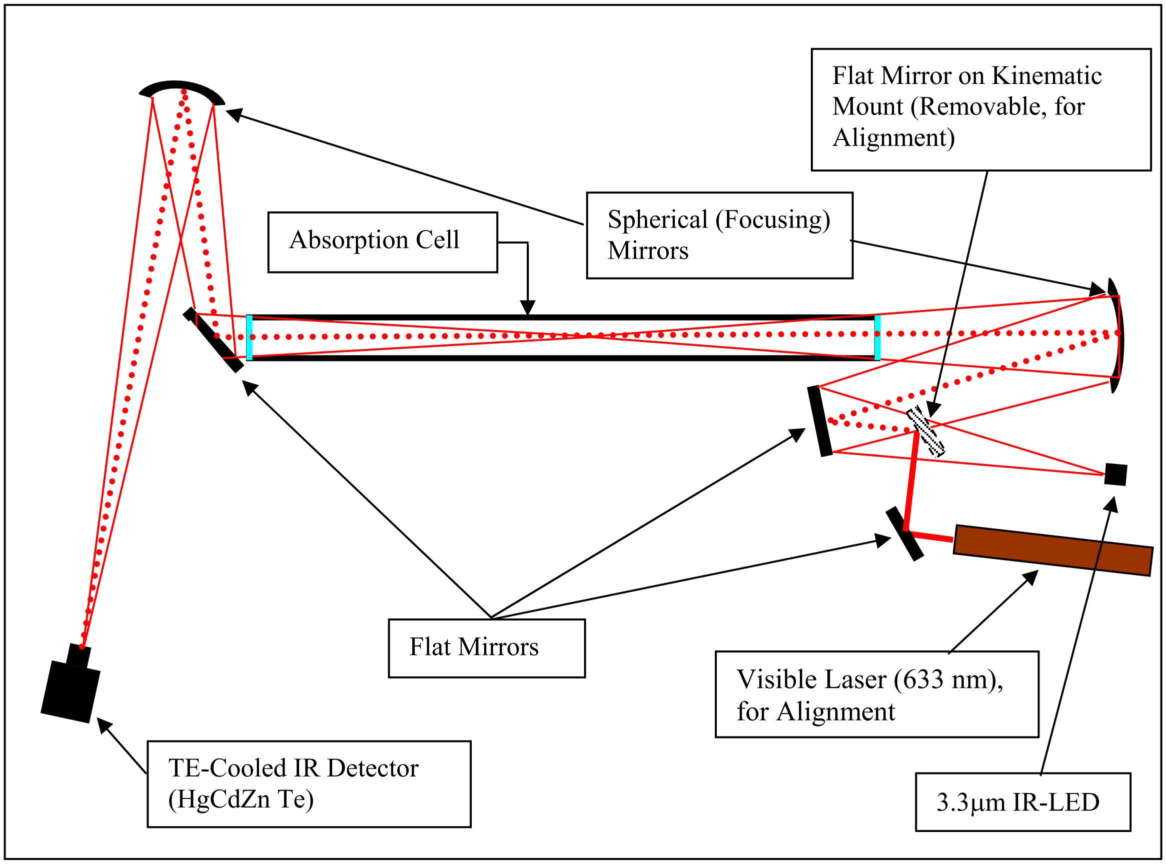

Figure 1: Schematic of IR-LED test stand. The He-Ne laser (633nm) ensures proper alignment of the IR-LED.

QUANTIFYING METHANE FUEL CONCENTRATION USING AN IR-LED

Experiments were carried out using a 3.3 μm IR-LED with a 66 cm path length at various cell pressures to determine the effect of pressure on the overall transmission of light from the IR-LED, through various concentrations of methane in nitrogen. Shown in Fig. 1, focusing mirrors reduced the effect of beam divergence, as represented by the change in measured IR-LED radiation with distance (see Fig. 1). The absorption cell shown in Fig. 1 was a vacuum-tested cylinder with sapphire windows on either end. The sample gases were passed through the absorption cell at controlled pressures. A visible laser (at 633 nm) was used for alignment purposes. As can be seen in Fig. 1, a flat mirror on a removable kinematic mount was used to make the visible laser beam collinear with the center of the solid angle of IR-LED radiation.

Once the IR-LED was made collinear with the visible laser, the remainder of the system was aligned with the visible laser. The cell has a relatively long path length, assuring that significant (≈ 50%) attenuation of the IR-LED light occurs. For measuring the IR-LED radiation with such a long path length, a chopper wheel was used with a phase-lock amplifier (Stanford Research Systems Model 530). This allowed for measurement of very low levels of radiation from the IR-LED (the phase-lock amplifier filters out all components of the detector signal that are not near the frequency of the chopper wheel, and amplifies components of the signal that are close in frequency to that of the chopper wheel; in this way, very small signals can be extracted in spite of large levels of noise).

Once the system was aligned, methane gas was passed through the absorption cell at various concentrations and cell pressures. The first set of experiments was performed with 5% methane in nitrogen and with 100% methane. These experiments were then repeated with a bandpass (BP) filter (OCLI, USA, model NO3399-4X) placed in front of the detector. Fig. 2 gives a spectral scan for the IR-LED together with a spectral scan for the BP filter employed (Krier, 2000).

