Miniature Infrared Emission Based Temperature Sensor and Light-Off Detector

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Abstract

The drive for higher efficiency and lower pollutant emission has necessitated the use of lean premixed combustion in commercial gas turbine engines. These new combustors have highlighted the importance of monitoring primary zone conditions to optimize emissions and control instability across the entire load range. Efforts to further reduce NO_X emissions will be even more dependent on precise temperature monitoring and combustion control. In addition, the detection of ignition or a flame inside the combustor is needed during start-up and shut down operations.

Commercial temperature sensors based on intrusive thermocouples which can be used in low speed reacting flows are available. However, such intrusive probes (even with very low frequency response) will not survive the harsh conditions present in a high speed gas turbine engine. There are laser based systems such as Raman scattering and laser induced fluorescence which have been used to obtain temperatures in laboratory scale flames. The major limitations of these techniques is that the signal obtained is very weak. The different sources of interference such as radiation from the combustor lining or small particulate in the flame will be much higher than the Raman or LIF signal. The high cost of the powerful lasers, detectors and electronic equipment needed for these measurements as well as the safety issues involved with high energy laser beams preclude their integration into a general purpose sensing and control circuit. Laser and FTIR absorption spectroscopy require sending and receiving ports in addition to lock-in amplification techniques to reduce noise. For temperature measurements a more passive scanning method such as emission spectroscopy is the most suitable means of achieving a low-cost control device.

The thrust of the proposed work is the development of a combustor wall-embedded miniature infrared fiber-optic probe for temperature sensing and light-off detection. The four major features of the fiber-optic probe are: (1) a miniature sensing head (approximately 10 mm) for accurately detecting the presence of a fire, (2) ability to withstand high temperatures and pressures, (3) non-intrusive measurement of the effective temperature of the combustion products in the presence of interference from the combustion liner and particulate, and (4) a high frequency response for effective control of the combustion process.

The proposed technique of infrared emission spectroscopy for flame temperature sensing has been tested using a lean premixed methane flat flame, stabilized on a McKenna Burner. The CO_2 and H_2O concentrations were measured using an intrusive gas sampling probe and subsequent gas chromatography. The temperature was measured using a Pt-Pt/30%Rh thermocouple. The measurements were obtained for the different closely space equivalence ratios of 0.81 and 0.86. The temperature and gas species concentrations were uniform across a 50 mm path.

The spectral radiation intensities leaving the same path were measured using a spectrometer in conjunction with a lead selenide detector. The spectral radiation intensities were obtained from 2.5 μm to 5 μm, with a wavelength resolution of 50 nm. An inverse algorithm was used to obtain the CO_2 and H_2O mole fractions in addition to the temperature. The gas species concentrations obtained by the inverting the infrared emission spectroscopy measurements were within 5% of those obtained using gas chromatography. The adiabatic temperature values for equivalence ratios of 0.81 and 0.86 are 2034 and 2112 K respectively. The temperature measured using the thermocouple was identical (1840 K) for both the flame conditions, and much lower than the adiabatic value. The temperatures obtained from inverting the infrared emission spectroscopic measurements for the two conditions were 1940 and 2011 K respectively. This change in temperature is only 7 K lower than those obtained from the adiabatic calculations. In addition, the lower temperatures are possibly a result of the flame losing heat to the burner by conduction and to the surroundings by radiation, which are not accounted for in the calculations. Therefore, the confidence level in the temperature values obtained are very high.

Based on the preliminary study, the feasibility of utilizing infrared emission spectroscopy to obtain gas species concentrations and to monitor the flame zone temperature is proven. The project will now concentrate on obtaining the infrared emission intensities from turbulent, lean premixed natural gas flames. The high level of turbulence is expected to cause inhomogeneities in the temperature and gas species concentration profiles. Therefore, inversion of the infrared emission spectroscopic measurements will result in Planck-Function weighted temperatures. Calculations show that the Planck-Function weighted temperatures are directly correlated with NO emission indices.

During the proposed project, we will collaborate with three participating industrial members of the ATS program. The proposed infrared fiber-optic probe, after initial development at Purdue University, will be evaluated at the three corporations (*Allison Engine Company, Westinghouse Electric Corporation, Solar Turbines)* by En'Urga Inc.

There are two advantages to the proposed work which will directly benefit control strategies to be employed in lean premixed natural-gas combustion systems: (1) a miniature sensor capable of accurately detecting light-off and measuring the temperature of the gaseous combustion products within a combustor in the presence of interference from the combustor walls and particulate will be developed, and (2) the miniature sensor will be field tested and ready for rapid utilization by the gas turbine industry.

