ABSTRACT

Infrared (IR) spectra of the exhaust emissions from a static gas turbine engine have been studied using Fourier Transform (FT) spectroscopic techniques. Passive detection of the infrared emission from remote (range ~ 3 m) hot exhaust gases was obtained non-intrusively using a high spectral resolution (0.25 cm⁻¹) FTIR spectrometer. Remote gas temperatures were determined from their emission spectra using the total radiant flux method or by analysis of rotational line structure. The HITRAN database of atmospheric species was used to model the emission from gas mixtures at the relevant temperatures.

The spatial distribution of molecular species across a section transverse to the exhaust plume ~ 10 cm downstream of the jet pipe nozzle was studied using a tomographic reconstruction procedure. Spectra of the infrared emission from the plume were taken along a number of transverse lines of sight from the centreline of the engine outwards. A mathematical matrix inversion technique was applied to reconstruct the molecular concentrations of CO and CO₂ in concentric regions about the centreline.

Quantitative measurements of the molecular species concentrations determined non-intrusively were compared with results from conventional extractive sampling techniques.

INTRODUCTION

Current awareness of environmental issues has prompted an increase in academic research on novel techniques for atmospheric pollution monitoring. Gas turbine engine manufacturers and end users have an interest in monitoring the emissions from combustion systems both to meet regulatory requirements and to improve combustion efficiency.

Conventional extractive sampling gas analysis techniques in current use have a number of disadvantages. They require expensive probe systems which must be traversed from point to point. Residual chemistry can occur in transporting the sample to the gas analysis equipment.

Optical non-intrusive techniques have potential to offer real time multicomponent gas analysis and in flight continuous monitoring of species concentrations. FTIR spectroscopy, costing an order of magnitude less than extractive probes systems is one of the techniques being studied for exhaust gas monitoring.

FTIR spectroscopic techniques have been used in a variety of configurations to study gases. Many atmospheric species have IR activity and can be monitored simultaneously and with high sensitivity. Extractive gas samples can be analyzed in an FTIR spectrometer using a long path cell (Herget and Lowry, 1991). The cell contains mirrors to generate multiple reflections and increase the path length over which absorption can occur. This active technique probes the target gas with a beam of modulated I.R. radiation and then measures the spectral absorption.

However, there are a number of applications where FTIR spectroscopic techniques have been useful in studying gases remotely rather than by obtaining samples. Industrial sites and landfill tips can be continuously monitored for gaseous pollutants using active long path systems (Herget, 1982, Partridge, 1990/91, Reid et al., 1993, Russwurm et al., 1991). Active double ended techniques require a source of modulated radiation to probe the target gas on the far side of which is an I.R. detector or retroreflector to return the beam to the detector in the spectrometer.

Passive single ended techniques involve the measurement of I.R. emission and are generally less sensitive than active (probe beam) systems by 1 or 2 orders of magnitude. However, there are some remote monitoring applications where
positioning a double ended system would be impractical, e.g. effluent plumes from tall smoke stacks and refinery flares. Passive I.R. radiation measurements have been used to retrieve the concentrations of CO, N₂O, NO, SO₂ and HCl in addition to CO₂ and H₂O vapour from the smoke stack effluent of thermal power plants and municipal incinerators (Womhoudt et al., 1985, Prengle et al., 1973, Carlson et al., 1988). The threshold detection limit of each species improves with increasing stack gas temperature.

Passive remote emissions monitoring systems have recently been used to study jet engine exhaust plumes in Holland and Germany (Schleijpen et al., 1993, Lindenmeir, 1994). Heland et al. (1994) have measured H₂O, CO₂, CO, NO levels in the exhaust plumes of JT8 and CFM56-3 gas turbine engines. Hilton and Lettington (1996) have previously described non-intrusive FTIR spectroscopic studies of CO and CO₂ concentrations in the exhaust gases of a Rolls Royce Avon gas turbine engine.

This paper describes the use of single ended passive techniques to obtain non intrusive measurements of gas temperature and concentration distributions in the exhaust plume of a Rolls Royce Spey gas turbine engine.

INFRARED ACTIVITY OF GAS MOLECULES

From quantum theory, gases which are infrared active absorb or emit radiation as their molecules undergo spontaneous or induced transitions between different energy levels. Photons are emitted or absorbed at characteristic wavelengths determined by the structure of the molecules. A molecular species may be identified from the observed intensity at these wavelengths. The relative population of the energy levels is determined by the temperature dependent Boltzmann distribution. The intensity of the absorption or emission is therefore determined by both the gas temperature and the number of molecules present. The net radiance detected by an FTIR spectrometer system depends on the relative temperatures of all the molecules in the field of view (FOV). The spectrometer observes emission lines when the gas temperature is higher than that of the background or absorption lines when this temperature differential is reversed.