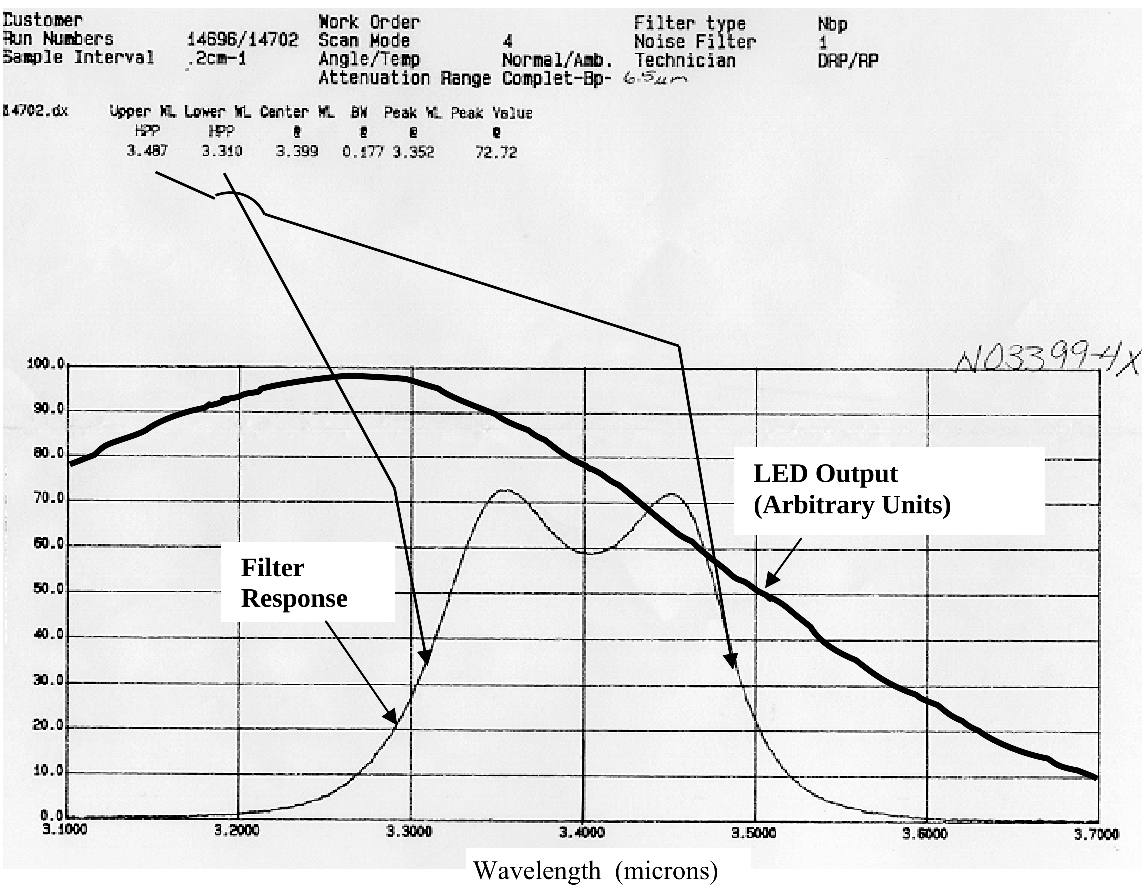

Figure 2: Spectral scan for OCLI Model NO3399-4X, BP filter used in IR-LED setup, with IR-LED output superimposed (Krier, 2000). Vertical Axis is Transmittance (%), see eq.(1). (Upper Wavelength = 3.487 microns, Lower Wavelength is 3.310 microns, Center Wavelength = 3.399 microns, bandwidth = 0.177 microns, Peak Wavelength = 3.352 microns, Peak Value is 72% Transmission)

Transmittance (T) is defined in equation 1:

$$T = \frac{I}{I_0} \qquad (1)$$

where T is the transmittance, I the intensity and I_o the baseline intensity. The results of transmittance versus cell pressure for the experiments with 5% and 100% methane are given in Fig. 3. The transmittance is lower when the filter is used for a given pressure and methane concentration. The reduction in transmittance is as expected, since the BP filter essentially reduces the bandwidth of the radiation hitting the detector, making the amount of the radiation absorbed by the methane a higher percentage of the total radiation (methane absorption lines are stronger in the wavelength range from 3.38 to 3.40 microns than they are in the ranges from 3.05 to 3.38 microns and from 3.40 to 3.55 microns). With the use of the BP filter at 1 atm, a sample gas containing 5% methane absorbs 30% of the IR-LED radiation. The amount of light absorbed by methane demonstrates that fuel concentration is measurable with this instrument at air-fuel ratios found in lean premixed gas turbine combustors.

Absorptance is defined in equation 2:

$$a = 1 - T = 1 - \frac{I}{I_0} \qquad (2)$$

where T is the transmittance.

It can also be seen from Fig. 3 that the amount of transmittance decreases with pressure for a given fuel concentration. Fig. 4 shows a portion of the data found in Fig. 3, only plotted on a log scale. The slight deviation from a straight line, shown in Fig. 4, is a consequence of the broadband nature of the IR-LED convolved with the methane absorption lines.

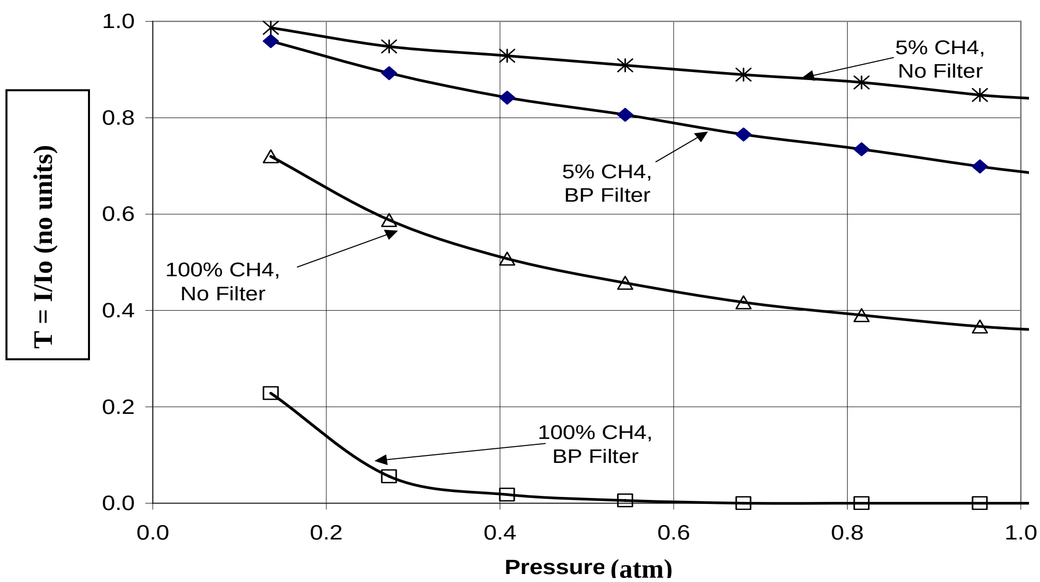

Figure 3: Transmittance versus pressure. Experiments were carried out using a 66 cm absorption cell with 5% and 100% methane using a 3.3 μm IR-LED with and without a BP filter.

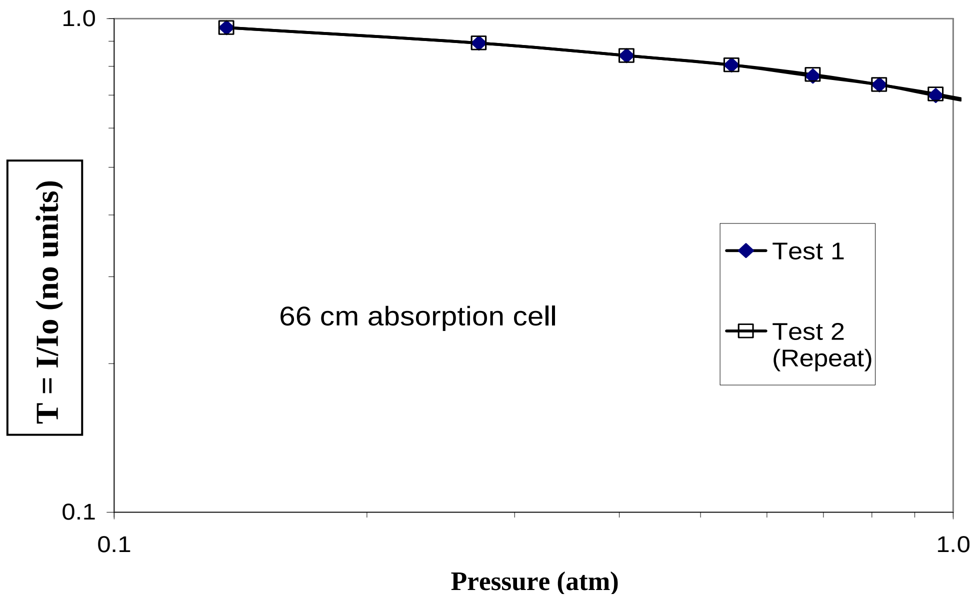

Figure 4: Log Log plot of Transmittance versus pressure, 5% methane using a 3.3 μm IR-LED with a BP filter, cell path length is 66 cm.