Acknowledgment

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OBJECTIVES

- **Operation of lean-premixed natural gas engines with optimal NO_X emissions require close control of the combustion process.**
- **In a turbulent flame, control variables such as temperature or fuel concentrations fluctuate both with position and time.**
- **The optimal control variable that is correlated with NO_X emission indices in a turbulent premixed natural gas flame is the Planck-Function weighted temperature.**
- **Develop instrumentation to monitor the Planck Function weighted temperature.**

PLANNED INDUSTRIAL COLLABORATION

- **The proposed miniature infrared emission fiber optical probe will be field tested at the experimental facilities of three of the industrial partners of AGTSR consortium.**

- **The three industrial partners in the present project are Westinghouse Power Corporation, Solar Turbines Inc., and Allison Engines Company.**

- **Field testing at the facilities of the other industrial partners of the AGTSR consortium are being pursued.**

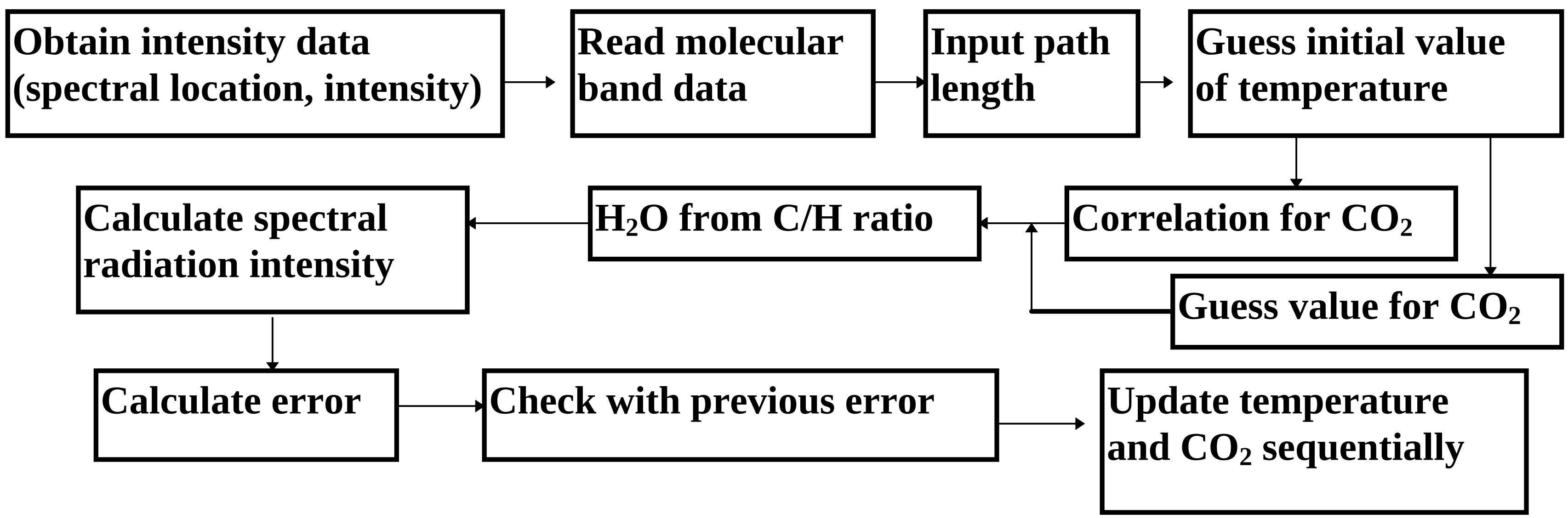
BACKGROUND ON EMISSION SPECTROSCOPY

- **The spectral radiation intensities emitted by the hot gases are measured at several discrete wavelengths in the infrared region.**
- **These intensities are used to obtain quantities of interest such as the temperature or gas species concentrations within flames.**
- **The spectral radiation intensity at one wavelength can be used to obtain the temperature if the gas concentrations are known.**
- **Simultaneous multi-wavelength measurement can be used to infer both the gas concentrations as well as the temperatures.**

MULTI-WAVELENGTH TECHNIQUE

- **Measure the spectral radiation intensities at several wavelengths.**
- **Guess the temperature, species concentrations and effective path length.**
- **Calculate the spectral radiation intensities that would be emitted by the hot gases using RADCAL.**
- **Update the guessed values based on the differences between measured and calculated spectral radiation intensities.**

FLOW CHART FOR TEMPERATURE MEASUREMENT



Converged value obtained at minima of error.