The instrument response function, its FOV and interferent species all affect the observed radiance of the target gas. In particular, the CO₂ and water vapour content of the atmosphere along the path absorb extensive regions of the emission spectrum. Concentration measurements made at long range (~100 m) are usually quoted in the form of concentration \( \times \) path length (ppm m) since the spectrometer detects the total contribution from all the molecules along the path from the detector to the gas plume. The temperature of the plume gases can be determined using techniques based on rotational line intensity distribution (Spellicy and Persky, 1985, Wang et al., 1990). When this temperature is known the concentration \( \times \) path length product can be obtained by matching the observed emission spectrum with modelled spectra (Haus et al., 1993, Schafer et al., 1993). Where the spatial extent of the plume is well defined, as with the Spey exhaust, the relative path lengths in air and the plume can be determined and molecular concentrations in the plume calculated.

SPATIAL DISTRIBUTIONS OF THE MOLECULAR SPECIES

FTIR spectroscopy has been used to study non intrusively, the change in molecular distributions across sections through laboratory hydrocarbon flames. The FOV of the spectrometer is traversed across the flame and spectra recorded along different lines of sight. The molecular distribution across the section is then reconstructed using a tomographic matrix inversion technique (Hilton, 1995a, Hilton et al., 1995b). The mathematical inversion procedure assumes that the flame is axially symmetric.

Since along each line of sight, the molecules in one region of the flame may absorb the radiation emitted by those in another region, a self absorption correction must be applied before quantitative measurements may be made. Best et al. (1991) and Solomon et al. (1992) have measured both the absorption and emission of flames to obtain the spatial distributions of temperatures and species concentrations. This work, however describes the use of purely passive non-intrusive FTIR spectroscopy to determine thermodynamic gas temperatures and relative molecular concentrations of CO and CO₂ in a gas turbine exhaust plume.

PASSIVE REMOTE FTIR SPECTROSCOPY

The FTIR spectrometer is based on a Michelson interferometer. In passive remote monitoring mode, I.R. radiation from an external source (in this case the thermal emission from the Spey engine exhaust gases) enters the spectrometer via an NaCl window. The parallel beam of input radiation is split by a KBr beamsplitter into two beams one of which is reflected back to the beamsplitter by a static retroreflector and the other by a moving retroreflector. The moving retroreflector introduces an optical path difference between the two beams recombining at the beamsplitter. As the optical path difference between the beams changes with the movement of one retroreflector the intensity of the output beam is modulated by constructive and destructive interference.

The intensity of modulated output is recorded by a liquid nitrogen cooled Mercury Cadmium Telluride detector. A Fast Fourier Transform chip inside the spectrometer converts the variation in intensity with optical path difference to produce a spectrum of the variation in intensity with spectral frequency. Data are collected over a time period of ~30 s, in which time 20 or so scans of the moving mirror have occurred. Increasing the number of scans improves the signal to noise ratio (SNR) at the expense of time taken. Spectral data are downloaded from the spectrometer via a serial data port to a laptop computer.

Thermodynamic gas temperature

While the wavelength of infrared spectral lines is determined by the molecular structure of each species, the relative intensity of the spectral lines changes with the
temperature of the molecules. Carbon monoxide has strong spectral lines which are widely spaced in a region of the spectrum which is relatively free from interference by other molecules. The relative intensity distribution of these spectral lines can be used to calculate thermodynamic gas temperatures. The gas temperature is found by determining the temperature dependent slope of a function of the CO line radiance plotted against line quantum number.

Concentrations

Molecular concentrations are determined from the observed emission spectra by comparison with modelled spectral lines. The HITRAN (Rothman et al., 1992) database contains line by line information about 32 naturally occurring atmospheric species. From this database, the temperature sensitive absolute line intensities can be calculated for individual spectral lines. The effect of atmospheric absorption by CO$_2$ or H$_2$O present in the path to the exhaust plume can be included in the model. Once the FTIR spectrometer has been calibrated for radiance measurements, the number of molecules of each species can be obtained by comparing the observed line intensity with the modelled absolute line intensity.

