Nationaal Lucht- en Ruimtevaartlaboratorium
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In-flight spectroscopic aircraft emission measurements

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Summary

Aircraft emit their exhaust gases for the larger part during cruise conditions. The knowledge about the emissions in these conditions is limited because adequate in situ measurement methods are not available. In this report the complications encountered measuring exhaust gases in flight are addressed. The potential of spectroscopic measurement methods for this application is discussed. Experimental data gathered on ground are used to support the argumentation.

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1 Introduction

Up to now the primary reason for the interest in the gaseous emissions of aircraft has been their impact on the environment around airports. This is reflected in current certification requirements for civil aircraft engines where the emissions during the landing, during taxiing and during take-off (the LTO cycle) are regulated [Ref. 1]. These emissions have a direct impact on the atmosphere around airports and therefore on the health of citizens. The impact of cruise emissions is much more indirect and long term. However, the amount of gas being emitted during the cruise phase of a typical flight is much larger than the gaseous emissions in the LTO cycle. Attention for the cruise emissions is growing as investigations show that the recovery of nature and the influence on health is much less straightforward for these impacts.

A quite different reason for interest in gaseous emissions of aircraft engines is the potential of detecting stealthy aircraft through gas detection [Ref. 2]. The exhaust gases are a potential omission in the stealthiness of aircraft where detection of military aircraft with traditional methods is increasingly being prevented.

An alternative to the measurement of gaseous emissions is the calculation of emissions. Carbon, hydrogen and sulphur are emitted almost uniquely as CO_2, H_2O and SO_2 molecules. The emission of these gases can be derived from the consumption of fuel and the composition of fuel, with some corrections for emissions of carbon, hydrogen and sulphur in other molecules. These molecules, as well as the important nitrogen oxides, can either be measured or calculated with models. Models of thermodynamic conditions in the engine, combined with chemical predictions of the production of exhaust gases, have been developed. With these models the emissions at cruise altitude can be calculated [e.g. Ref. 3]. Models have been validated with results of measurements in test rigs, whereas the validation in-flight is still in an early stage. In-flight measurements are required for the ultimate validation of these and future models, resulting in a demand for instrumentation.

In the future it is very likely that regulations with respect to aircraft emissions are expanded to include the gaseous emissions in cruise conditions. In the International Civil Aviation Organisation (ICAO) the Committee on Aviation Environmental Protection (CAEP), workgroup 3, dealing with gaseous emissions at altitude, has expressed the need for the development of methods to measure the gaseous emissions in flight conditions.

The need for validation of models for the calculation of gaseous engine emissions, together with the need for future certification methods initiated in the Netherlands the evaluation and development of measurement methodology for the in-flight gaseous emissions of aircraft engines. The approach for the development of the technique is presented and other activities on this field are referenced. The work was supported by the Dutch Ministry of Housing, Physical Planning and Environment (VROM) and the Netherlands Agency for Aerospace Programmes (NIVR).

2 Measurement techniques

Standard measurement techniques on the ground are based on sampling exhaust gases and leading the samples to analysers analysing the concentrations of gases [Ref. 1]. The method is not feasible for in-flight application, because the installation of a sampling rake behind an engine would be a major effort, and, moreover, proving that the sampling rake is deriving a representative sample from the total exhaust gases being emitted is not trivial at all. Leading the gases through a heated tube (heated to prevent the water in the exhaust gas from condensing) from the engine to analysers is not simple either.

Trailing an aircraft engine under investigation with another aircraft equipped with gas sampling and gas analysis instrumentation is an option [Ref. 4] where the installation of equipment on the aircraft under investigation is not necessary. Installation of a broad range of instruments in the trailing aircraft is manageable. However, in the measurement results the dilution of emissions in the environment has to be eliminated which introduces a considerable uncertainty in measurements.

Open-path spectroscopic measurements close behind the exhaust of engines have been introduced for test rigs and ground tests to avoid the installation of gas-sample systems [Ref. 5, 6, 7]. These are also being developed for in flight tests [Ref. 8]. The remote sensing of gases with spectroscopy requires a manageable installation effort on the aircraft and is therefore investigated for the application.

