SOOT EMISSIONS FROM JET AIRCRAFT

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Introduction

Recently, international governmental regulating agencies have begun examination of the effects of emanations from aircraft engines on the environment with the intent of regulating these emissions at cruise. Two of the emanations under examination are NO_x and soot. For stratospheric aircraft, these species may contribute to ozone depletion. For tropospheric aircraft, NO_x is a greenhouse gas while soot may contribute to the formation of clouds. As a result of these environmental concerns, NASA , working with industry and the scientific community, has established a program determine the impact of aircraft on the environment with a goal to develop a new generation of environmentally-friendly engines.

Measurements of NO_x emissions have been made for a number of years on engines during ground testing. The techniques used for these measurements are relatively mature and adaptation of these techniques is straightforward. Measurements of soot emissions, are not as mature. The industry standard for soot characterization in jet engine emissions is the "smoke number" technique. This technique is useful for characterizing the optical density of the soot but it does not provide the essential characteristics for environmental impact: total particle and non-volatile particle concentration, size distribution, and hydration or growth as measured by soluble mass fraction and critical supersaturation spectrum. These characteristics are needed in order to effectively monitor the environmental impact of engine emissions. They also represent the input parameters required by models designed to describe the production and dispersion of engine aerosol emittants from the combustor, through the exhaust nozzle plane to their eventual equilibration with the ambient atmosphere.
McDonnell Douglas and the University of Missouri Rolla have formed a team which with support from NASA are developing the methodologies needed to characterize soot aerosols (soot particles coated with water vapor) that are emitted from engines. In this paper we describe the application of a mobile aerosol monitoring facility, the Mobile Aerosol Sampling System (MASS), to characterize engine aerosol emissions. The multi-configurational MASS has been employed in both ground and airborne field operations. It has been successfully flown on the National Center for Atmospheric Research (NCAR) Sabreliner research aircraft [2], the DLR (German Aerospace Research Establishment) Falcon research aircraft [3,4] and is soon to be flown on the NASA DC8 research platform [5]. In ground tests, the MASS has participated in numerous jet engine related ground tests at NASA Lewis, Pratt and Whitney, Arnold Engineering Development Center (AEDC) and McDonnell Douglas [6,7] and has been deployed to the Air Force's Phillips Laboratory to resolve aerosol generation problems in a high power chemical laser system. [8] In all cases the measurements were made on samples taken from a harsh physical and chemical environment: with both high and low temperature and pressure, and in the presence of highly reactive gases.

Experiment

A schematic diagram of the MASS (Mobile Aerosol Sampling System) configured for the AEDC Studies is shown in Figure (1). For this test, the MASS was divided into two work stations. The first, located close to the extractive sampling probe selection manifolds, was used in conjunction with the extractive sampling system to acquire total CN concentrations for all aerosols in real-time and to fill and pressurize sample tanks. Exhaust sample was delivered to the MASS from individual and ganged probe sources. An isobaric cooler for supersaturation pulse simulation, a laser aerosol spectrometer for real-time large diameter aerosol measurement (diameters from 1.0-30 microns), and a needle to grid electric precipitator for aerosol collection on electron microscope grids, were also located at the first work station. The second work station consisted of two EAC's (Electrostatic Aerosol Classifier) configured in series as shown in the figure. With this system the tank samples taken at the first work station were analyzed for size distribution, and growth and/or hydration (critical supersaturation) information for aerosols in the submicron range 10 nm to 0.5 microns.