Tomographic reconstructions

Emission spectra are taken with the spectrometer sighted horizontally, on consecutive positions from the centreline down to the outer edge of the exhaust plume, transverse to the gas flow. At each of these positions the radiance detected by the spectrometer is the sum of all the contributions from each volume element along the path.

Assuming the plume has axial symmetry, then the spectral data measured along these linear paths may be expressed simply as a sum of the contributions from a number of concentric regions about the axis of the plume. In this way a set of simultaneous equations is built up summing the contribution from each element to the total emission detected along each linear path. These equations are solved to determine the spectral contribution from each of the volume elements.

Spectra obtained near the centre of the flame will contain contributions from the largest number of elements, those near the boundaries the least. The central element will be well defined spatially. Computational analysis using a matrix inversion which is valid for systems with axial symmetry is used to reconstruct the distribution of different molecular species within the traversed section of the plume.

The algorithms were originally derived for axially symmetric flames and it should be noted that the exhaust plume does not in practice possess perfect symmetry. However, it is a reasonable approximation in the region of the exit plane.

ENGINE INSTRUMENTATION

The Spey engine studied at DRA Pyestock has been used for a number of experimental projects and the temperature and molecular species distribution in its exhaust gases monitored extensively using conventional probe systems.

Extractive gas samples were obtained using a single point multiposition probe positioned in a plane transverse to the exhaust gas flow, 10 cm behind the jet pipe nozzle. The probe can be sited at any radial distance from the centreline or circumferential angle of the plume. A stainless steel gas sampling tube heated to 150±5 °C transferred the combustion products to gas analysis equipment mounted in a mobile laboratory outside the test bed. Intrusive temperature measurements were made at the extractive sampling positions using a radiation shielded thermocouple. It was necessary that the line of sight of the spectrometer was clear during the non-intrusive measurements. Therefore, extractive samples and thermocouple measurements were taken during engine runs preceding and subsequent to the non-intrusive studies but with the engine operating at identical idle and max continuous conditions. Previous experience has shown that reproducible gas analysis results can be obtained by restoring the same engine conditions on different occasions.

![Figure 1. FTIR spectrometer and traverse optics with Spey engine on Glen test bed.](image-url)
positioned so that the optical axis of the system was directed 10 cm aft of the jet pipe nozzle and initially along the engine axis (centreline). The stepper motor control computer and the spectrometer were operated remotely from the test bed control room.

Prior to engine running, the spectrometer was topped up with liquid nitrogen, firmly mounted and encased with substantial acoustic padding. Calibration spectra were obtained using a high emissivity black body IR source at temperatures up to 670 K.

**TEST RESULTS**

The engine was allowed to soak at both idle and max continuous before IR spectra were obtained at 7 traverse mirror points starting with line of sight along the centreline and stepping 50 mm down between points.

Figure 2 shows typical CO emission bands in spectra taken along the centreline at the two engine conditions. The vertical scale is a measure of the radiance in arbitrary instrument units. The horizontal scale is reciprocal wavelengths or cm⁻¹. The regularly spaced spectral lines separated by 4 cm⁻¹ are characteristic of CO while those more irregularly and widely spaced are those of H₂O.

![Spey engine, exhaust emission, CO region](image)

Figure 2

At idle, CO lines can readily be observed in the whole family of spectra obtained as the line of sight was moved down from the centreline position. However, at max continuous, the engine runs very efficiently, typically generating CO levels of <20 ppm. CO emission line intensities at these concentrations are small compared with the noise levels of the observed spectra so no quantitative information could be obtained for CO levels at max continuous.

The CO₂ band emits strongly and in some regions becomes saturated, i.e. the gas becomes opaque. Thermodynamic gas temperatures were determined by comparing the band intensity in the saturated region with calibration spectra. At idle, there was sufficient CO band intensity for an analysis of rotational line intensities to compare with the CO₂ temperature measurements. These showed agreement to ± 1%.

Figure 3 shows the temperature distribution across the plane through the exhaust gases as typically measured by thermocouples and as calculated from the saturated CO₂ band. For the IR spectra analysis, the temperature and molecular concentration distribution across the plume have been assumed to be symmetrical about the centreline of the engine.

There is good agreement between the two types of temperature measurements at idle but the non-intrusive measurements are lower than the thermocouple measurements at max continuous, particularly near the centre of the plume. The observed IR spectra are the net result of absorption and emission contributions from all molecules along the line of sight. High intensity lines emitted by CO₂ near the centre of the plume can be absorbed by cooler CO₂ molecules in the outer regions of the plume. This effect is called self absorption and could cause apparently low line intensities to be observed.

