Abstract Theo Rindlisbacher

Non-Volatile Particle Mass and Number Standard for Aircraft Gas Turbines

Emissions from aircraft gas turbines are regulated with global standards and recommended practices as described in ICAO Annex 16 Volume II (International Civil Aviation Organization). Presently, regulated are emissions of oxides of nitrogen (NO and NO_2), carbon monoxide, total unburned hydrocarbons and smoke (a non-visibility criteria for emission plumes). The smoke standard was a response to visible smoke trails left by aircraft engines built in the 1960s and earlier, and the result has been that current engine designs no longer leave a visible smoke trail on take-off. So the Smoke Number measurement requirement has had the desired goal of a less visible exhaust and has probably resulted in lower PM mass emissions. The Smoke Number measurements have been correlated to nvPM mass emissions from various aircraft engines to quantify inventory contributions; however do not provide a useful metric for measuring the mass and number of ultrafine PM emissions from current engines nor for continuing to reduce the ultrafine PM emissions from future aircraft engines. Increasing evidence for health impacts from ultrafine combustion particles and for their negative climate impact was leading to substantial particle emissions research and testing of aircraft gas turbines in the last ten years. Most of the work was funded by the US Federal Aviation Administration and Environmental Protection Agency, the Swiss Federal Office of Civil Aviation, the European Aviation Safety Agency and Transport Canada. The development of a standardized measurement system and appropriate instrumentation for non-volatile particles was done within the Society of Automotive Engineers SAE-E31 Committee. In 2011, the Swiss Federal Office of Civil Aviation (FOCA) engineered, built and installed a prototype measurement system at the SR Technics Engine Maintenance Facility at Zurich Airport. An outstanding support from SR Technics, to accept system installation in their engine test cell and make use of their engine maintenance runs were a real break-through. Following this effort, a number of international test campaigns took place in Zurich. The activities so far have culminated in the SAE specification document AIR6241 planned to be published in September 2013. The AIR6241 with the title “Procedure for the Continuous Sampling and Measurement of Non-Volatile Particle Emissions from Aircraft Turbine Engines” is the reference for standardized engine tests and final validation of the methodology. Several systems independently built and equipped with instruments to the specifications have so far shown excellent agreement, with variations of measured values primarily attributed to variations in the instrument calibrations.
In February 2013, the ICAO Committee on Aviation Environmental Protection (CAEP) agreed to develop a non-volatile particle mass and number standard for medium to large aircraft gas turbines with a target date for a first regulation by 2016. The AIR6241 still has to be fully validated at engine manufacturer sites. One particular aspect is the use of certification probes, tailored to each individual engine type, being able to provide a representative sample from the large exhaust plane and prove full functionality with the PM sampling system.
The Swiss PM Test Site in Zurich is now run by the Swiss Institute for Materials and Testing (EMPA) together with ETH and the Paul Scherrer Institute (PSI). Aircraft engine certification related activities are performed together with international aviation partners. Additionally, further aircraft particulate matter research is planned at the SR Technics facility until the end of 2015, funded by the Swiss Government and International Partners.

Due to high cost of large engine testing, the sampling system is designed to allow for simultaneous measurement of gaseous pollutant emissions, smoke and non-volatile PM (nvPM). Engine probe specifications are taken from the existing ICAO Annex 16 Volume II for gaseous and smoke emission certification. The nvPM sampling system splits from the existing gaseous and smoke measurement sampling line at a distance of maximum 8 meters from the sampling probe tip. The exhaust sample is diluted and at the same time cooled to 60°C before it is pumped at a high flow rate through a standardized 25m long line to the instruments, making sure it fits the required dimensions of the largest engines and test cells in the world. In front of the instruments, there is a cyclone, removing larger particles that can build up in the sampling system that are not originating from the engine. The instruments measure nvPM mass and number concentrations. For particle number, the whole size range of emitted nvPM is counted. From sampling probe tip to the instrument inlet, the sampling system line length must not exceed 35m. Measurements are normalized by CO_2, resulting in emissions per kg of fuel as a function of engine thrust. The standardized system and instrumentation is characterized for particle losses and the measurements can be loss corrected, if necessary. The instrument specification for non-volatile mass instruments allows the choice between an instrument based on the photoacoustic principle (like an AVL MSS) or based on laser induced incandescence (like an Artium LII-300) together with the prescribed calibration protocol NIOSH5040.
Due to the presence of nano-sized soot particles from gas turbines, the Condensation Particle Counter (CPC) lower size cut-off for the non-volatile particle number measurement is different from existing vehicle regulation: The 50% counting efficiency for the CPC is specified at 10 nm mobility diameter or below. The 90% counting efficiency is at 15nm or below. The calibration aerosol is emery oil or any other material but only if equal performance to emery oil can be shown. Flow split or photometric mode is not allowed for the CPC. The volatile particle removal (VPR) requirements are more demanding than currently defined in the European PMP, asking for 99.9% removal of 15 nm and 30 nm tetracontane ($CH_3(CH_2)_{38}CH_3$) particles with an inlet concentration of ≥10,000 particles/cm^3 and ≥50,000 particles/cm^3 respectively. It is important to note that the sampling system and VPR specifications combined with the characteristics of aircraft turbine emissions allow the use of any CPC size cut-off curve below 10nm, as specified above. Currently, there is just one number instrumentation commercially available, which meets all the respective specifications (AVL APC with Catalytic Stripper). AVL List GmbH announced to deliver the first commercially available complete aviation nvPM system, including the front end, mass and number instrumentation according to AIR6241 specifications by December 2013.

Apart from full validation of AIR6241 at engine manufacturer sites, gathering of robust engine data to inform standard setting will be a high priority for the coming years.