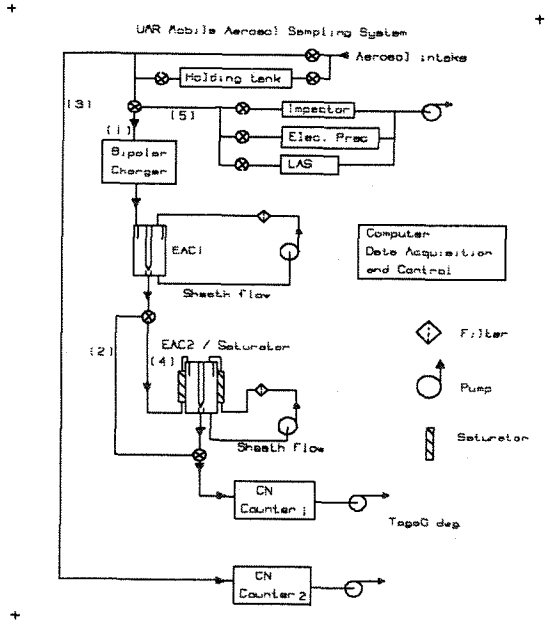

FIGURE 1 - Schematic of MASS

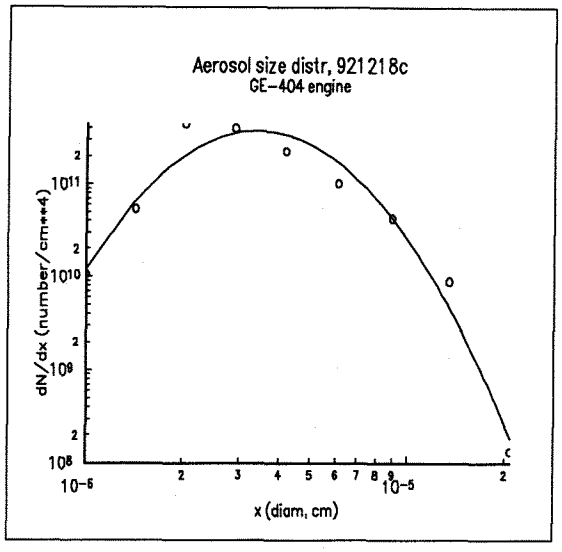

FIGURE 2 - Size distribution from the G.E. 404 engine.

The MASS methodology is described as follows:

Total CN Concentrations - For total CN the incoming sample stream is routed straight to a CN Counter. Aerosol concentrations are measured continuously with typically a 3 second counting period. In situations where the sample pressure drops below 0.5 atm it is found that particle counting efficiency falls off and must be accounted for. The efficiencies for the counters used in this work were measured during a recent study devoted to calibration and operation of CNC's.

Size Distribution Measurement - Aerosol size distribution measurements are made using a single EAC [9] where sample aerosol laden air is drawn from the source and ducted to the MASS (see Figure 1). In cases where the sample is available only for a short time, i.e. seconds, an intermediate storage tank is used to store the sample for subsequent processing with the MASS. For size distribution and hydration characterization the air is directed along path (1) and given an electrical charge in the bipolar charger. The aerosol then passes through EAC1 and a selected size aerosol (monodispersed) emerges. Clean sheath air is provided by the pump and absolute filter. The monodispersed aerosol is directed around EAC2 via path (2) and on into the CN counter. EAC1 is stepped through a selection of voltages (aerosol particle sizes) and a particle concentration is taken at each particle size with the CN counter, and hence a size distribution is generated. A typical size distribution for exhaust from the exit plane of the exhaust nozzle of a G.E. 404 jet engine is shown in Fig. (2). The aerosol can be directed around both EAC's via path (3) and sent directly to the CN counter to get a total CN count. The count vs. voltage data set must be numerically analyzed in order to generate the actual size distribution. [10] Here we note that an interesting feature of the EAC is that it not only takes a polydisperse aerosol and separates out a monodisperse fraction, but it also transfers this monodisperse fraction to the clean sheath air stream. The EAC can likewise be used to remove aerosol from the original sample air stream. This methodology applies for both total aerosol sampling and for non-volatile aerosol sampling. In the latter case an in line preheater set at 175°C provides the means to separate the non-volatile component of the total aerosol flow.

