

Procedure for Measurement of Gaseous Emissions from Aircraft Gas Turbine Engines Using Fourier Transform Infrared Analysis

RATIONALE

Fourier transform infrared (FTIR) analyzers can measure gaseous emissions from combustion sources with similar accuracy to present non-dispersive infrared (NDIR) and chemiluminescent-type analyzers recommended by ARP1256 and required by ICAO Annex 16 Vol II. This Aerospace Information Report (AIR) summarizes experience in the use of FTIR instruments in measuring aircraft gas turbine engine and combustion rig exhaust effluents by extraction. The intent of this AIR is to discuss the FTIR analysis method and document the use of FTIR gas analyzer instrumentation prior to development of a future FTIR ARP document. Adoption of FTIR instruments in a measurement system will reduce the number of analyzers currently necessary and may provide the capability to measure detailed hydrocarbon species.

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1. SCOPE

This Aerospace Information Report (AIR) describes the use of FTIR analyzers for measurements of gaseous emissions from aircraft gas turbine engines and combustion rigs. The use of FTIR analyzers can be demonstrated as a suitable and cost-effective equivalent to NDIR and chemiluminescence analyzers as prescribed in ARP1256 for the measurement of CO, CO₂, NO, and NO₂, where NO_x is closely approximated by the sum of NO and NO₂ concentrations. FTIR analyzers may be proven suitable for equivalency of analyzers used in current emission testing. Additionally, FTIR analyzers have potential for equivalent measurements of "total" hydrocarbon (THC) as currently defined in ARP1256.

1.1 Purpose

This report is intended to provide a basis for the generation of an Aerospace Recommended Practice describing the use of FTIR analyzer technology for measurements of measurementse of exhaust gas emissions from aircraft gas turbine engines.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP1256 Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines

ARP1533 Procedure for the Analysis and Evaluation of Gaseous Emissions from Aircraft Engines

2.1.2 Other References

- [1] ASTM Standard D6348 - Revision #1: Standard Test Method for Determination of Gaseous Compounds by Extractive Direct Interface Fourier Transform Infrared (FTIR) Spectroscopy (March 2000).
- [2] "Energy Conserving Tool for Combustion Dependent Industries," Final Technical Report for U.S. Department of Energy, Grant No. DE-FG41-R110915, October 2002.
- [3] "EPA Protocol for the Use of Extractive Fourier Transform Infrared (FTIR) Spectrometry in the Analysis of Gas from Stationary Industrial Sources," U.S. EPA Document, Emission Measurement Technical Information Center Bulletin Board, 1995.
- [4] Gardner, D.G., Zaccardi, V.A., Jalbert, P.A., and Bryant, M.D., "Reducing the Cost of Aircraft Engine Emission Measurements," Isa Vol. 443, Paper 2302/lis03-P081 (2003).
- [5] Jalbert, P. and Zaccardi, V., "Improved Methodology for Turbine Engine Emissions Measurement," IGTI Paper No. GT-2002-30306 (2002).
- [6] Jalbert, P.A., Zaccardi, V.A., Bryant, M.D., Winkleman, B.C., Markham, J.R., Bush, P.M., and Bonzani, P.J., "Rapid, Complete Nozzle Exhaust Gas Measurement Capability for Gas Turbine Engines," The 50th International Instrumentation Symposium of ISA, San Antonio, TX (May 9-13, 2004).