3 Spectroscopic measurement techniques

Several spectroscopic techniques are available for the measurements. Spectroscopic detection is based on the excitation of electrons in molecules or the excitation of vibrational or rotational modes of molecules. Electron excitation is in the ultraviolet (UV) and for some molecules partly in the visible light wavelengths (the brown colour of NO_2). Vibrational and rotational modes are excited at infrared (IR) wavelengths.

A feasibility study of NLR and TNO showed that spectroscopy applied in light-absorption as well as in light-emission mode can give relevant information. In the light-emission mode the radiation of molecules is detected and analysed. The emission intensity is dependent on number of molecules in the gas, on the emissivity of the gas, but also very much on the temperature of the gas. Accurate knowledge about the temperature of the gases is essential for accurate gas concentration measurements in this mode. Light emission at infrared wavelengths is intense enough for detection at temperatures of the exhaust gases, i.e. below 1000 degree Celsius. Emission spectroscopy is not feasible at UV wavelengths.

Absorption spectroscopy needs an external light source. A light path is created from source to detector through the exhaust gas under investigation. Photons with wavelengths corresponding to excitation modes of molecules are absorbed, leading to a decreased intensity in the spectrum of transmitted light. The dependence of the transmission characteristics of gases on the temperature is much less than the dependence of emission characteristics on temperature. Information on the exact temperature of the gas is therefore less crucial for absorption measurements. Absorption spectroscopy at IR and UV wavelengths can be applied.

In the feasibility study both sensitivity and selectivity of spectroscopic techniques appeared to be crucial parameters. The sensitivity has to be sufficient for detection of gas components in the concentration range found in exhaust gases. The selectivity, detecting a gas component in a matrix of other gases, is also a critical parameter for obtaining accurate results.

Spectroscopic measurements are taken along a light beam. Information about the density of gas molecules in the light beam is derived. Gas velocity information and information on the spatial distribution of gases is necessary to calculate total emissions of exhaust gases. Approximations are commonly made to simplify the measurements. A simplification can be achieved by assuming that each of exhaust gases has the same spatial distribution in the plume, which is likely at the exhaust. Now contemplate the carbon atoms. By measuring the carbon density, which is primarily equivalent to measuring the CO_2 density, the amount of fuel, burnt to produce the sample of exhaust gas being probed, can be traced back. Gaseous carbon production is related to the fuel consumption and the fuel consumption can be measured easily. The total mass of emitted gas species can be calculated in this case from the fuel consumption, the carbon density and the densities of other gas species in the probed volume [Ref. 8].

More advanced methods have been developed modelling the exhaust gas plume in layers with homogeneous conditions. Contributions from the different layers to the spectrum are estimated.

4 Installation on aircraft

Spectrometers to be installed on an aircraft should perform in an environment with vibrations and pressure changes. Special design or modification of instruments may be necessary for these requirements, but no basic problems are to be expected in this respect. The installation of optical components inside the cabin of aircraft imposes less severe requirements on the components than outside the cabin and may therefore be the favourable option. The primary design challenge is the light transmission from the exhaust gases to the spectrometer and, for absorption spectroscopy additionally, from the light source to the exhaust gas. For some aircraft the exhaust can be seen from the cabin through a cabin window or a modified cabin window and in this case the installation of the spectrometer in the cabin and open-path light transmission is a good option. The best spectrometer installation may also be in the cabin for aircraft with the engine exhaust out of sight from cabin windows, using fibre optics for light transmission. However, this is not simple at IR wavelengths, because of the poor transmission properties and the brittleness of commercially available fibres.

For an absorption spectrometer the installation of a retroreflector on the engine exhaust may be considered anyhow, enabling easy alignment of source and detector and enabling the installation of both the source and the detector inside the cabin.

