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Particulate sizing and emission indices for a jet engine exhaust sampled at cruise

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Abstract. Particle size and emission indices measurements for jet engines, primarily the Rolls Royce RB211 engines on a NASA 757 aircraft are reported. These data were used to estimate the fraction of fuel sulfur that was converted to particulates. These measurements were made in-situ with the sampling aircraft several kilometers behind the source. Some complimentary ground measurements on the same source aircraft and engines are also reported. Significant differences are seen between the ground observations and the in-situ observations, indicating that plume processes are changing the aerosol's characteristics.

Introduction

With the knowledge that jet engines inject a significant amount of material into the atmosphere where they operate; the chemical and physical characteristics of turbine engine emissions has begun to receive attention (*Ferri* 1972; *Luther et al.* 1979; *Widhopf et al.* 1977; *Hagen et al.* 1989, 1990, 1991, 1992, 1993a, 1993b, 1996; *Pitchford et al.* 1991; *Baumgardner and Cooper*, 1994). This paper describes results from particle characterization measurements made primarily during NASA project SUCCESS, using the University of Missouri Mobile Aerosol Sampling System (UMR-MASS). The UMR instrumentation was flown on the NASA DC-8 research aircraft for in-situ atmospheric measurements both in aircraft exhaust trails and in the ambient background.

Experimental

The UMR-MASS approach to aerosol characterization of combustion sources is well developed. It uses condensation nucleus counting techniques coupled with differential mobility analysis to measure, in realtime, aerosol concentrations, size distributions, and hydration properties from a wide dynamic range of source environments. The MASS has been described extensively in the literature (*Hagen et al.* 1994, 1996; *Whitefield et al.* 1993,1995,1996; *Lilenfeld et al.* 1995, 1996; *Arnold et al.* 1997; *Schlager et al.* 1997; *Howard* 1996; and *Schumann* 1996). Cumulative instrument uncertainties are estimated to be in the range of 10% for particle number concentration and 12% for surface area and volume due to statistical counting, flow rate, CN counter efficiency, and transport loss errors. Ambient water and ice are removed from sampled particles before they reach the instrumentation due to the large temperature increase, typically near 60°C, and relative humidity decrease the sample experiences when it is brought into the aircraft cabin.

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Results

Size Distributions

Particle size distributions taken with the DMA (Differential Mobility Analyzer) onboard the NASA DC-8 during the 757 plume chasing flight, 3 May 96, are shown in Fig. 1. The circles indicate the measurements taken when the 757 was using the high sulfur fuel (700 ppm), and the squares indicate a low fuel sulfur content (70 ppm) case. In order to facilitate comparison with ground test data, an emission index (reference to CO_2 concentration) based differential particle concentration is presented rather than one referenced to a unit volume of sample gas. The background particulate concentration was subtracted out to focus on the jet engine contributions. The two in-plume cases show roughly the same size distribution shape, Junge type, both exhibiting higher particle populations than in clear air cases. The high sulfur distribution shows a relatively higher concentration of small particles when compared to the low sulfur case, and the high and low sulfur size distributions tend to agree in the large particle regime. These in-situ engine exhaust size distributions are similar in shape to those observed from trans-Atlantic aircraft also observed (*Hagen et al.*, 1996) at cruise under project POLINAT for near field encounters. Fig. 1 also shows a comparison between the two flight measurements for the 757 plume and ground test measurements (triangles) from NASA project SNIF, which were taken on 12 Feb 96 from the same 757 used in project SUCCESS. In the ground test, the sample was extracted from 1 m behind the exhaust plane of the engine under a 3800 lbs/hr fuel flow rate chosen to approximate cruise conditions. Both the left and right engines were found to produce similar exhaust emission size distributions. These ground test exhaust size distributions are similar to those observed for other engines sampled near their exhaust plane (*Howard* 1996). The ground test exhaust aerosol was more highly concentrated (per unit volume of sample) but is lower than the airborne samples when referenced to fuel mass in the emission index representation. Clearly plume processing produces additional particles. Also, the size spectrum shape changed from ground samples to airborne samples, with statistically significant enhancement in the airborne samples for particles > 100nm in diameter.