RATIO VS ABSOLUTE TECHNIQUE

Two measures of error between predicted intensity and measured intensity

$$L_2 \text{ norm} \equiv \sum_{j=1}^{N} (I_{\lambda m_j} - I_{\lambda R_j})^2 ; j = 1, N$$

N is the number of wavelengths at which intensities ($I_{\lambda m}$) are measured or predicted ($I_{\lambda R}$).

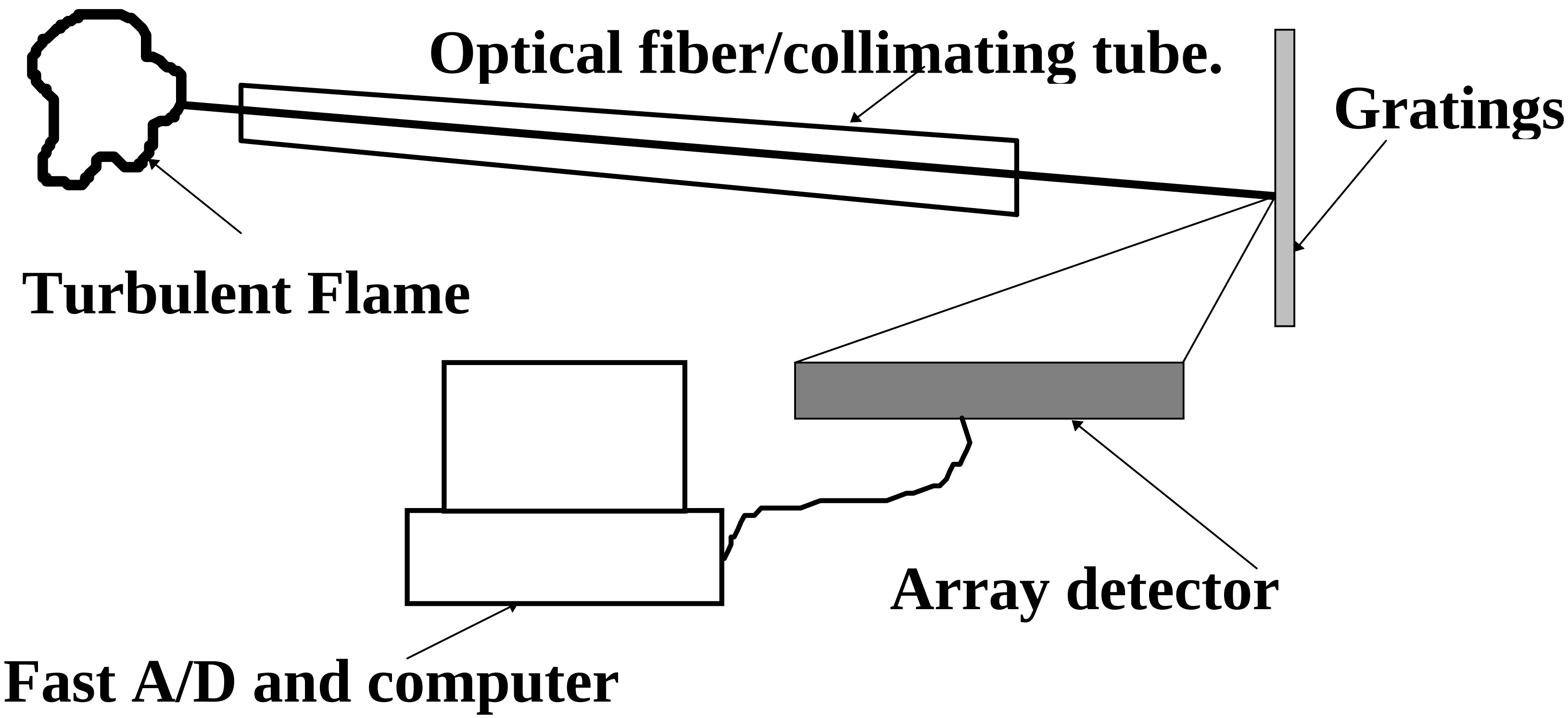
$$R_{err} = \sum_{j=1}^{N} \sum_{k=1}^{N} \left| \frac{I_{\lambda m_j}}{I_{\lambda m_k}} - \frac{I_{\lambda mR_j}}{I_{\lambda m_k}} \right| ; j, k = 1, N$$

Convergence at minima of either L_2 norm or R_{err}.