- [7] Markham, J.R., Bush, P.M., Bonzani, P.J., Scire, J.J., Zaccardi, V.A., Jalbert, P.A., Bryant, M.D., and Gardner, D.G., "Integrated Gas Analyzer for Complete Monitoring of Turbine Engine Test Cells," Applied Spectroscopy, Volume 58, Number 1, 2004.
- [8] Marran, D., Kenny, P., Markham, J., Jalbert, P., Moyers, R., and Gardner, D., "The Application of FTIR Spectroscopy to Turbine Engine Exhaust Monitoring," AIAA Paper 2000-2211 (2000).
- [9] McIntosh, B.C., "Fourier Transform Infrared (FTIR) Analyzers," Chapter 29, Analytical Instrumentation, Instrument Society of America, 1996.
- [10] Oliver, W., Marran, D.F., Spartz, M.L., Lee, J.C.Y., and Nazeer, W., "Evaluation of the MKS On-Line FTIR Multi-Gas Analyzer for Gas Turbine Applications, ASME," ASME/LGTI Paper Gt-2003-38656 (2003).
- [11] Aroui, H., Orphal, J., and Tchana, F.K., "Fourier Transform Infrared Spectroscopy for the Measurement of Spectral Line Profiles, Fourier Transform - Materials Analysis," Dr Salih Salih (Ed.), ISBN: 978-953-51-0594-7 (2012) InTech.
- [12] Unpublished Results of U.S. Air Force Contract # C-F40600-02-C-0018.
- [13] Siegman, A.E., "Lasers," Aiden Kelly (Ed.), ISBN: 0-935702-11-3 (1986).
- [14] Spicer, C.W., Holdren, M.W., Rigglin, R.M. and Lyon, T.F., "Chemical Composition and Photochemical Reactivity of Exhaust from Aircraft Turbine Engines," Ann. Geophysicae, 1994, Vol. 12:944-955.
- [15] Recommended Best Practices for Quantifying Speciated Organic Gas Emissions from Aircraft Equipped with Turbofan, Turbojet, and Turboprop Engines, Volume 1, FAA and USEPA 2009.
- [16] Measuring stack gas emissions using FTIR instruments, UK EA Technical Guidance Note (Monitoring) M22, Version 3, 2012
- [17] ICAO, Annex 16 to the Convention on International Civil Aviation - Environmental Protection, Volume II - Aircraft Engine Emissions, Fourth Edition July 2017 and latest amendments

2.1.3 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

Griffiths, P.R. and deHaseth, J.A., "Fourier Transform Infrared Spectrometry," Wiley Interscience, New York, 1986.

Spellicy, R.L., "Challenges to CLS Analysis in the Real World," presented at the National Air and Waste Management Association (AWMA) conference, Salt Lake City, Utah (June 18-22, 2000).

14 CFR Part 34, Fuel Venting and Exhaust Emissions Requirements for Turbine Engine Powered Airplanes, Federal Register Vol. 64, Number 22, 1999.

40 CFR, Part 87, Control of Air Pollution from Aircraft and Aircraft Engines; Emission Standards and Test Procedures, Federal Register, Vol. 62, Number 89, p. 25355-25367, May 8, 1997.

2.2 Definitions and Terminology

Definitions and terminology specified in ARP1256 are applicable in this AIR. Other definitions and terminology include:

ABSORBANCE SPECTRUM: The resultant spectrum calculated from the negative logarithm of the quotient resulting from dividing the sample spectrum by the background spectrum.

BACKGROUND SPECTRUM: The FTIR spectrum of the light source transmitted through the sampling cell in the absence of absorbing species; typically conducted using dry nitrogen or zero air (CO₂ and hydrocarbons substantially reduced or removed) as the sampled gas.

ELECTROMAGNETIC SPECTRUM: The total set of all possible frequencies of electromagnetic radiation.

EXTRACTIVE FTIR: A means of employing FTIR to quantify concentrations of gaseous emissions by extracting exhaust gas sample from the combustion exhaust stream and directing this sample to an FTIR gas-sampling cell.

FTIR: An abbreviation for Fourier transform infrared typically used as the short form of FTIR spectrometer: a spectroscopic instrument operating on the infrared portion of the electromagnetic spectrum. Also used as the short form of the analytical method, FTIR spectrometry. For an in-depth description of FTIR, refer to Griffith and deHaseth, section 2.2.1.

FTIR GAS SAMPLING CELL: The chamber of an FTIR analyzer where the gas sample is passed through and exposed to the infrared portion of the electromagnetic spectrum for measurement of spectral absorption.