Several sets of computations were done exploring the absorption spectrum of methane mole fractions at high pressures. These calculations used a software program called MOLSPEC (version 2.3) – a molecular spectroscopy calculation program that uses the HI-TRAN database to calculate absorption spectra for various gas mixtures (Offenhartz, 1992). Fig. 5 and 6 illustrate the variation in the methane absorption spectrum with pressure. More results are in the PhD thesis of Girard (Girard, 2003). Unlike the laser, which is at 3.39 microns, the IR-LED transmission (using the BP filter band) is approximately from 3.3 to 3.5 μm.

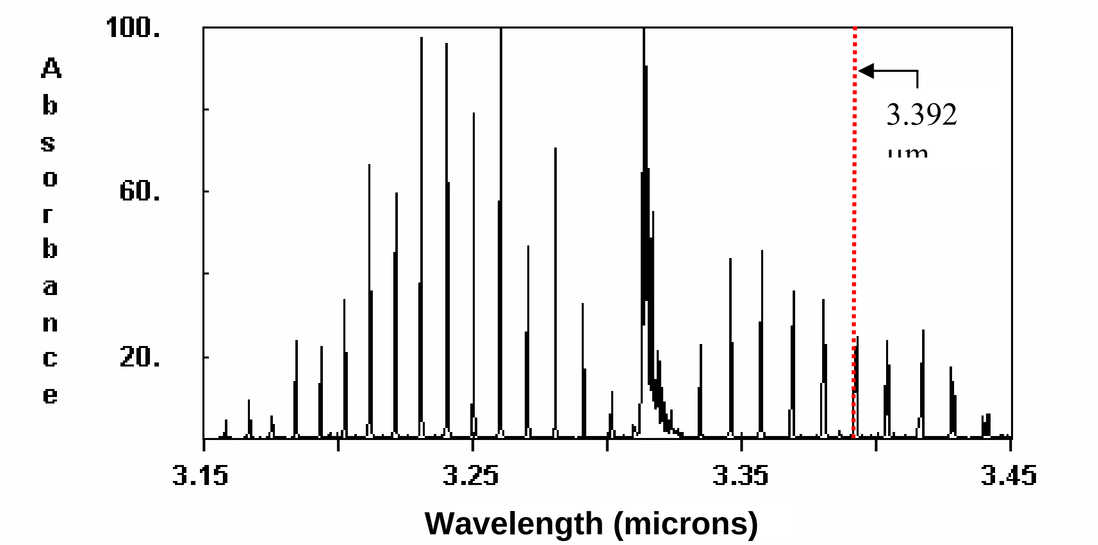

Figure 5 Absorbance calculated using MOLSPEC at P = 1.0 atm, 5% CH_4 in N_2, 66 cm path length. The HeNe laser line is at 3.392 microns.

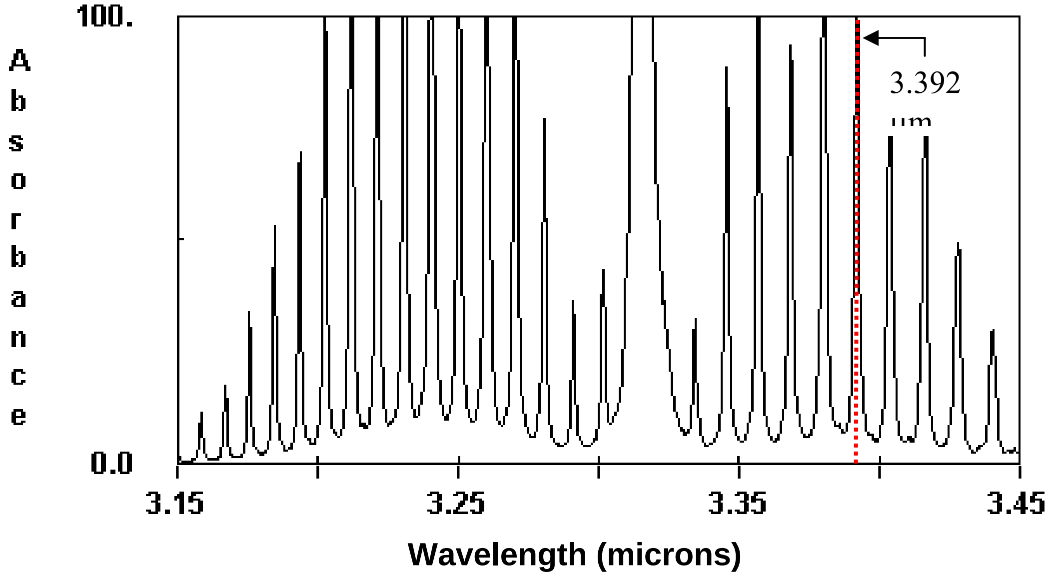

Figure 6 Absorbance calculated using MOLSPEC at P = 10 atm, 5% CH_4 in N_2, 66 cm path length.

The output shown in Figures 5 and 6 is given in terms of Absorbance (A). Absorbance, A, is defined in equation 3 (Atkins, 1994):

$$A = -\log\left(\frac{I}{I_0}\right) = -\log(T) \tag{3}$$

Fig. 5 and 6 show that the absorbance of light at these wavelengths by methane increases with pressure. The methane absorption lines in Fig. 5 and 6 are pressure broadened due to the relatively high pressure (Simon and Nichols, 1997). With a typical 3.392 μm He-Ne laser, nearly all of the laser light would be absorbed under the conditions shown in Fig. 5 and 6, due to the long path length (66 cm) for 5% methane (Yoshiyama et al., 1996). With the IR-LED, however, the transmittance versus concentration is higher, meaning that the increased pressure should make quantifying the methane concentration easier (because a measurable amount of radiation would reach the detector).

Based on the results of MOLSPEC (Offenhartz, 1992) calculations, an absorption coefficient for the monochromatic laser light can be generated. This relation is shown in equation 4, for the case of constant concentration across the path length of the radiation,

$$X_{CH_4} = -\frac{\ln(I / I_o)}{(\alpha \cdot L \cdot P_{abs})} \tag{4}$$

where, as previously, I denotes intensity of laser radiation, I_o the initial (un-attenuated) laser radiation intensity, α the absorption coefficient for the given fuel (*atm*$^{-1}$*cm*$^{-1}$), L is the path length of absorption (*cm*), P_{abs} the absolute pressure (*atm*), and X_{CH4} the fuel mole fraction.