MEASUREMENT REQUIREMENTS

- **A well defined measurement volume is desirable.**
- **Accurate spectral locations and band widths are needed.**
- **Calibration should be performed using a blackbody.**
- **Long term drift effects have to be considered.**
- **Multiple wavelength measurements for the same volume should be obtained simultaneously.**

PROPOSED MEASUREMENT OF INFRARED INTENSITY



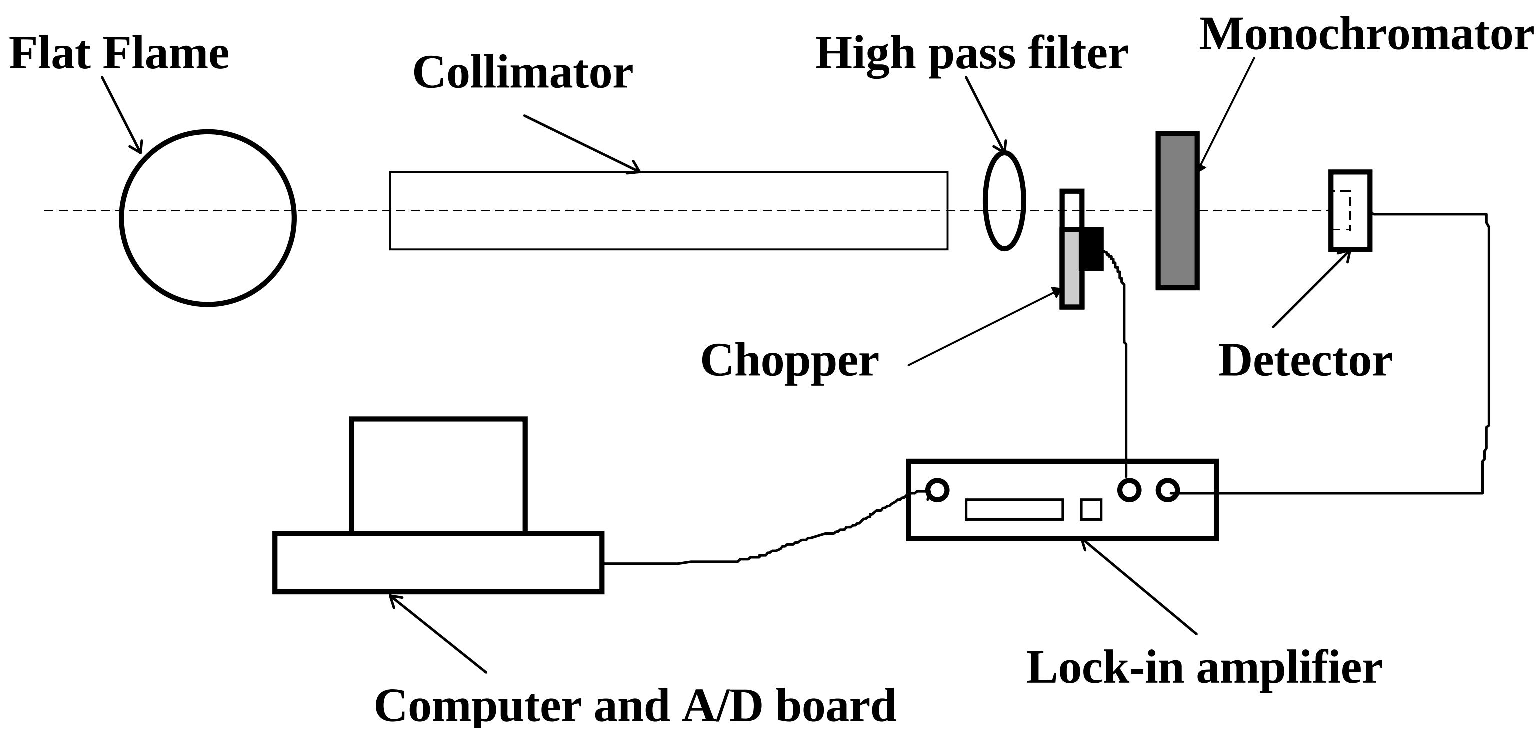
DIFFICULTIES ASSOCIATED WITH INVERSION

- **The number of variables for most general applications include H_2O and CO_2 concentrations, temperatures, soot volume fractions and path lengths.**