Aerosol Hydration Experiment - The UMR MASS can access aerosol hydration properties through the haze chamber or Laktionov technique. [11,12,13] Sample air is drawn into the MASS and size selected in EAC1 as above. This preselected monodispersed aerosol passes via path (4) to the saturator integrated into EAC2. Here it is brought to 100% relative humidity in the saturator, and the aerosol particles deliquesce to their equilibrium size at 100% relative humidity. Even though the particles entering the saturator are monodispersed in size, a spectrum of particle sizes will exit the saturator because of differences in particle chemistry and soluble mass fraction. To investigate the deliquesced particle size spectrum, the voltage on EAC1 is held fixed. The voltage (size setting) on EAC2 is then stepped through various values. The aerosol is passed onto the CN counter, and a count is taken for each voltage setting of EAC2. These counts can then be translated into a critical supersaturation spectrum for the particles of the size given by EAC1.

Particle Emission Indices - Particle emission indices are used to determine the impact of jet engines on the environment. One important emission index is defined as the number of particles produced per kilogram of fuel burned. Under conditions where the particles are sampled at or near the exit plane of the engine, this index can be determined by (1) measurement of the number of particles emanating from the engine per cm^3 gas in the effluent and (2) a measurement of the weight ratio of the fuel and air that is burned in the engine. The latter quantity can be simply related to the kilograms of fuel burned for each cm^3 of gas that passes through the engine. Taking the ratio of the particles/cm^3 to the kilograms of fuel /cm^3 yields the emission index.
If the particle sampling is performed far enough downstream of the engine such that background air is entrained in the effluent, the emission index is determined using another method. Along with the measurement of particles/cm^3, the CO_2 concentration is measured. As long as the CO_2 concentration is significantly above background (300 ppm), the CO_2 can be assumed to be the product of the combustion of fuel. The CO_2 emission index (grams of CO_2/per kilogram of fuel) does not vary more than a few percent for most aviation fuels, and can be determined very accurately for any fuel by chemical analysis of the carbon percentage in the fuel. The particle emission index for the engine exhaust is then determined by dividing the particle density (part./cm^3) in the exhaust by the CO_2 weight density (gm./cm^3) in the exhaust and multiplying the result by the CO_2 emission index. We have made particle emission index measurements under varying conditions by employing either or both methods described above.

Results and Discussion

We made particle (soot) measurements at two test venues. The first measurements were ground tests made on a Rolls Royce engine mounted in an Air France Concorde. The second set were in-flight plume measurements made by chasing various aircraft in European flight corridors.

Concorde Measurements - During the week of 31 July 1995 the MDC/UMR team made measurements of particulates emanating from the a Rolls Royce Olympus engine mounted in an Air France Concorde aircraft during engine run-up tests at Charles de Gaulle Airport near Paris. These tests were sponsored by NASA since they permitted: (1) an opportunity to provide ground-based emissions characterization of a supersonic transport engine operating under cruise-like conditions, and (2) they would provide data to allow a comparison with the results of a recent sampling by the NASA ER-2 research platform of the Concorde exhaust as it cruised supersonically in transit between Fiji and New Zealand. [1] A diagram of the specific test set-up is given in Fig.(3). The aerosol sampling probe was installed on the engine centerline in a silencing tunnel located at CDG airport. The silencing structure consisted of two cylindrical tubes (5m dia.) joined at an oblique angle as shown in Fig.(3). The uncooled particle probe was installed just upstream of the upward turn of the silencing structure. The separation between probe and exit-plane of the exhaust nozzle on the Concorde was 30 m. This assured sufficient cooling in the exhaust flow to eliminate the need for active cooling of the probe and that the exhaust flow velocity was subsonic.

A truck containing the MASS and CO_2 detector was located outside the silencing structure in the approximate vicinity of the probe. A sample line (6mm o.d.) was run from the particle probe to the measurement stations in the truck. Particle-free diluent air was injected into the exhaust sample at the probe sampling orifice. This air was added to ensure that no condensation could occur in the sample transit from probe orifice to measurement stations.

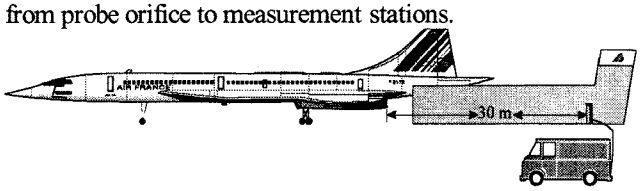

FIGURE 3 - Schematic of Concorde test setup.