FTIR METHOD: The analytical process for determining the species concentration from the spectral absorption measurement and includes the blueprint for dictating the spectral resolution, scanning frequency, pressure, temperature, spectral fitting regions, calibration (reference) spectra of compounds expected, interference minimization, and correction for collisional broadening (water).

HYDROCARBONS: The sum of all hydrocarbon compounds of all classes and molecular weights as measured by an instrument incorporating a flame ionization-type detector (FID). Hydrocarbons are sometimes referred to as total hydrocarbons (THC) or unburned hydrocarbons (UHC). Hydrocarbons are referenced against a propane (C₃H₈) span gas, but reported as methane (CH₄) equivalent, commonly referred to as C₁. The final hydrocarbon emission index result (refer to the latest revision of ARP1533) is expressed as CH_α, where “α” is the hydrogen to carbon ratio, reflecting the composition of the hydrocarbons in the exhaust.

INFRARED PORTION OF THE ELECTROMAGNETIC SPECTRUM: The portion of the electromagnetic spectrum from about 20 cm⁻¹ (500 μm) to about 12500 cm⁻¹ (0.8 μm).

PRECISION: The closeness of agreement between independent test results obtained under stipulated conditions as defined in ARP1256.

SAMPLE SPECTRUM: The FTIR analyzer spectrum of a light source passing through the sampling cell containing the sampled gas, usually containing absorbing species.

SINGLE GAS ANALYZERS: Generalized term for the individual analytical instruments described in ARP1256 for measuring a single gas species of gaseous emissions from aircraft turbine engines, or in the case of the FID measuring “total” hydrocarbons.

SPECTRAL RESOLUTION: The minimum separation that two distinct spectral features can have and still, in some manner, be distinguished from one another. The quality of the spectrum (the amount of spectral detail) increases as the number of resolution elements becomes larger or the frequency intervals between measurements become smaller in an FTIR analyzer instrument.

WAVENUMBER: The number of electromagnetic waves per centimeter. This term has units of reciprocal centimeters (cm⁻¹) and is proportional to frequency.

2.3 Acronyms and Unit Symbols

AIR	Aerospace Information Report (SAE)
AEDC	Arnold Engineering Development Complex
AFR	Advanced Fuels Research
ARP	Aerospace Recommended Practice (SAE)
ASTM	American Society for Testing and Materials
CFR	Code of Federal Regulations
CO	Carbon monoxide
CO ₂	Carbon dioxide
DNPH	2, 4-dinitrophenylhydrazine
EA	Environment Agency
EPA	Environmental Protection Agency
FAA	Federal Aviation Authority
FTIR	Fourier transform infrared
FID	Flame ionization detector
HPLC	High performance liquid chromatography
ICAO	International Civil Aviation Organization
IR	Infrared
KBr	Potassium bromide
LOD	Limit of detection
LOQ	Limit of quantification
NASA	National Aeronautics and Space Administration
NDIR	Non-dispersive infra-red spectroscopy
NMHC	Non-methane hydrocarbon
NMNEHC	Non-methane non-ethane hydrocarbon
NMOG	Non-methane organic gas
NO	Nitrogen oxide
NO ₂	Nitrogen dioxide
NO _x	Nitrogen oxides represented as the sum of NO and NO ₂
OG	Organic gas

OEM	Original engine manufacturer
ppmv	Parts per million by volume
SO ₂	Sulfur dioxide
THC	Total hydrocarbon
TOG	Total organic gas
μm	Micron or micrometer
USAF	United States Air Force
VOC	Volatile organic compound
ZnSe	Zinc selenide

3. INTRODUCTION

3.1 Background

Gaseous emission measurement recommendations for aircraft gas turbines are derived from ARP1256 engine. Setting up the recommended instruments can be expensive, technically demanding, and time consuming. Marran et al. [8] describes how aircraft engine exhaust, using the procedures specified in ARP1256, is typically measured using an array of single gas analyzers. In the same test series, an FTIR gas analyzer was demonstrated to measure simultaneously the required concentrations of CO₂, CO, NO, and NO₂. Speciated hydrocarbons were also measured by the FTIR analyzer. These tests demonstrated that FTIR spectroscopy, in these cases, had similar or lower detection limits for CO₂, CO, NO, and NO_x. FTIR spectroscopy can have an advantage over an array of single gas analyzers, providing the quantification of multiple gaseous species concentrations while offering space savings and potentially lower cost [4, 7, 10].

