Demonstration of a Regulatory Method for Aircraft Engine Non-volatile PM Emissions Measurements with Conventional and Iso-Paraffinic Kerosene fuels

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ABSTRACT

The aviation industry is exploring the economic viability and environmental sustainability of the use of alternative fuels to power aircraft main engines and auxiliary power units. The International Civil Aviation Organization is also developing a regulatory standard for aircraft engine non-volatile Particulate Matter (nvPM) emissions to meet the growing public demand for improvement in air quality. This study compared the nvPM emissions in the exhaust stream of a small (<26.7 kN thrust) mixed turbofan aircraft engine burning a conventional Jet A fuel as well as a Sasol Iso-Paraffinic Kerosene (IPK) fuel derived from coal, using a standardized sampling and measurement system. The goal of the study was to demonstrate the regulatory system on a small mixed turbofan engine and to assess the suitability and limitations of using such systems for turbofan engines burning fuels with different fuel properties. Significant reductions in both nvPM number- and mass-based emission indices were observed with the IPK fuel across the full spectrum of engine thrust settings. The percent reduction in nvPM mass-based emissions was higher than the reduction in nvPM number-based emissions for the corresponding engine thrust settings because smaller and fewer particles were generated with IPK fuel combustion. PM size distribution mean diameters for the IPK fuel were found to be smaller than that for Jet A. The composition of the organic PM emissions for the two fuels was almost identical, and the organic PM was also found to be proportional to the soot concentration. The nvPM mass-based emissions for the mixed turbofan engine measured with the standardized system exhibited a high degree of measurement uncertainty at low engine thrust settings. This limitation was not encountered for nvPM number-based emissions.

INTRODUCTION

Aircraft main engines and auxiliary power units emit gaseous and particulate matter (PM) emissions which impact local air quality, global climate, and health. Standards for gaseous emissions such as oxides of nitrogen (NOx), carbon monoxide (CO), and unburned hydrocarbons (UHC), and smoke emissions reported in terms of Smoke Number (SN) are set by the International Civil Aviation Organization (ICAO) [1] for turbofan/turbojet engines of >26.7 kN maximum rated thrust. ICAO also sets SN standards for engines < 26.7 kN rated thrust. The ICAO Aircraft Engine Emissions Databank [2] reports these emissions data for different aircraft engine types at four engine thrust settings corresponding to the Landing Take-Off (LTO) cycle – idle (7% rated thrust), approach (30% rated thrust), climb out (85% rated thrust), and take-off (100% rated thrust) [1].

ICAO's Committee on Aviation Environmental Protection (CAEP) is currently developing a regulatory standard for non-volatile Particulate Matter (nvPM) emissions from aircraft engines with a maximum rated thrust of >26.7 kN. In this context, nvPM is defined as the particles emitted at the aircraft engine exhaust nozzle exit plane that do not volatilize below a temperature of 350 °C. The new standard for aircraft engines nvPM emissions will align the aviation sector with other transportation modes that currently regulate PM emissions. ICAO/CAEP is also evaluating the contribution of nvPM emissions from all aircraft engines; including those of ≤26.7 kN rated thrust, such as turboprop, turboshaft, and auxiliary power unit engines.

A standard methodology for the sampling and measurement of nvPM emissions from the exhaust of aircraft engines, designed to operate in parallel with existing sampling systems for gaseous emissions and smoke certification, has been developed by the Society of Automotive Engineers (SAE) and specified in Aerospace Information Report (AIR) 6241 [3]. Performance

evaluation and comparisons of the AIR6241 compliant systems have been successfully completed [4]. The data obtained using these standardized systems will assist ICAO/CAEP in the development of a protocol that will be used for the certification of nvPM emissions from aircraft engines, and it will also be used to better assess the impacts of aviation operations on local air quality, global climate, and health.

The aviation industry, including engine manufacturers and commercial airlines, is actively exploring the economic viability and environmental sustainability of the use of alternative fuels [5]. Any new fuel must be certified by the American Society for Testing and Materials (ASTM) before it can be used in aircraft systems [6]. Iso-Paraffinic Kerosene (IPK) became the first jet fuel component (up to 50% in a blend with petroleum kerosene) to gain approval for commercial use. Sasol's IPK is used to blend semi-synthetic jet fuel approved for use by both United Kingdom Ministry of Defence's DEF STAN 91-91 [7] and ASTM D1655 [8]. Aircraft engines burning alternative fuels have shown a dramatic reduction in their PM emissions [9-14]. The impact of using alternative fuels in mixed turbofan engines <26.7kN rated thrust on nvPM emissions employing the standardized measurement system has not been previously explored. This information is critical for ICAO/CAEP in evaluating the relative contribution of nvPM emissions for different aircraft engine size categories.

This paper presents the results of a demonstration of the regulatory method to measure nvPM number- and mass-based emissions in the exhaust stream of a small (<26.7 kN thrust) mixed turbofan aircraft engine burning a conventional Jet A fuel as well as a Sasol IPK fuel derived from coal via the Fischer-Tropsch process. The nvPM number- and mass-based emissions were measured using the AIR6241 compliant North American mobile reference system operated by the Missouri University of Science and Technology. The nvPM emissions were also

characterized in terms of particle size distributions and non-refractory (organic) emissions. The measurements were performed at the Williams International engine test facilities in Walled Lake, MI in May 2013.