Also, while the thermocouple is measuring the temperature at a single point in space, the non-intrusive measurements are made by gathering the radiation emitted from a horizontal column of finite cross sectional area (aperture ~ 50 mm, beam divergence 2 mrad). The non-intrusive temperature measurements are effectively an average over the FOV of the instrument. This results in a smoothing out of the radiation intensity from highly localised regions of high or low gas temperature.

Figures 4, 5 and 6 show the results of the mathematical inversion procedure to calculate the CO₂ and CO concentrations in 6 concentric regions of the plume from 8 line of sight traverse points. Thermocouple measurements of plume temperature distribution were used in the inversion model rather than the apparent temperatures obtained from the CO₂ band intensities. Only 6 of the 7 traverse points were used in the inversion because the 7th point looking horizontally through the section of the plume 300 mm down from the centreline had very low spectral line intensities comparable with the noise levels of the FTIR spectrometer.

The figures plot the calculated and extractive concentration
distributions from the centre of the plume out horizontally. The non-intrusive results shown are the calculated concentrations of CO and CO$_2$ within the 6 concentric annular regions about the centre of the plume predicted by the mathematical inversion.

The agreement between the extractive gas analysis results and the non-intrusive measurements is best for CO$_2$ at idle and in the outer regions of the plume at max continuous. The CO concentrations determined non-intrusively were consistently low. There are a number of factors which have contributed to these discrepancies. As discussed previously, the non-intrusive measurements are made over a finite FOV. The non-intrusive data points are plotted assuming an even distribution within 6 bands across the plume. Extractive measurements taken at a single point can not be expected to match exactly with concentrations averaged over a wider area. The proposed addition of front end optics to reduce the FOV of the spectrometer should improve the correspondence between the non-intrusive and extractive measurements.

The current inversion model is unsophisticated and relies on a small number of line of sight projections on which to base the reconstruction. More projections would improve the reconstruction by reducing the significance of noise in the small number of line intensity measurements.

Self absorption can reduce the apparent intensity of the spectral lines emitted near the centre of the plume resulting in the region of low CO$_2$ concentrations observed in Fig. 5. This is likely to be more significant at max continuous than at idle because of the increased temperature gradients present. The self absorption correction used in the model is being revised.

Observed CO line intensities are an order of magnitude lower than those of CO$_2$ because of the smaller quantities emitting. This results in a lower SNR for CO compared with CO$_2$. The sensitivity to detector noise and non linearity, instrument line shape function, self absorption effects, baseline drift, errors in temperature measurements etc. will be heightened where the SNR is low. Improvements to the model by which the CO concentration is calculated are under consideration. However, the results have shown that some agreement can be obtained between extractive gas analysis measurements and those obtained non-intrusively.

CONCLUSIONS

FTIR spectroscopy has been shown to provide useful information by non intrusively monitoring the exhaust gas flow. In this instance the molecular species CO and CO$_2$ have been studied since their distinctive strong spectral lines can be easily identified and intensities measured. However, there are other species which could be detected from their I.R. spectra including H$_2$O, NO, NO$_2$ and unburnt hydrocarbons. The quantitative analysis of these compounds from their I.R. spectra is more difficult because of the complexity and/or weakness of the lines. Increasing the instrument sensitivity by using an Indium Antimonide detector and modifications to the modelling would improve the ability of the system to study low concentration species.

Thermodynamic gas temperatures have been calculated from saturated CO$_2$ band intensities with results that agree well with thermocouple measurements except in regions of very
high temperature gradients.

The radiance calibration, instrument response factors of the FTIR spectrometer and limitations of the current inversion reduce the efficiency of the molecular concentration distribution reconstruction. A number of methods to improve the technique are currently under investigation.

The mathematical inversion procedure has reconstructed the molecular concentration distribution within 8 concentric regions of the plume. The reconstruction works best when the plume temperatures are lower than 650 K and molecular concentrations are high. The current inversion assumes axial plume symmetry and could be improved by accounting for the true geometry and increasing the number of linear projections (line of sight measurements) used in the model. However, this work has demonstrated that FTIR spectroscopy can make useful non-intrusive measurements of gas turbine exhaust emissions. While the accuracy of non-intrusive measurements is not that of probe systems, the technique has a number of advantages over extractive exhaust gas monitoring. One instrument can monitor a number of species simultaneously, the exhaust gas flow is not perturbed by intrusions, the response is rapid and unlike probe systems it could in future be used for in flight monitoring.

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REFERENCES