3.2 FTIR Analyzers

FTIR instruments have been used for over 40 years in research and industry to measure the concentrations of specific gaseous compounds including exhaust gases from stationary combustion sources [9]. These instruments are well developed and commercially available. They operate on the principle that most molecules of interest in gas phase have unique spectral absorption features in the mid-range infrared region. The IR absorption signal is related to concentration and is measured and recorded for multiple compounds simultaneously.

Although the FTIR analysis method shares similarities to NDIR, there are important differences. The NDIR analysis method does not “disperse” or deconvolute individual IR spectral lines and therefore is incapable of multicomponent gaseous analysis in a mixture of gas species. Similar to FTIR, NDIR utilizes polychromatic mid-IR light generated from a black body filament. However, it uses an optic filter to direct a narrow bandwidth of the spectrum either into the sample cell or after the sample cell in front of an IR optical sensor. In the former case, the detector is opto-pneumatic and operates by sensing a pressure differential created between a sample and zero gas (typically nitrogen gas) cell. The pressure differential is created by component specific IR bandwidth absorption in the measurement tube that creates a pressure increase at constant temperature, which is converted to an electronic signal. In the latter case, photonic detectors (photodiodes, phototransistors) respond to IR photons by creating a current in semiconducting materials. Thus, the NDIR is limited in multicomponent identification/quantification by the quality and number of optical filters employed.

An FTIR can replace the suite of NDIR and chemiluminescent instruments required for most exhaust species measurements described in ARP1256.

An FTIR analyzer offers the capability to:

- Simultaneously measure CO, CO₂, NO, NO₂, H₂O, and other infrared-active gas species in a single instrument
- Distinguish and quantify individual hydrocarbon species that are a subset of the total hydrocarbons
- Provide near real-time measurements and evaluation of exhaust constituent concentrations
- Measure exhaust gas on a wet basis (i.e., without the need for removing water vapor upstream of the analyzer)
- Measure at relevant aircraft engine exhaust concentrations

4. MEASUREMENT METHOD

4.1 Background

FTIR analyzers have been used to measure the chemical composition of solids, liquids, and gases throughout industry. These analyzers have been used in laboratories since the 1960s, in process industries since the mid-1980s, and to measure compounds in the effluent of stationary combustion sources since the 1990s. Their application range is extremely broad and extends from analyzing toxic gases in air at parts per billion concentrations to determining percentages of components in solids [9].

FTIR instruments interrogate the fundamental and unique infrared spectral responses of individual compounds simultaneously in a complex mixture. Critical to this ability for field applications has been the advancement of fast, robust Fourier transform spectrometers with relatively high (0.5 cm^{-1}) spectral resolution. Higher resolution spectrometers can differentiate finer spectral structure that previously had been hidden in broad features produced by lower resolution field-ready spectrometers. This not only aids in compound differentiation and quantification, but also importantly provides more structure essential to designing methods that minimize interferences between compounds. Because of relatively recent increases in scanning frequencies, FTIR analyzers are capable of rapid response on the order of 5 Hz, allowing emission measurements for performance and routine engine testing. FTIR measurement speed depends on instrument hardware, as well as spectral resolution and signal averaging settings. Depending on the instrument, the speed of measurement can vary from a high of 5 Hz (0.2 second/measurement) to one measurement in several minutes.