During flights, particle size distributions were taken at selected times using the DMA technique, which covered the size range from 8nm to 250 nm, and were taken continuously

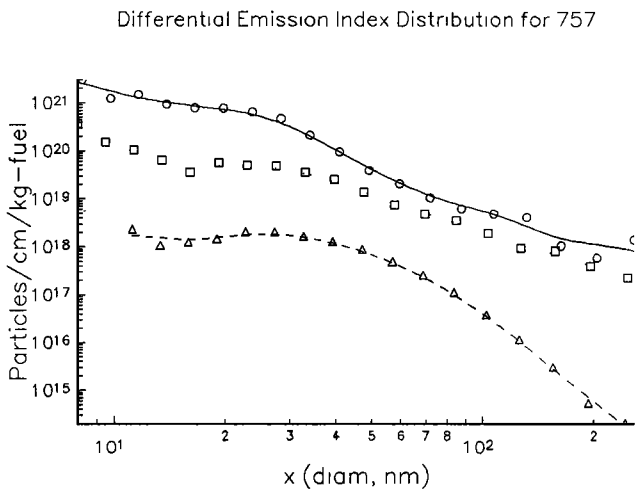

Figure 1. Differential size distributions in emission index format (number of particles per unit size interval per kg - fuel burned) for two plume encounters on 3 May 1996 during the 757 chase, with the circles indicating the measurement made when the 757 was burning high sulfur fuel and the squares indicate the measurement made for low sulfur fuel. The lower curve (triangles) is a size distribution for one of the engines on the same 757 that was measured in a ground test at NASA Langley under NASA project SNIF on 12 Feb. 1996.

using a PMS Instruments Laser Aerosol Spectrometer (LAS) for larger sizes. Fig. 2 shows a typical comparison of the data from the two instruments by superimposing the data from the smallest two LAS channels onto the DMA size spectrum. The circles indicate the DMA points and the squares the LAS points. The two instruments were intercompared (near 250nm) over a 5 hour period on the 21 April 1996 flight. Their average difference in differential concentration over this period was 26%, a small value considering the sometimes rapid variation in concentration with time and the differing integration times of the devices. Thus these two instrument, one using an electric mobility technique and the other using optical sizing, gave good agreement with one another.

Emissions Indices

It is customary to normalize emission species against the amount of fuel (mass) that was used to generate the exhaust emissions. This parameterization, the EI (Emission Index) then takes into account the dilution that naturally occurs between the time the emission occurs and when it sampled. For particulates, the relevant EI can be represented in terms of the number of particles per kg of fuel or the mass of particulates (g) per kg of fuel. Since particulate emissions are known to participate in heterogeneous chemical processes involving trace gaseous constituents in the exhaust, the amount of particulate surface area produced per kg of fuel is also of interest. Here, particulate EI's are referenced to the measured CO_2 concentration above ambient, using an EI for CO_2 of 3150 g/kg-fuel.

The project SUCCESS DC-8 missions which followed the NASA 757, and sampled from its exhaust, provided measurements of CO2, NOx, CN (Condensation nuclei) concentrations, and particle size distributions. From these data, emission indices for particulates have been calculated for the total and non-volatile aerosol. Using data from 757 plume penetrations, as evidenced by spikes in the NO and CO_2 (*Paladino et al.*, 1997), a number based particle EI was calculated for plume penetrations. The effect of changing the fuel's sulfur content was studied in the 3 May 96 flight, using the NASA 757 as the exhaust source. During the time period 72000 SAM (seconds after midnight) to 72700, a high sulfur content fuel (700 ppm) was used, and for times beyond 72730 a low sulfur content (70 ppm) was burned. The EI's were separated into high and low sulfur fuel cases, and average EI's were calculated and the results shown in Table 1. The standard deviations are also included to indicate the variability in the EI. This variability was much larger than the measurement errors in aerosol properties and CO_2 concentration above background. During the 757 chasing flights on 3 May and 7 May, ten particle size distributions were taken during 757 plume penetrations. From these distributions, an average particle size with respect to aerosol surface area and an average particle size with respect to aerosol volume were determined. These, along with an assumed particle density of 1.9 g/cm^3, were used to calculate areal and mass based EI's. These were again separated into high and low sulfur fuel cases, and the results given in Table 1.

Fuel sulfur was found the have a statistically significant impact for total particle EI's, however, no such impact was observed for the non-volatile component. Pueschel observed a similar particle emission enhancement factor between the low and high sulfur cases (*Pueschel* 1997) for this 757 chase, but with higher reported emission indices.

The EI's for total particles for the entire flight were also segmented according to distance between the 757 and DC-8 for separation distances ranging from 3 km to 24 km. Averages for points sharing similar distances, e.g. 3 to 5 km, were calculated. In this separation distance regime, the number-based particulate EI appeared to decrease slightly with distance. However, linear regression analysis revealed no statistical significance to the slope.