Typically the absorption coefficient α for laser absorption measurements is a measure of the amount of laser light at a given wavelength that will be absorbed by the molecules of a certain compound. In order to apply equation 4 to broad-band nature of IR-LED radiation, the absorption coefficient α must be convolved over the wavelength range of the IR-LED radiation, the bandpass filter, and the detector sensitivity. The broad band absorption coefficient α_{BB} was found by taking the MOLSPEC output, finding the absorption coefficient at closely spaced wavelengths, and convolving the values subject to a weighting factor. The weighting factor was used to compensate for the fact that the IR-LED does not emit radiation with a flat wavelength distribution over its wavelength range, as seen in Fig. 2 and 7. Rather, the peak radiation is at the center wavelength of 3.3 μm, with a FWHM band of roughly 10% of 3.3 microns or 0.33 microns. The tapering off of the IR-LED radiation at wavelengths other than 3.3 μm is depicted in Fig. 2. Fig. 7 shows the methane absorbance at 10 atm (reproduction of Fig. 6) with the BP filter spectral response and the IR-LED radiation versus wavelength superimposed. In obtaining the broad band absorption coefficient, the IR-LED radiation was convolved with the transmittance of the BP filter at each wavelength, and convolved with methane absorbance data from MOLSPEC.

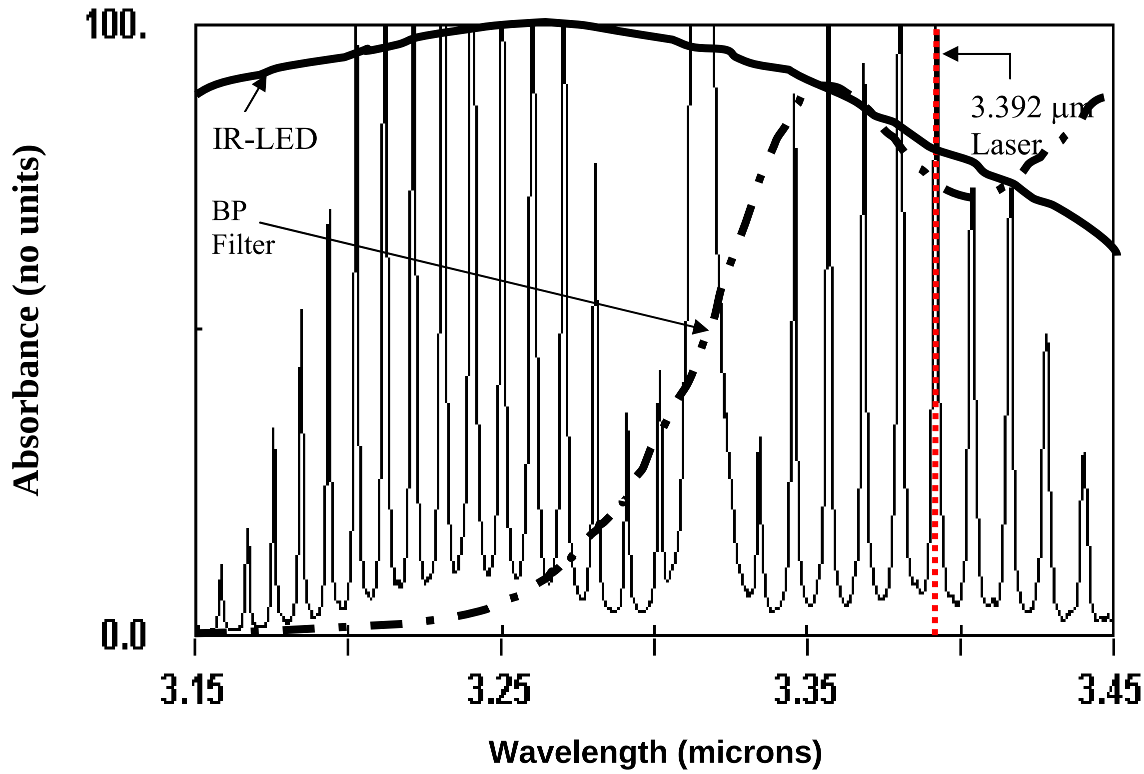

Figure 7: Absorbance calculated using MOLSPEC at P = 10 atm, 5% CH_4 in N_2, 66 cm path length, with BP filter transmission spectra and IR-LED radiation superimposed.

Equation 5 gives the convolution integral for the IR-LED radiation, the BP filter transmission and the MOLSPEC data for methane absorbance.

$$\alpha_{BB} = \frac{\ln\left[\dfrac{\int_{\lambda_0}^{\lambda_1} W(\lambda) \bullet T_{BP}(\lambda) \bullet T_{MS}(\lambda) \bullet D(\lambda) \bullet d\lambda}{\int_{\lambda_0}^{\lambda_1} W(\lambda) \bullet T_{BP}(\lambda) \bullet D(\lambda) \bullet d\lambda}\right]}{L \bullet X_{CH_4} \bullet P_{abs}} \tag{5}$$

Where λ is the wavelength, $T_{MS}(\lambda)$ is the wavelength-dependent transmittance of methane from MOLSPEC, $T_{BP}(\lambda)$ is the wavelength-dependent transmittance of the BP filter, $D(\lambda)$ is the spectral response of the detector (approximated as constant for the range of 3.2 µm to 3.5 µm), and $W(\lambda)$ is the wavelength-dependent weighting factor for the intensity of radiation from the IR-LED, which emits light between λ_0 and λ_1 . This weighting factor $W(\lambda)$ is used because the intensity of radiation from the IR-LED is not constant at each wavelength, as can be seen from Fig. 2 and 7. Equation 6 defines the weighing factor as

$$W(\lambda) = \frac{I(\lambda)}{\int_{\lambda_0}^{\lambda_1} I(\lambda) \bullet d\lambda} \tag{6}$$

The broad band absorption coefficient α_{BB} for the IR-LED was found using the MOLSPEC results at several pressures. The resulting broad band absorption coefficient is given in Fig. 8.