4.2 Principle of Measurement

FTIR gas analysis is a full spectroscopic technique that makes it possible to monitor many species simultaneously in a single instrument. Every molecule, except homonuclear diatomic molecules (oxygen or nitrogen for example), has a unique set of rotational and vibrational frequencies that absorb and emit infrared energy in a characteristic manner. In general, it is possible to identify and quantify constituents of gases based on the spectral region and magnitude of molecular absorptions. Because an FTIR spectrometer can detect the absorption of infrared wavelengths from approximately 500 to 7700 cm^{-1} wave numbers (20 to 1.3 μm), almost an unlimited variety of compounds can be identified [8]. Fortunately, most species of interest have spectral signatures within the mid-infrared range, a small subset of this range. Figure 1 shows a composite infrared spectrum of many of the compounds detected in a gas turbine exhaust using an FTIR analyzer.

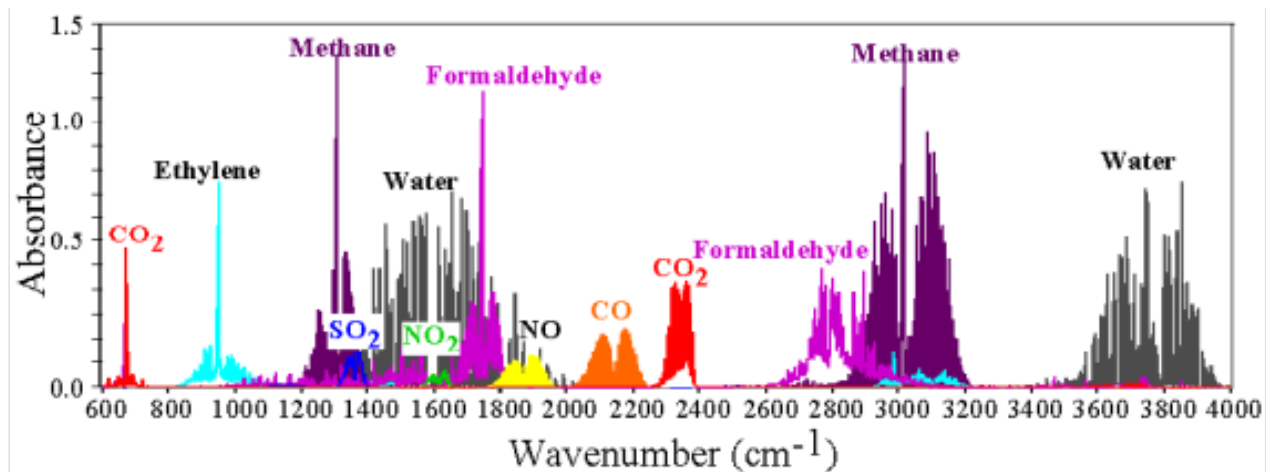


Figure 1 - Overlaid, composite infrared spectra of individual compounds commonly found in gas turbine exhaust detected by FTIR spectroscopy

This AIR discusses FTIR analyzers used for measuring gas turbine exhaust constituents by extracting the exhaust gas to a specifically designed sample cell with an effective path length greater than 5 m. This is accomplished in a relatively small volume cell on the order of 200 cm³ by multiple reflections of the IR light from highly polished gold-plated mirrors on either end of the cell. The light is reflected back and forth through the length of the cell on the order of 30 times. The spectral absorption signature, related to the identity and concentration of each constituent, is detected as a loss of mid-IR light intensity relative to the intensity of the same mid-IR light passing through nitrogen gas that does not absorb mid-IR light. The Beer-Lambert Law describes the spectral absorption of a molecular species by:

$$\text{Absorbance} = -\log(I/I_0) = \epsilon bc \quad (\text{Eq. 1})$$

where:

I = intensity of transmitted light through the sample

I_0 = intensity of the transmitted light with no absorption

ϵ = compound's molar extinction coefficient (Mol⁻¹)

b = light path length through the sample

c = compound's concentration.

From this relationship, it is possible to determine a compound's concentration by simply measuring its absorption because both the molar extinction coefficient and the path length are constants. In order to accomplish both compound identification and quantification, FTIR analyzers must minimally consist of the following:

- A source of mid-IR radiation
- An interferometer
- An enclosed sample cell of known absorption path length, temperature, and pressure
- An IR detector
- Optical elements for the transfer of IR radiation between components
- Gas flow control and measurement components
- A computer