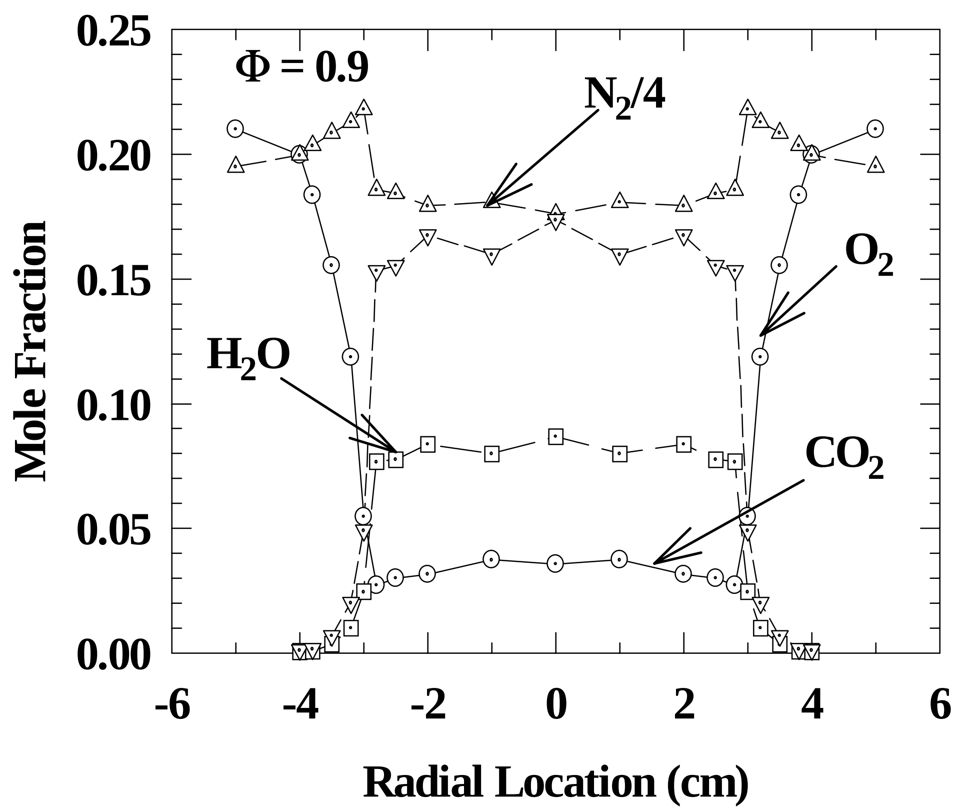
- **Computationally very intensive to calculate the spectral radiation intensities for all possible values of engineering interest (i.e. 200 K < T < 3000 K, $0.0 < X_{CO2} < 0.2$, $0.0 < X_{H2O} < 0.2$, 0.0 ppm < f_v < 40 ppm)**