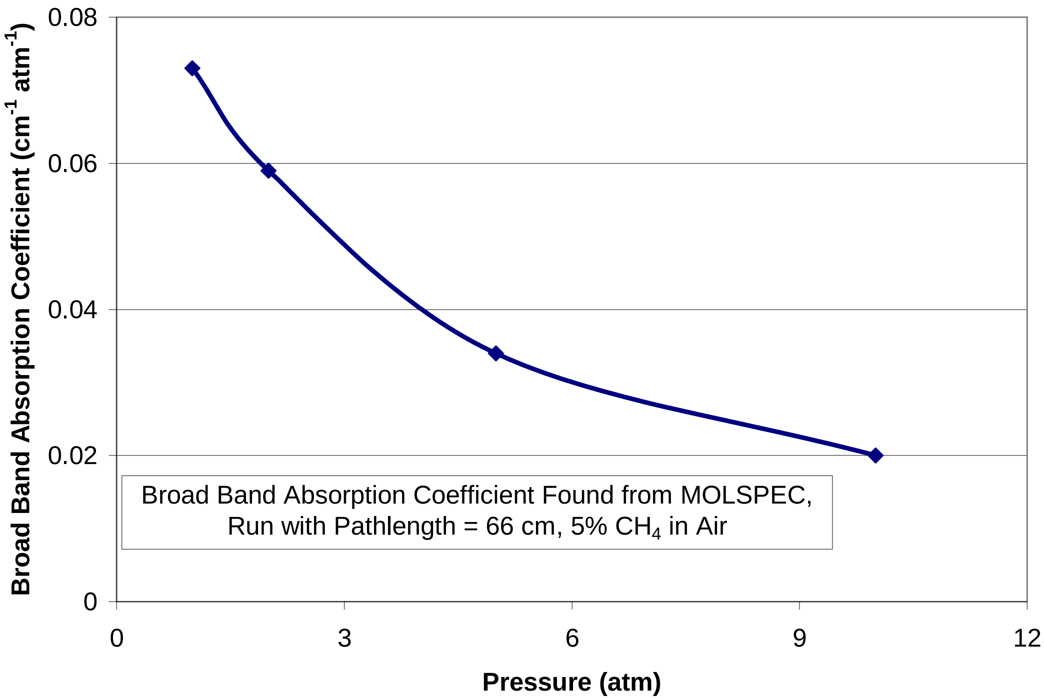

Figure 8: Broad band absorption coefficient (Eq.(5) from MOLSPEC results versus pressure. The simulation was for a 66 cm path length with 5% methane in air for a 3.3µm IR-LED, with band pass filter as per Fig. 2.

Further experiments were performed at pressures above atmospheric as a test of the accuracy of the calculated broad band absorption coefficient. Fig. 9 gives the results of the high pressure experiments using calibration gases (see Fig. 1). The test gas for the high pressure experiments consisted of calibration gases with varied concentrations of methane in nitrogen. A further experiment was done with methane in air instead of methane in nitrogen to test the influence of the diluent on the transmission of the IR-LED radiation. As can be seen from Fig. 9, the amount of transmission of the IR-LED radiation was measurably dependent on the concentration of the methane. Further, one should note from Fig. 9 that the methane-in-air mixture showed negligible difference in transmission of IR-LED radiation versus the methane-in-nitrogen mixture.

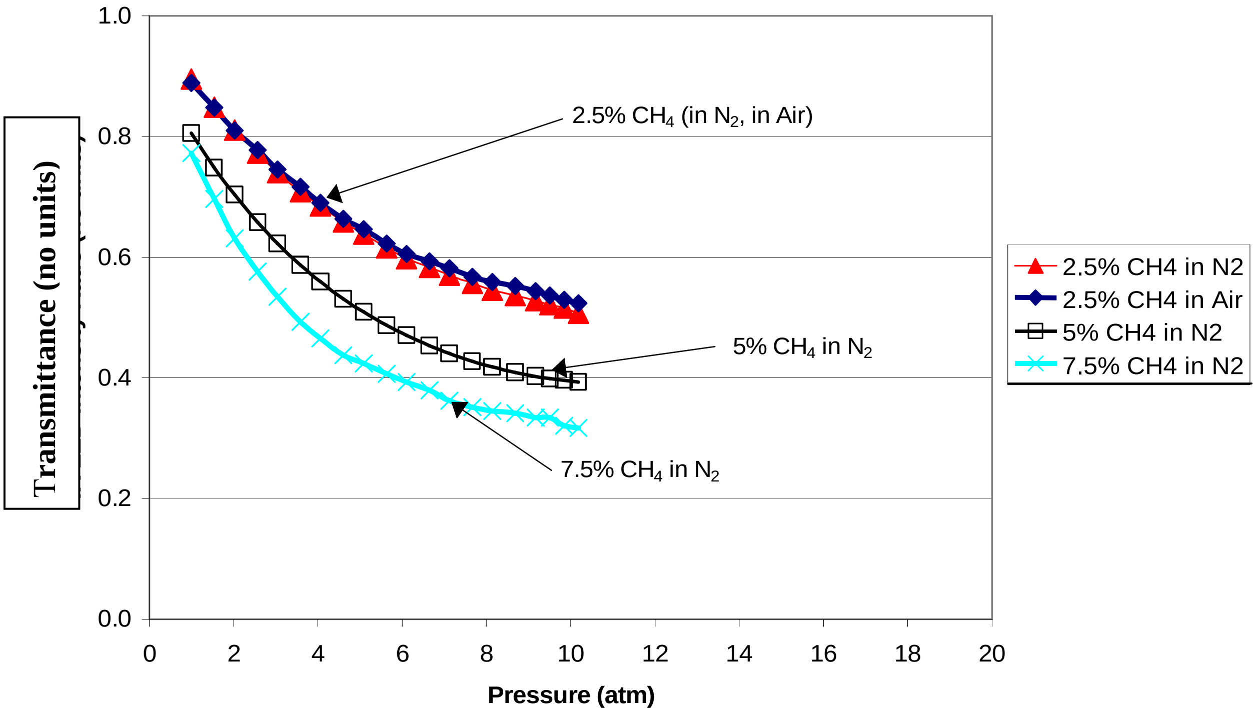

Figure 9: Transmittance versus pressure for a 66 cm absorption cell with varied methane concentrations in N_2 and air using a 3.3μm IR-LED.

Additionally, the broad band absorption coefficient α_{BB} has been found experimentally. The experimentally determined broad band absorption coefficient versus partial pressure of methane for several concentrations is given in Fig. 10. The broad band absorption coefficient α_{BB} is found using equation 4, where the fuel volume fraction, pressure, temperature and path length are known and the intensity ratio I/I_o is measured; thus, leaving the broad band absorption coefficient α_{BB} as the only unknown. Fig. 10 also shows the computationally determined broad band absorption coefficient (found using MOLSPEC results). The experimental results in Fig. 10 show that the relationship between the broad band absorption coefficient and the partial pressure has only a small dependence on the absolute pressure. The absolute pressure at each given methane partial pressure is different for each of the lines of experimental results in Fig. 10.

For example, at a methane partial pressure of 0.2, the point from data with 2.5% methane was measured at a pressure of 8.0 atm, while the point from data with 7.5% methane was measured at a pressure of 2.7 atm. The small dependence on absolute pressure of the relation between the broad band absorption coefficient and the partial pressure of methane can be seen by the slightly different slopes of the data measured at different fuel volume fractions in Fig. 10. The value of the calculated broad band absorption coefficient is in good agreement with the experimental results in Fig. 10, but the slope of the calculated broad band absorption coefficient versus partial pressure is slightly steeper, showing that the calculated broad band absorption coefficient has a stronger dependence on the partial pressure of the fuel than the experimental results show.