The outboard port (number 1) engine was operated at the following nominal thrust settings: 65%(idle), 85%(intermediate) and 100%. When steady-state operation was reached the thrust was held constant for test periods of typically 5 minute each. During each steady state period the following data were acquired: total particle concentrations, total and non-volatile size distributions, hydration properties and CO_2 concentrations.

Total particle concentrations: -The total particle concentrations ranged from 10^{10} to 10^{11} particles cm^{-3}. Using the analysis described above these concentrations correspond to emission indices of between 5×10^{17} and 1×10^{19} particles per kilogram of fuel burned.

Size distributions: - A typical size distribution taken during these measurements in shown in Fig. (4). This type of distribution is very different from that seen for all other ground-based measurements made with the MASS to date. All previous ground-based measurements demonstrate log-normal like distributions similar to those shown in Fig. 5 measured for an engine mounted in a NASA 737 aircraft. and a G.E. 404 engine (Fig. 2) , where a marked decrease in the number of smaller diameter particles(<40nm) is observed compared to the Olympus engine where there is an ever increasing fraction of particles with diameters < 100 nm.

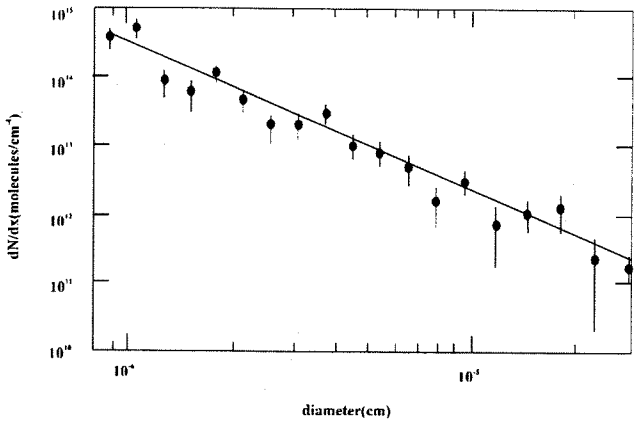

FIGURE 4 - Typical size distribution for Concorde measurements.

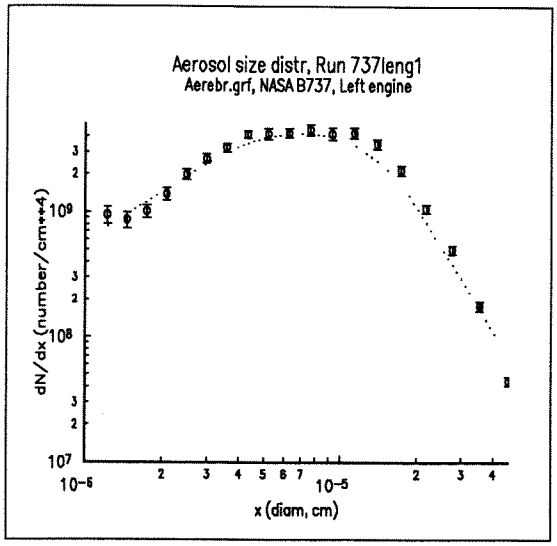

FIGURE 5 - Size distribution for an engine from a NASA 737 aircraft.

Volatile & non-volatile component: - The total particle sample flow was analyzed for its non-volatile component by passing the incoming sample flow through an in-line preheater designed to have sufficient residence time to raise the particulate sample temperature to 170°C. The results of several of these experiments are shown in Table (1).

Table 1. Total and Non-volatile Particle Densities

Thrust	Total Part./cm^3	NV Part./cm^3
65%	$1.3x10^{10}$	$8x10^{10}$
85%	$1.3x10^{11}$	$6x10^{10}$

Hydration Properties: - The hydration properties represented as the fraction of a give aerosol sample population as a function of soluble mass fraction were acquired for aerosol dry sizes 20, 50 and 80nm and continue to be deconvolved. The general observation from these data is that many of the particles measured for the Olympus engine have soluble mass fractions > 10% The dry sizes of 20,50 and 80nm were chosen as these sizes tend to encompass the peak in the size distribution typically observed for aircraft engine soot emissions.