- **Path length is not homogeneous in some applications.**

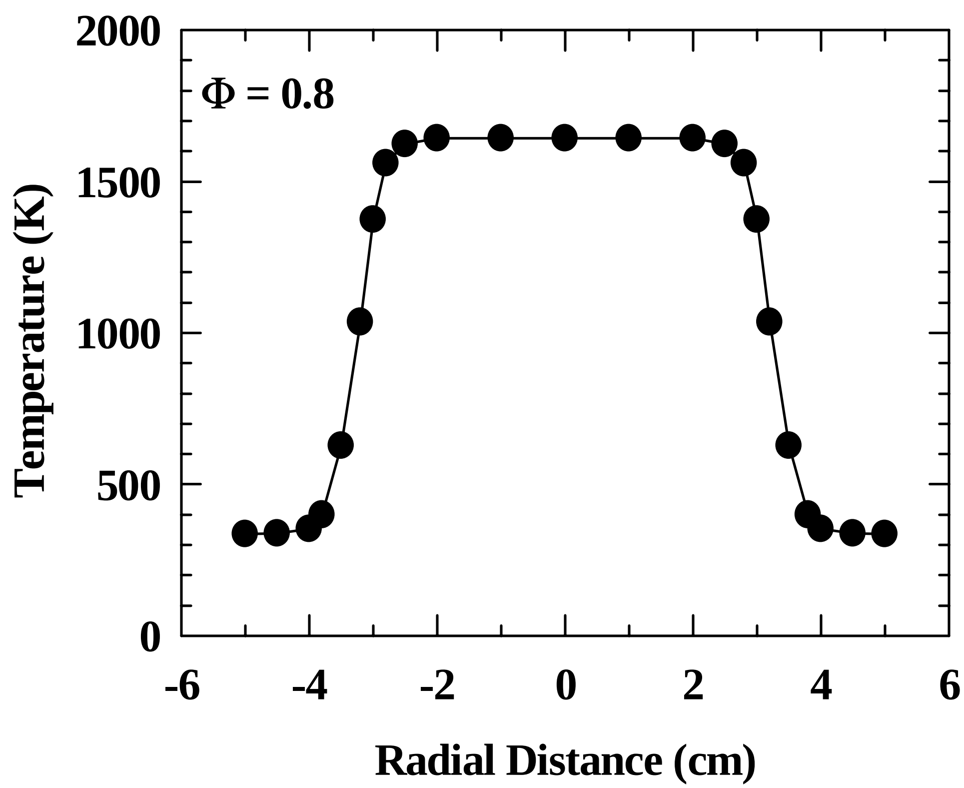
LAMINAR FLAME EVALUATION



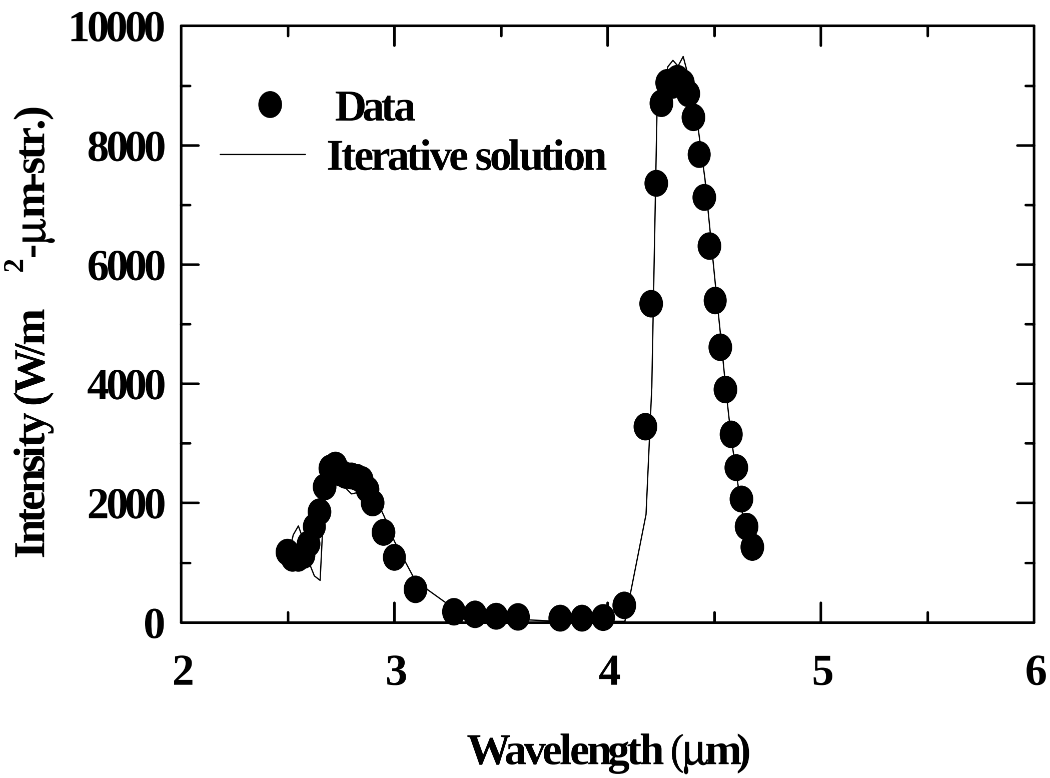
Experimental arrangement used for evaluation of IR emission spectroscopy



Mole fraction profiles in a laminar premixed CH_4/air flame.



Temperature profile in a flat premixed methane/air flame.