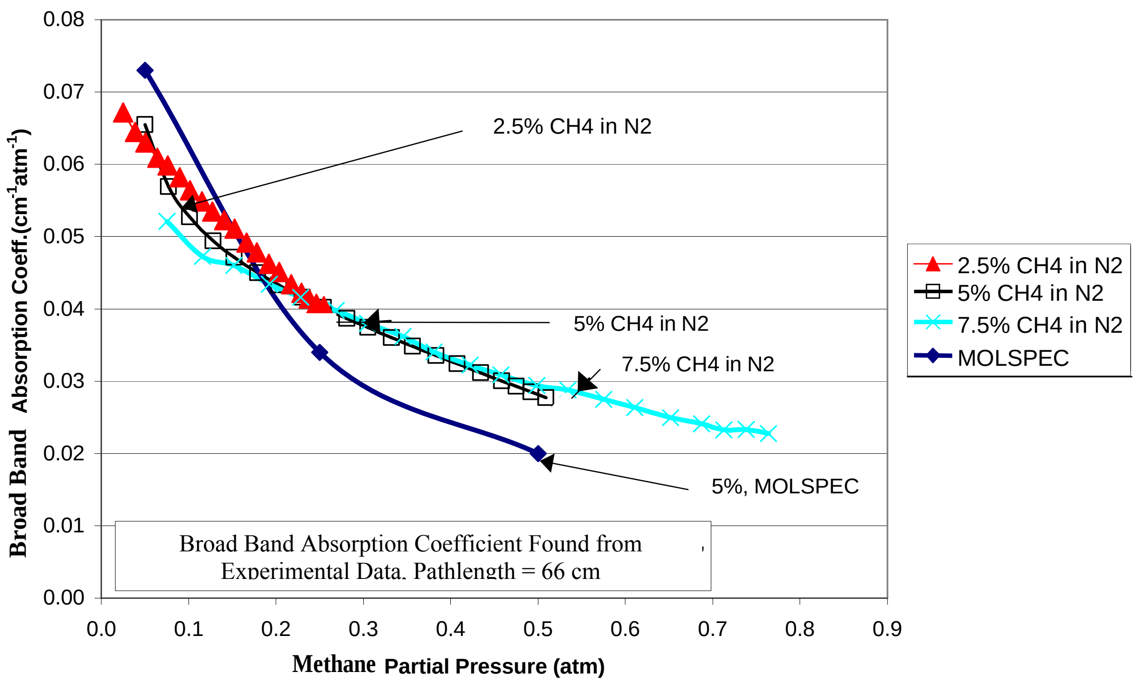

Figure 10: Broad band absorption coefficient versus partial pressure of methane from experiments with a 66 cm absorption cell with varied methane concentrations in N_2 using a 3.3μm IR-LED. The total pressure was varied from 1 atm to 10 atm.

Fig. 11 ,below, shows the broad band absorption coefficient for the IR-LED on the same graph with the absorption coefficient for a 3.392 μm He-Ne laser. The trends of the absorption coefficients for the laser and for the IR-LED versus pressure are similar. The magnitude of the broad band absorption coefficient is about 100 times smaller than the absorption coefficient of the laser. The lower magnitude of the broad band absorption coefficient means that the IR-LED can be used for measurements at pressure-path length combinations 100 times larger than the IR laser before the gas becomes essentially opaque to the radiation. Thus, for applications where the pressure is high and path lengths are long, the IR-LED would become the preferred instrument for concentration measurements.

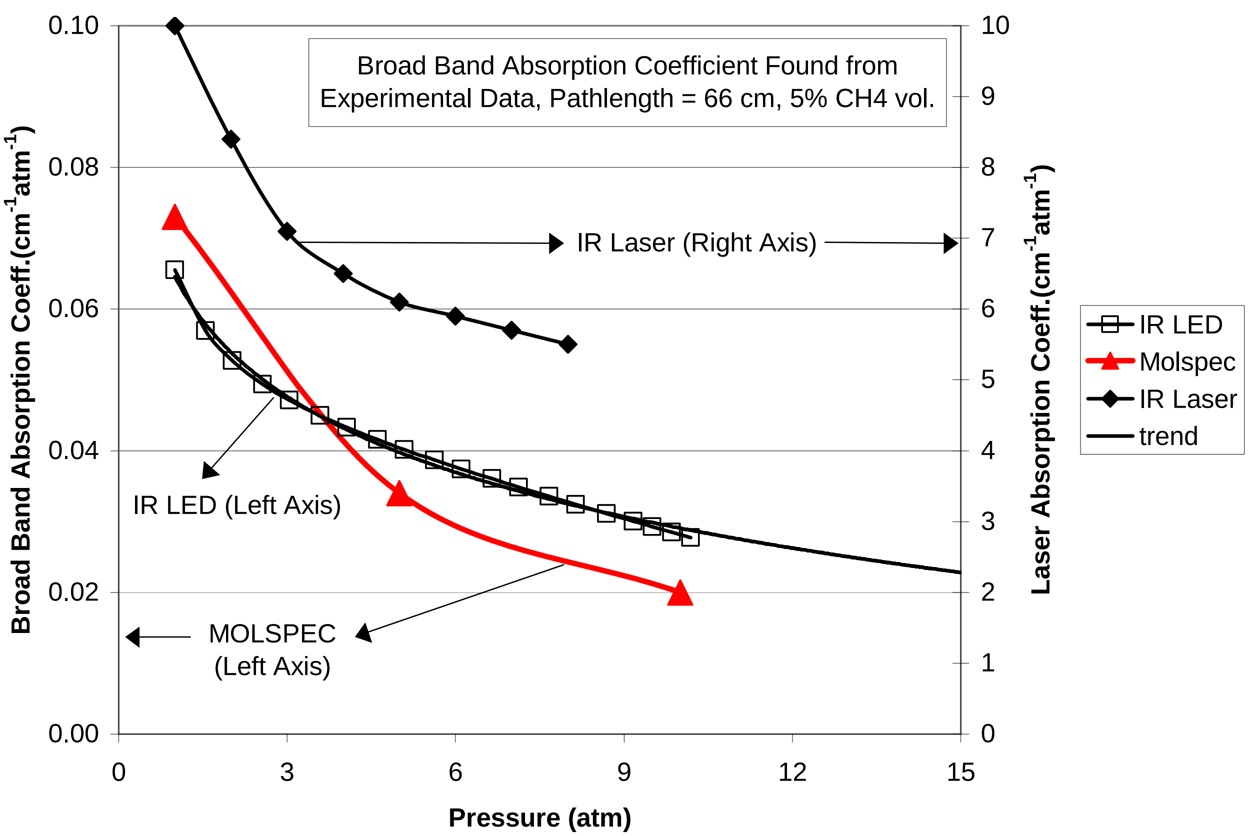

Figure 11: Comparison of 3.392 μm IR laser absorption coefficient and broad band absorption coefficient from a 3.3μm IR-LED versus pressure. The IR laser results are from Perrin and Hartman (1989). IR-LED experimental results were obtained with a 66 cm absorption cell using 5% methane in N_2. The MOLSPEC results are also for the IR-LED and used data from Fig. 5 and 6.