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Federal Office for Civil Aviation FOCA

Non-volatile Particle Mass and Number Standard for Aircraft Gas Turbines

17th ETH Conference on Combustion Generated Nanoparticles,
25th June 2013, Theo Rindlisbacher

Outline

- Global Regulation for Civil Aviation
- New Non-Volatile Particulate Matter (PM) Regulation
- Regulatory Agencies Involved
- Milestone SAE-E31 Document
- A Validation Issue

- Sampling System Overview
- Number Instrument Specs (Extract)
- Mass Instrument Specs (Extract)

- Outlook

Global Regulation for Civil Aviation

- Emissions from aircraft gas turbines are regulated with global standards as described in ICAO Annex 16 Volume II (International Civil Aviation Organization).

- Presently, regulated are emissions of oxides of nitrogen (NO and NO2), carbon monoxide, total unburned hydrocarbons and smoke (a non-visibility criteria for emission plumes).

Existing Non-visibility Smoke Criteria

New Non-Volatile PM Regulation

ICAO CAEP (Committee on Aviation Environmental Protection) agreed remits until February 2016:

- Develop an aircraft engine based non-volatile ***PM mass and number metric and methodology*** for application as a non-volatile PM mass and number emissions certification requirement for turbofan/turbojet engines >26.7kN. Note input from SAE-International ***E-31 Committee***

- Develop an aircraft engine based non-volatile ***PM mass and number standard*** for turbofan/turbojet engines >26.7kN.

Active Regulatory Agencies

- EASA (European Aviation Safety Agency), FOCA (Swiss Federal Office of Civil Aviation, FAA (US Federal Aviation Administration), USEPA (US Environmental Protection Agency), TC (Transport Canada)

- Note: Considerable investments from PM instrument and aircraft engine manufacturer industry!

Milestone SAE-E31 Document

- SAE International E-31 committee is finalising the **Aerospace Information Report AIR6241** these days.
  (planned to be published soon)

SAE Aerospace
An SAE International Group

Procedure for the Continuous Sampling and Measurement of Non-Volatile Particle Emissions from Aircraft Turbine Engines

- AIR6241 is the reference for standardised engine tests and final validation of the methodology.

Milestone SAE-E31 Document

- AIR6241 was largely developed using the Swiss PM Test Site at SR Technics, Zurich, built by FOCA in 2011 in collaboration with

- The system is now operated by EMPA, in collaboration with ETH and PSI in a Swiss Government funded project until 2015.

- AVL List GmbH will deliver the first commercially available AIR6241 compliant measurement system by end of 2013.

A Validation Issue

- A particular aspect of final AIR6241 validation is system operability with *emission certification probes providing full exhaust representative emissions.*

Sampling System Overview

Engine Test Cell | Instrumentation Room

PM Instrumentation

Dump

Dilutor
~ 1:10

25 SLPM

60°C

ID 7.7 – 8.05 mm

1 µm
Cyclone

a= ca. 5 SLPM

APC (VPR +CPC)
(PM Number)

CO_2

25 – a – b SLPM

60°C

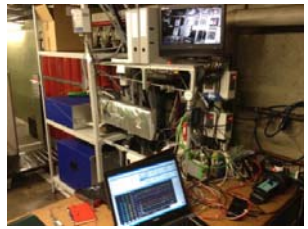
Filter

MFC

CO_2

b= ca. 5 SLPM

MSS or LII (PM
Mass)



Probe

160°C

13.5 -16 SLPM

Gas Phase Instrumentation (includes undiluted CO2)

<= 8m | < 1m | 25m | <= 3m

<= 35m

Drawing:

Adapted from B. Brem, EMPA

Number Instrument Specs (Extract)

- **Volatile Particle Removal**: Achieve **>99.9%** removal of 15 nm and 30 nm tetracontane ($CH_3(CH_2)_{38}CH_3$) particles with an inlet concentration of ≥10,000 particles/cm^3 and ≥50,000 particles/cm^3 respectively.

Condensation Particle Counter:

- Use reagent grade n-butanol as working fluid.
- Operate under full flow operating conditions (flow splitting inside the CPC is not allowed).
- Photometric mode not allowed (single count mode only)
- **Have counting efficiency of ≥50% at 10 nm and ≥90% at 15 nm electrical mobility diameter respectively using an Emery Oil aerosol.**

Mass Instrument Specs (Extract)

Instruments currently meeting the specs: AVL Micro Soot Sensor (Photoacustic Principle), Atrium LII 300 (Laser Induced Incandescence Principle

Performance specification	Reference for definition	Value
Range	Display or digital channel	1 mg/m^3
Resolution	Display or digital channel	1 µg/m^3
Repeatability	ISO* 6.4.5.3	10 µg/m^3
Zero drift	ISO 6.6 (for C_0 only)	10 µg/m^3/hr
Linearity	ISO* 6.4.5.4	15 µg /m^3
Limit of detection (LOD)	ISO* 6.4.5.5	3 µg/m^3
Rise time	ISO 6.3	2 sec
Sample rate	ISO 2.1.7	1 Hz
Accuracy -- Agreement with EC determined by NIOSH 5040 (at 15 $\pm$ 5 µg/cm^2 EC loading)	Slope of the linear regression between mass instrument and EC determined by NIOSH 5040 (see Table 5.4 below)	0.90 ≤ slope ≤ 1.10

Outlook

- **A**viation **P**article **R**egulatory **I**nstrumentation **D**emonstration **E**xperiments (**A-PRIDE**): More dedicated tests to demonstrate methods, making much use of SR Technics facilities in Zürich.

- Industry demonstrations with AIR6241 compatible measurement systems *at industry facilities using certification probe systems.*

- Industry measurement system comparisons with AIR6241 reference system (e.g. in Zurich)

- Obtain engine data that inform standard setting

Questions