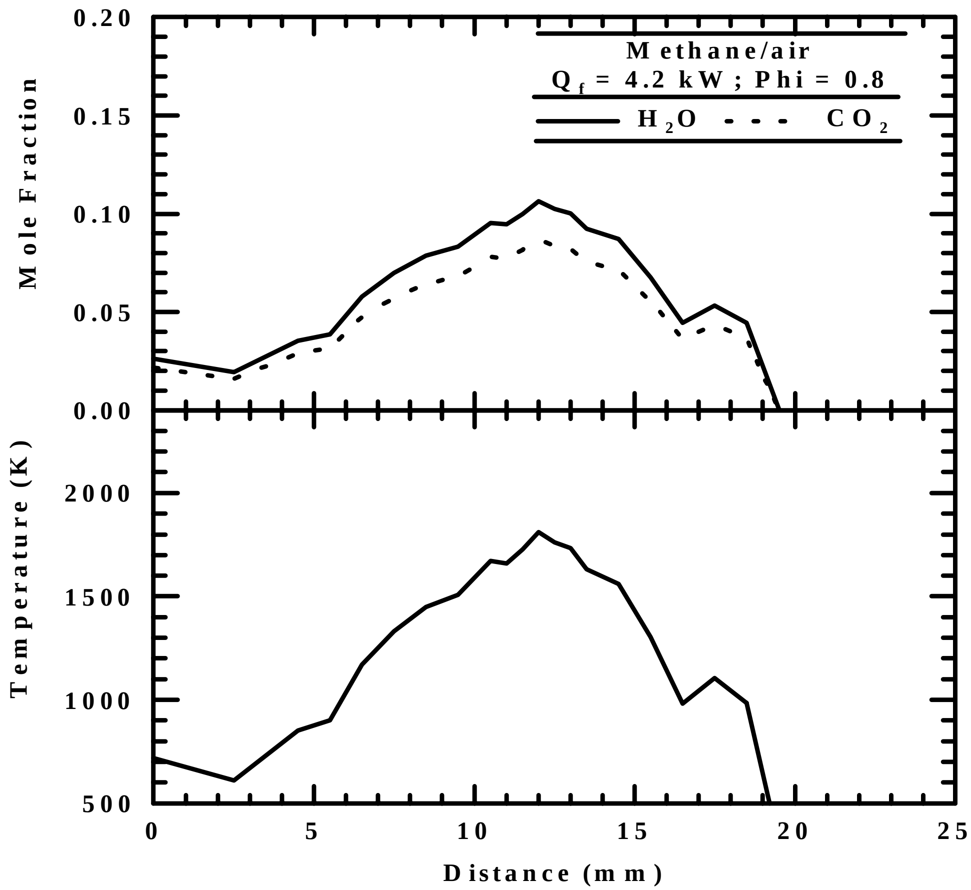


Radiation intensity predicted by RADCAL at point of convergence

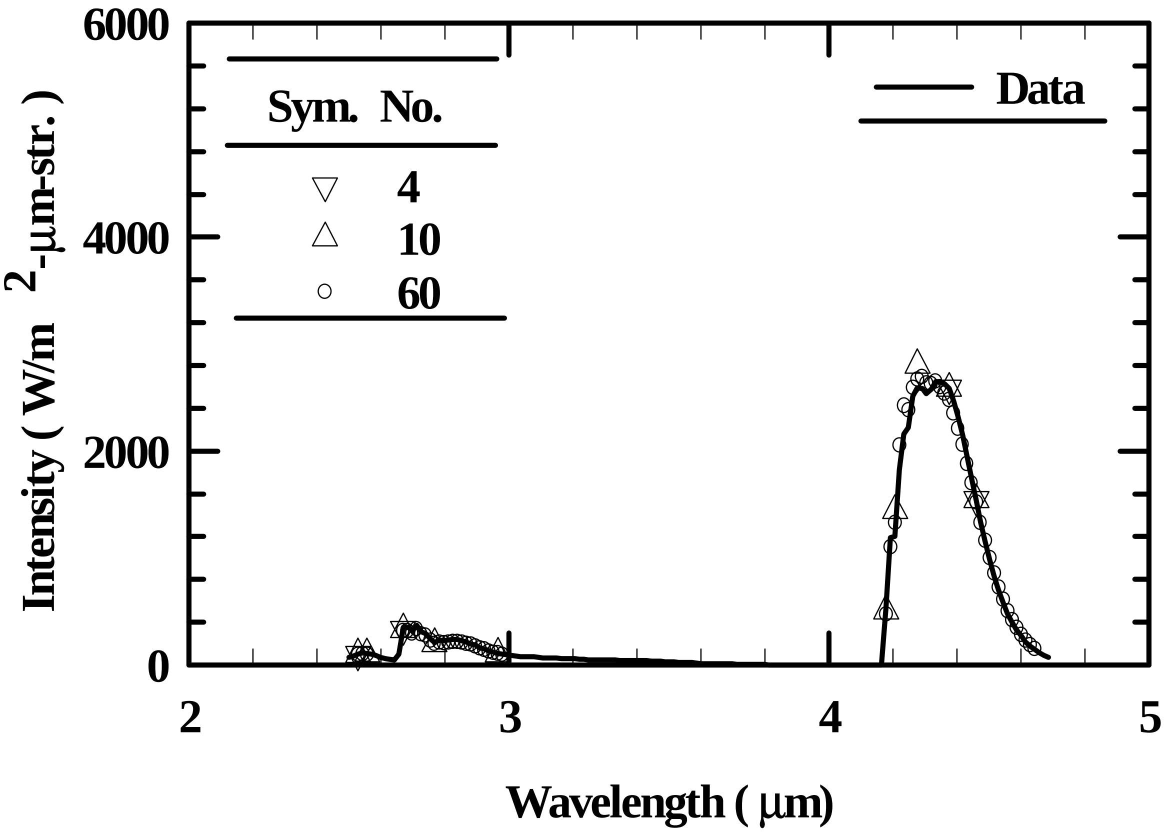
RESULTS OF FULL INVERSION WITH HOMOGENEOUS PATH