IR-LED MEASUREMENTS ON Lean Pre-mixed (LPM) GAS TURBINE

Experiments using the IR-LED were performed at Solar Turbines, Inc. (San Diego, CA) in one of their pressurized test cells to characterize the mixing performance of a production lean premixed fuel injector. The experiments were performed on a standard LPM gas turbine fuel injector. The experimental setup is given in Fig. 12. The focusing optics are not shown in Fig. 12, for simplicity, but were the same as those shown in Fig. 1.

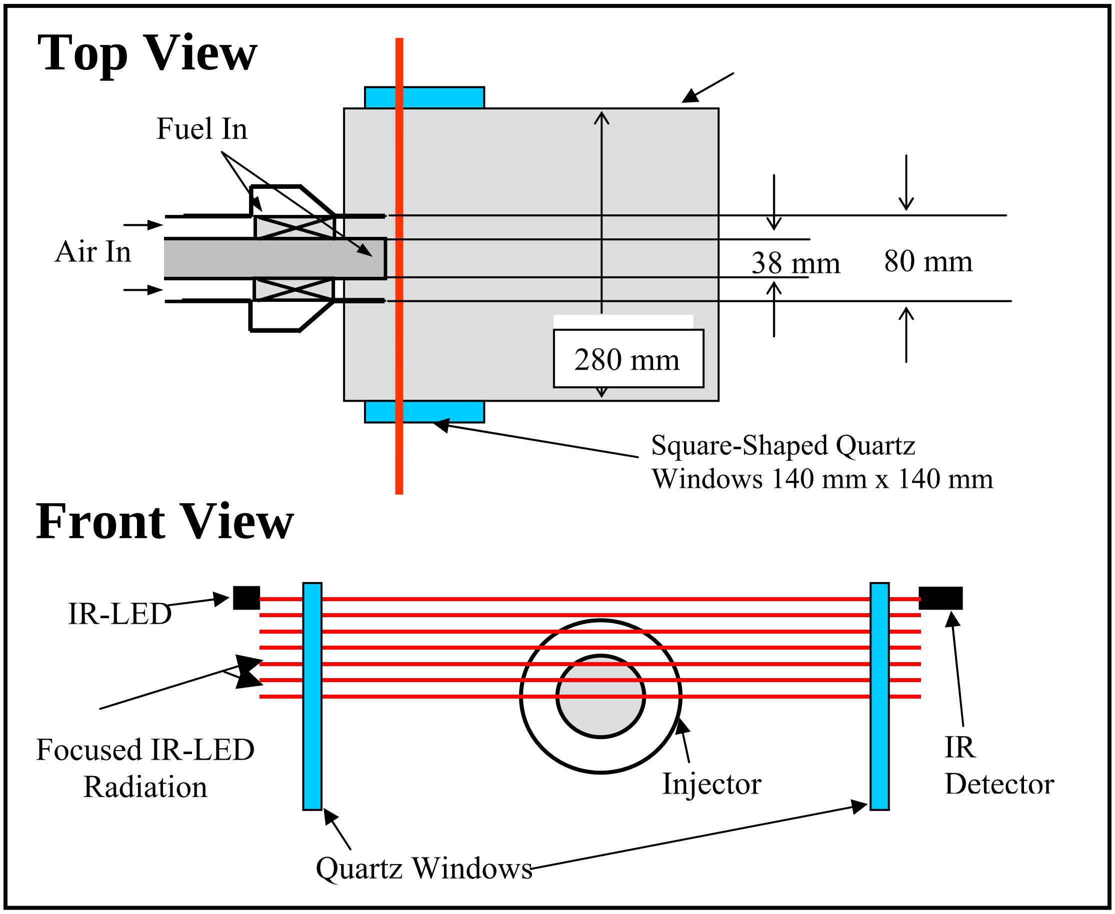

Figure 12: Test setup for experiments on an optical access gas turbine combustor. Note that the focusing optics are not included in the schematic but were similar to those shown in Fig. 1.

The results are given in Fig. 13. With our past experimental results showing that the IR-LED absorptance by methane is improved at higher pressures, we decided that performing experiments at these high pressures would be ideal for the IR-LED. Line-of-sight (LOS) measurements were performed on the optical access combustor at an axial distance of approximately 2 cm from the fuel injector exit plane. The experiments were performed at a combustor pressure of 7.5 bars with an average fuel volume fraction of 6%. The LOS absorption measurements from the IR-LED were converted to a fuel volume fraction profile using a reconstruction algorithm (see Girard, 2003 for more details on the reconstruction method).

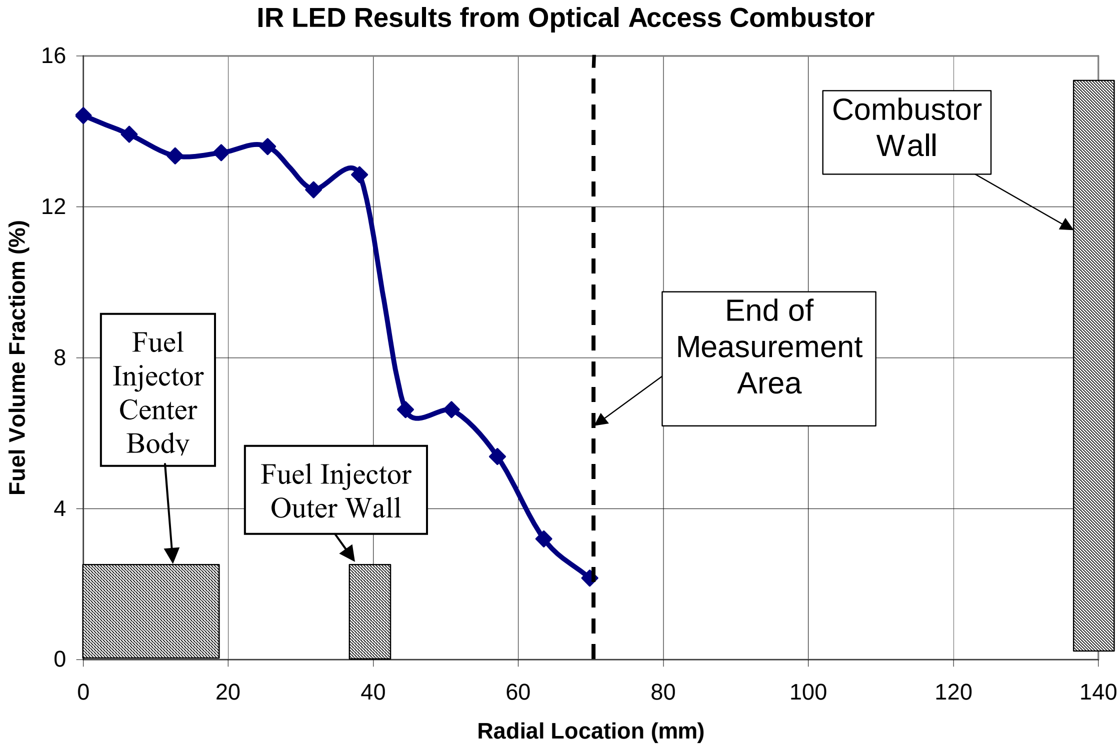

Figure 13: Radial fuel volume fraction profile in optical access gas turbine combustor.