In-flight Measurements of Emission Indices - During July of 1995 the MASS was installed as one of several experiments aboard a Falcon aircraft as part of a flight campaign named POLINAT. The purpose of this campaign is to understand the environmental impact of tropospheric aircraft. Several times during this campaign the Falcon was used to chase various commercial aircraft including Boeing 747's, McDonnell Douglas DC10's and AirBus 34's which were powered by engines which are though to be representative of the fleet. During this time, measurements were made by several groups. These included soot, NO_x and CO_2 measurements.

The results of two of these plume chasing experiments are shown in Table 2. For these experiments we simultaneously measured both the total particle density in the plume and the non-volatile component of the particle density. To accomplish this we employed two particle counters. The contrail was sampled through a nozzle located on the side of the Falcon aircraft. Air flowed through the nozzle directly to one of the particle counters which continuously measured the total particle density. Part of the flow through the nozzle was directed through the second particle counter after passing through a section of tubing that was heated to 170 °C. In this manner the second counter measured the non-volatile component of the particles density. This procedure allowed us to discriminate the pure soot component of the particles (i.e. non-volatile component) from the volatile component which is thought to be sulfuric acid aerosol. Sulfuric acid particles are known to form in aircraft wakes.

In a similar manner co-experimenters aboard the aircraft made measurements through another nozzle sampling port, of the gas-phase species in the air on the side of the aircraft. As the Falcon passed through a contrail of a commercial aircraft the concentrations of all of these species (both gas-phase and particles) increased above the background. By integration of the above ambient signals for total particles, non-volatile particles and CO_2 we obtained particle emission indices using the procedure described above.

Table 2. Inflight Measurement of Particle Emission Indices.

Date	Time UTC	Plane	Engine	N.V. E.I. part/kg. fuel	Total E.I. part/kg. fuel
July 5 1995	2:28	747	CF1-50E2	$4.0x10^{14}$	$1.2x10^{15}$
July 5 1995	3:28	EA34	CFM56-5C2	$1.3x10^{15}$	$2.2x10^{16}$

Conclusions

Concorde Measurements - The data presented here, on the particle characterization of the Concorde's Rolls Royce Olympus Engine are consistent with the following conclusions:

(1) The particle number-based emission index for the Olympus engine is high ranging from 5×10^{17} to 1×10^{19} particles/kg fuel burned. These data are reasonably consistent with the in-flight measurements of Fahey et al., $1.7\text{-}6.5 \times 10^{17}$. [1] The higher emissions at ground level may reflect differences in operation at cruise and on the ground. Some consideration should be given to the influence of the silencing structure on natural exhaust plume dispersion.

(2) A large fraction (40-50%) of the particles are volatile at 170°C. This result is again consistent with the in-flight measurements[1] and unique in the current database acquired with the MASS. The hydration data are consistent with the volatility data and tend to support the speculation that a significant proportion of the fuel sulfur is converted into sulfate particles in the jet/wake regime of the dispersing exhaust plume.

(3) Compared to subsonic transport engines studied to date the Olympus emissions are unique. However, it is important to note that in all previous tests measurements were made typically a distances no greater than 3m, that the plume dispersion did not experience confinement in a silencing structure and the fuel (Jet A) may have a uniquely high sulfur content. An analysis of the fuel composition is currently being performed but the data are not available at the time of submission of this manuscript.

In-flight Measurements of Particle Emission Indices - Particle emission indices were obtained for two aircraft, a Boeing 747 and an Airbus EA 34. The non-volatile E.I. for the 747 was 4.0×10^{14} part./kg fuel and the total E.I. was 1.2×10^{15}. The non-volatile E. I. for the EA 34 was 1.3×10^{15} and the total E. I. was 2.2×10^{16}. These values are similar to the values we have obtained in ground test measurements [6] but are smaller than those obtained for the Concorde engine. More data needs to be obtained in order to draw any conclusions as to differing E.I.s for different subsonic transport engines.

Acknowledgments

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