Quantity	Infrared Spectroscopy	Thermocouple/ Gas sampling	Theoretical (Adiabatic)
CO_2 (Φ=0.81)	0.0695	0.0785	--------
H_2O (Φ=0.81)	0.158	-------	0.157
Temperature	1940	1840	2004
CO_2 (Φ=0.81)	0.0735	0.0828	--------
H_2O (Φ=0.81)	0.168	-------	0.166
Temperature	2011	1840	2112

TURBULENT FLAME EVALUATION



Instantaneous concentrations and temperature in a turbulent flame



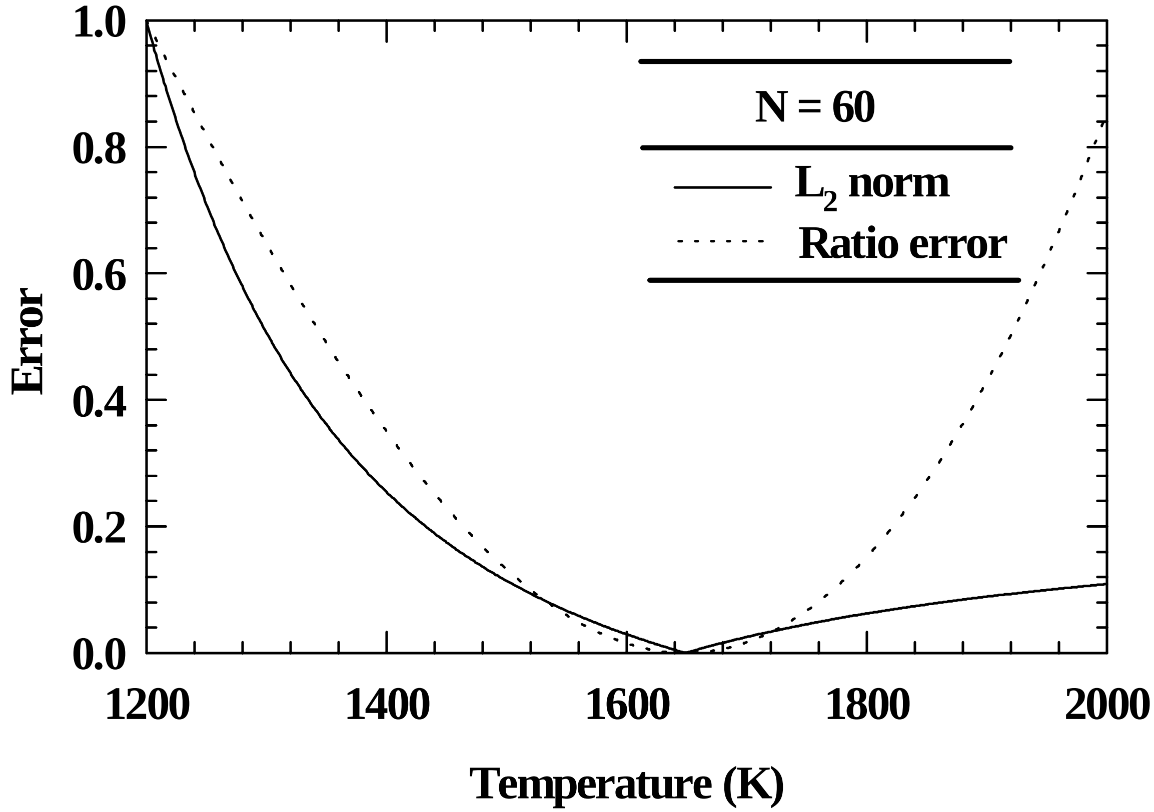
Converged radiation predictions in a turbulent flame

RESULTS FROM TURBULENT PREMIXED FLAME

- PLANCK FUNCTION WEIGHTED TEMPERATURE IS 1580 K, WHILE AVERAGE TEMPERATURE IS 1235 K.

- FOR 60, 10 AND 4 WAVELENGTHS, THE NUMBER OF WAVELENGTH PAIRS ARE 1770, 45 AND 6 RESPECTIVELY.

- THE TEMPERATURES OBTAINED FOR THE THREE CHOICES ARE 1605, 1605 AND 1644 RESPECTIVELY.



Error using 4 wavelengths for a non-homogeneous path

CONCLUSIONS

- **Infrared emission spectroscopy is a promising method of obtaining temperature and gas concentration information in turbulent and laminar flows.**

- **Measurements at four wavelengths are sufficient to obtain accurate Planck function weighted temperature.**

- **Initial evaluation in laminar and turbulent flames have been completed.**

FUTURE WORK

- **Optimization of the temperature inversion program is required.**
- **Selection of the spectral location of the four wavelengths has to be finalized by studying more closely the errors associated with the different choices.**
- **Hardware modification to obtain an economical high speed sensor is required.**