The results seen in Fig. 13 are an example of the use of an IR-LED to quantitatively measure the fuel volume fraction in a high pressure gas turbine combustor.

SUMMARY

The use of an IR-LED for quantitative gaseous fuel concentration measurements has been studied. The IR-LED emits radiation over a fairly wide wavelength range (Approximately 3.2 to 3.5 μm when used with a BP filter), so that the development of an absorption coefficient to relate the fuel concentration to the absorption of the light emitting diode radiation is not as direct as the development would be for the absorption of laser light. Controlled experiments were performed where the pressure, path length and fuel concentration were varied to study the effects of these three parameters on the absorption of radiation from the IR-LED. From these experiments a broad band absorption coefficient was developed relating the absorption of light from the light emitting diode to the fuel concentration. This broad band absorption coefficient was in fairly good agreement with a calculated broad band absorption coefficient for the light emitting diode found using the MOLSPEC, a molecular spectroscopy software package. Experiments were performed on an LPM gas turbine combustor using the IR-LED. The combustor had been modified to allow optical access. The concentration profile inside of this high pressure combustor was reconstructed tomographically from LOS absorption measurements using the IR-

LED. The LPM combustor experiments demonstrated that the IR-LED can be used for quantitative measurements of the fuel concentration for high pressure systems.

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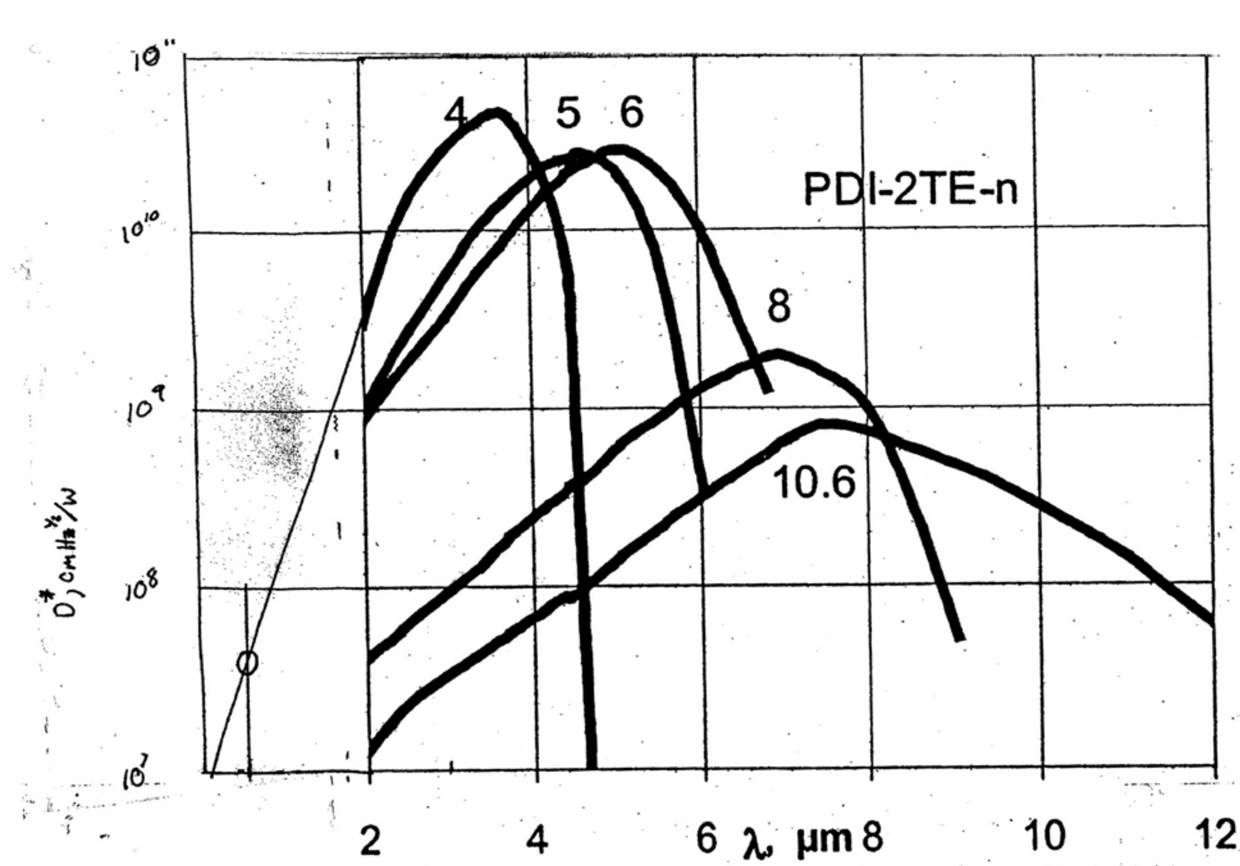
Appendix A. IR Detector response function.

Curve Number 4 is the detector used in this experiment. Thermoelectrically cooled. D* has units of (cm-Hz^(1/2)/W). Vertical axis from 10^7 to 10^11 (cm-Hz^(1/2)/W)



Appendix B. Characteristics of a typical IR LED analogous to the type used in this experiment.

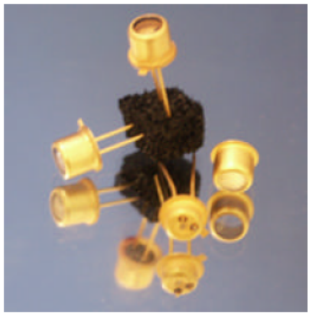
LIGHT EMITTING DIODES 1.6÷4.6 µm

Model LED34 *3.4 µm 24 µW*

•Light Emitting Diodes ***LED34*** are designed for emitting at a spectral range around 3400 nm. Heterostructures (HS) are grown on InAs substrates. The output emission can be modulated by current flowing in a forward direction.

•Light Emitting Diodes ***LED34*** are developed for using in optical gas sensors and medical diagnostics. They have stable output power and lifetime more then 10000 hours.

•Related products: ***LED34*** can be used in optical pair with our photodiodes ***PD36***. Our standard ***LED Driver*** provides power supply of ***LED34*** in two recommended here regimes (Quasi-CW and Pulsed).



Parameters	Min	Typ	Max
Wavelength, µm	3.30	3.40	3.50
FWHM, µm	0.60	0.70	0.80
Optical Power, µW Quasi-CW @ 200 mA Pulsed@1A	 20 320	 24 400	 28 480
Switching Time, ns	10	30	50
Operating Temperature Range, °C	-240÷+50		
Emitting Area, µm	300x300		
Soldering temperature	260 °C		
Package	TO-18		

Recommended regimes of operation