5 Towards in-flight measurements

A co-operation between NLR and TNO was set up to develop a spectrometer for the in-flight measurement. On the road towards in-flight spectroscopy it was decided to start with the evaluation of the capabilities of available spectrometers in ground tests. Spectrometers developed for other environmental applications, such as the measurement of emissions from chimneys, were considered as a good starting point for the development. Spectrometers were installed next to the NLR research aircraft in a test run facility. An engine of a NLR research aircraft, the Cessna Citation II, was run at several thrust settings. Exhaust gases from the engine were sampled simultaneously with the spectroscopic measurements. Gas samples were analysed as a reference for the spectroscopic measurements, which should lead to a validation of the measurement method for low altitudes. The method for the sample analysis was based on standard ICAO procedures [Ref. 1], with some simplifications to keep instrumentation and the engine run time limited. In Fig. 1 the test set-up is shown.

Fig. 1 Set-up for evaluating spectrometers. Gas samples are taken from the perforated tube installed behind the exhaust of the engine and led to gas analysers. A retroreflector is visible behind the tail of the aircraft

Several spectrometers available on the market have been evaluated. FTIR spectrometry in light emission mode was demonstrated to give good results for CO_2, CO and NO measurements. This is in accordance with results reported earlier [Ref. 6, 7, 8]. First results for UV absorption with the Differential Optical Absorption Spectroscopy (DOAS) techniques were obtained detecting NO. This technique is expected also to have potential for NO_2 measurements, but this has not been demonstrated yet. The potential for this type of measurements is in accordance with results reported in test rigs [Ref. 5]. Further research on the reproducibility and accuracy of measurements is needed for definite selection of the spectrometer.

Once that the best spectrometer will have been selected, the next phase of the development will be the installation of a spectrometer in another NLR research aircraft, a Fairchild Metro II. This aircraft has good testing options for spectrometry as the spectrometer can be installed in the aircraft cabin where light can be transmitted and received through inserts in a dummy window (Fig. 2). For absorption measurements a small retroreflector can be installed on the exhaust.

Fig. 2 The Fairchild Metro II research aircraft. This aircraft has the exhaust in sight of cabin windows, enabling easy installation of open-path spectrometers.

6 Conclusion

The in-flight measurement of gas emissions of aircraft engines is demanded for several reasons. The remote spectroscopic methodology has considerable potential for achieving this. Characteristics of the application are listed and a strategy towards in-flight measurements is drafted. Commercially available instruments are being evaluated for this application, showing good prospects.

7 References

1 ICAO *"Environmental Protection, International Standards and Recommended Practices*", Annex 16, vol. II, *"Aircraft Emissions"*, Second Edition (1993)

2 Wilson C., Brundish K., Moncrieff J.T.M., Wootton A.G., *"DIAL Measurements on a Gas Turbine Exhaust"*, AGARD CP 598, paper 9, 90th PEP Symposium *"Advanced Non-Intrusive Instrumentation for Propulsion Engines"*, Brussels, Belgium, 20-24 October 1997

3 Visser W.P.J., Kluiters S.C.A., *"Modeling the Effects of Operating Conditions and Alternative Fuels on Gas Turbine Performance and Emissions"*, RTO-AVT Symposium *"Gas Turbine Engine Combustion, Emissions and Alternative fuels"*, Lisbon, Portugal, 12-16 October 1998, paper 21

4 Schulte P., Schlager H., *"In-flight measurements of cruise altitude nitric oxide emission indices of commercial jet aircraft"*, Geophysical Res. Letters, vol. 23, p.165 (1996)

5 Howard R.P., *"Experimental Characterization of Gas Turbine Emissions at Simulated flight Altitude Conditions"*, AEDC-TR-96-3 (1996)

6 Bittner H., et. al., *"Optical Remote Sensing of Aircraft Emissions with the K300"*, IEEE Trans. Geosc. and Remote Sensing vol. 31, p. 1 (1993)

7 Heland J., Schäfer K., *"Analysis of aircraft exhausts with Fourier-transform infrared emission spectroscopy"*, Applied Optics vol. 36, p. 4922 (1997)

8 Haschberger P., Lindermeir E., "Spectrometric inflight Measurement of Aircraft Exhaust Emissions: First results of the June 1995 Campaign", J. of Geophys. Research vol. 101, p. 25995 (1996)