Under NASA project SNIF, particle measurements were made in ground tests on the same NASA 757 at NASA Langley. In this case, the exhaust was sampled with an extraction probe located 1 m behind the exhaust nozzle of the engine. Using total CN measurements and estimating the CO_2

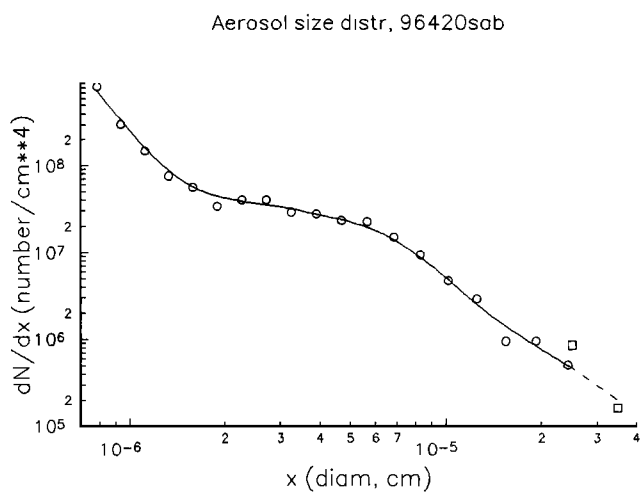

Figure 2. Differential particle concentrations taken during the 20 Apr. 1996 DC-8 flight showing a comparison between the Electric Aerosol Classifier (circles) and the Laser Aerosol Spectrometer (squares) in their region of overlap.

Table 1. Emission Indices

	High Sulfur	Low Sulfur	Units
EI(numb,tot)	(2.6±0.4)E+15	(2.8±0.3)E+14	Number/kg-fuel
EI(numb,nv)	(1.2±0.2)E+14	(7.0±0.3)E+13	"
EI(area,tot)	(3.6±0.6)E+4	(3.9±0.4)E+3	cm^2/kg-fuel
EI(area,nv)	(1.6±0.3)E+3	980±40	"
EI(mass,tot)	0.62±0.10	0.067±0.007	g/kg-fuel
EI(mass,nv)	0.042±0.007	0.026±0.001	"

(errors quoted are 1σ)

concentrations using the fuel flow method, number based EI's were found to be 1.7E+13 (right engine) and 1.5E+13 (left engine). These values are smaller by factors of 4-7 depending on the fuel sulfur content when compared to the airborne non-volatile EI measurements taken under project SUCCESS. The airborne total particle EI's in Table 1 are an order of magnitude larger than the non-volatile EI's. This would indicate that plume processing is generating large numbers of volatile particles and also adding a small number of non-volatile particles.

Since the fuel sulfur content was known for the 757 sampling flights, the fraction of fuel sulfur converted to aerosol can be estimated. Assuming a complete conversion of sulfur into sulfuric acid aerosol, the 700 ppm S fuel yields an upper limit EI(H_2SO_4) = 2.2 g/kg-fuel, and the 70 ppm S fuel yields a limit of 0.22 g/kg-fuel. Using the mass based EI's from Table 1, and attributing the difference between the total and non-volatile EI's to H_2SO_4 aerosol, the observed H_2SO_4 aerosol EI's are 0.58±0.11 g/kg-fuel for the high sulfur fuel case and 0.041±0.008 g/kg-fuel for the low sulfur fuel case. This gives conversion efficiencies of 26%for the high sulfur case and 19% for the low sulfur case, but the low sulfur case has a substantial uncertainty. These values fall between the conversion factor ranges reported in modeling and experimental studies.

Summary

Jet exhaust aerosols are clearly distinguishable from the ambient background atmospheric aerosol and as such can be used to detect the presence of a plume. Particle size distribution measurements made in exhaust plumes using the electric mobility technique show a characteristic Junge type shape. As compared to the ground measurements, the flight size distributions show a higher population of particles, especially at large size. Size distributions made using two different techniques, electric mobility and optical, demonstrated good agreement in the size range around 250 nm, the region of overlap.

Particulate EI's were measured for exhaust plume penetrations. In the experiment involving changing the sulfur content in the 757's fuel, the high sulfur case was found to significantly increase the EI for total particles as compared to low sulfur, but no significant increase in the non-volatile EI was observed. The ground based EI's for the 757 were smaller by an order of magnitude than the total particle EI's measured in flight, and below the non-volatile EI's by factors of 4-7 dependent on fuel sulfur content, indicating that initial plume processing was generating particles in the measurable size regime, via gas-to-particle conversion, and condensation processes. The EI was found to have no real dependence on distance from the source aircraft, in the range 3 - 24 km.

Size distribution information was used to develop mass based EI's for the 757, which together with the known fuel sulfur contents, were used to estimate sulfur conversion efficiencies. These were found to be 26% for the high sulfur fuel case and 19% for the low sulfur fuel case.

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