EXPERIMENTAL METHODS

Engine and operating conditions. The test vehicle used during this demonstration was a small (<26.7 kN thrust) mixed turbofan aircraft engine, for which emissions data are not reported in the ICAO Emissions Databank. The operating conditions selected to perform emissions measurements were chosen based on the engine's rated thrust and the standard LTO cycle, spanning idle to maximum thrust. Emissions measurements were also performed above and below the LTO range for engineering evaluation. The engine operators cycled the engine through a range of thrust conditions while the engine was burning Jet A, and following an engine shutdown, IPK. No bleeds or shaft power was extracted during the ground test.

Sampling System and Instrumentation. A rotating multi-point probe was used to extract gaseous and PM emissions samples from the mixed flow environment within half a nozzle diameter of the engine exit plane. The cruciform probe consisted of hollow tubes lined with a series of sampling holes of equal diameter and in number always greater than 12. Prior to testing, a carbon balance was performed to show consistency between the air-fuel ratio (AFR) within the engine and that measured by emissions extracted with the probe. The probe rotated through the exhaust cross-section in order to ensure the collection of representative emissions data at each engine thrust setting [1]. The probe was connected to a heated 7.6 m line (7.9 mm i.d.) maintained at 160°C that conveyed the sample to a heated box with two compartments. The first compartment was maintained at 160 ± 15 °C and consisted of a 3-way splitter which divided the

total exhaust sample among three flow streams – nvPM, pressure control, and Annex 16 lines. The Annex 16 line was used to measure UHC using a Thermo Environmental Instruments Model 51C-HT flame ionization detector (FID), and CO and carbon dioxide (CO_2) using a Fuji ZRH non-dispersive infrared (NDIR) detector. The second compartment of the heated box was maintained at 60 ± 15 °C and housed a Dekati DI-1000 ejector diluter. The nvPM sample was diluted using filtered, dry nitrogen. The dilution factor was maintained in the range 8-13, as prescribed by AIR6241 [3]. The diluted nvPM sample with a flow rate 25 ± 2 slpm was transferred by a temperature controlled carbon loaded PTFE sample transfer line 25m in length, 7.9 mm i.d., maintained at 60 ± 15 °C to a 1μm cyclone and then a second 3-way splitter to direct the sample to the instrumentation in the nvPM measurement system.

The nvPM emissions were characterized in terms of number, mass, size distributions, and chemical composition using real-time, high resolution instruments. The AVL Particle Counter (APC) Advanced [4] was used to measure nvPM number concentration. The APC used in this study consisted of a two stage diluter with a catalytic stripper in between to remove volatile particles, and an n-butanol based TSI 3790E condensation particle counter (CPC) which has a >50% counting efficiency at 10 nm. The dilution in the APC was adjusted such that the nvPM number concentration measured by the CPC always remained in the single particle count mode (<10,000 particles/cm^3). Three instruments were used for nvPM mass measurements - an Artium Laser Induced Incandescence LII-300 (LII) [15], an AVL Micro Soot Sensor (MSS) [16], and a Cavity Attenuated Phase Shift - PM extinction monitor (CAPS-PM_{ex}) [17, 18]. The LII-300 and MSS rely on absorption whereas the CAPS-PMex measures light extinction, which results from a combination of absorption and scattering. The LII measures refractory black carbon (rBC), while the MSS and CAPS-PM_{ex} report the equivalent black carbon (EBC) [19]. In this case, both rBC

and EBC are considered as surrogates for nvPM. The LII-300 uses laser-induced incandescence technique which heats particles with a high power pulsed laser to temperatures up to 4000K. Photomultipliers detect the quasi blackbody radiation, and the intensity of the measured signal coupled with time-resolved particle temperature is used obtain nvPM mass concentration. The photoacoustic method is employed by the MSS to quantify nvPM mass concentration. The MSS uses a continuous wave laser cycled on and off at 4kHz to heat light-absorbing particles which transfers heat to the surrounding gas, generating pressure waves which are detected by a highly-sensitive microphone. The CAPS-PMex uses a square wave modulated light emitting diode (LED) as a light source, as opposed to a laser in the case of the LII and MSS, and measures the change in the phase shift of the distorted waveform of the modulated light leaving the highly reflective optical cavity. The measured change in phase shift is proportional to the particle extinction and is used to derive nvPM mass concentration. The limit of detection for the LII and MSS is 1 $\mu g/m^3$, whereas for the CAPS-PMex it is 0.1 $\mu g/m^3$.

Only the LII and MSS were calibrated to the NIOSH 5040 protocol specified in AIR6241. Since in principle, the extinction method measures the intensity ratio of incoming and outgoing light beams, no calibration on light intensity or sample concentration is necessary for the CAPS-PMex. The accuracy of the CAPS-PMex technique was verified prior to the study by comparing the measured extinction cross section with the calculated results from Mie theory, using mono-dispersed polystyrene latex (PSL) spheres (300-600 nm in diameter). The results obtained showed that the CAPS-PMex measurements were in excellent agreement with the Mie calculations.

Particle size distributions in mobility diameter from 5nm to 1000nm were measured using the Cambustion DMS500 [20, 21]. Non-refractory PM organic emissions were evaluated with a

compact Time of Flight Aerosol Mass Spectrometer (CToF-AMS) [21]. The CO_2 concentration in the diluted nvPM line was measured using a LiCor 840A NDIR detector. A schematic of the sampling and measurement system deployed in this campaign is presented in Figure 1. The sampling and measurement system was fully compliant with the specification outlined in AIR6241 and has been used previously to measure nvPM emissions from a turbofan engine [4] and an aircraft auxiliary power unit [23].

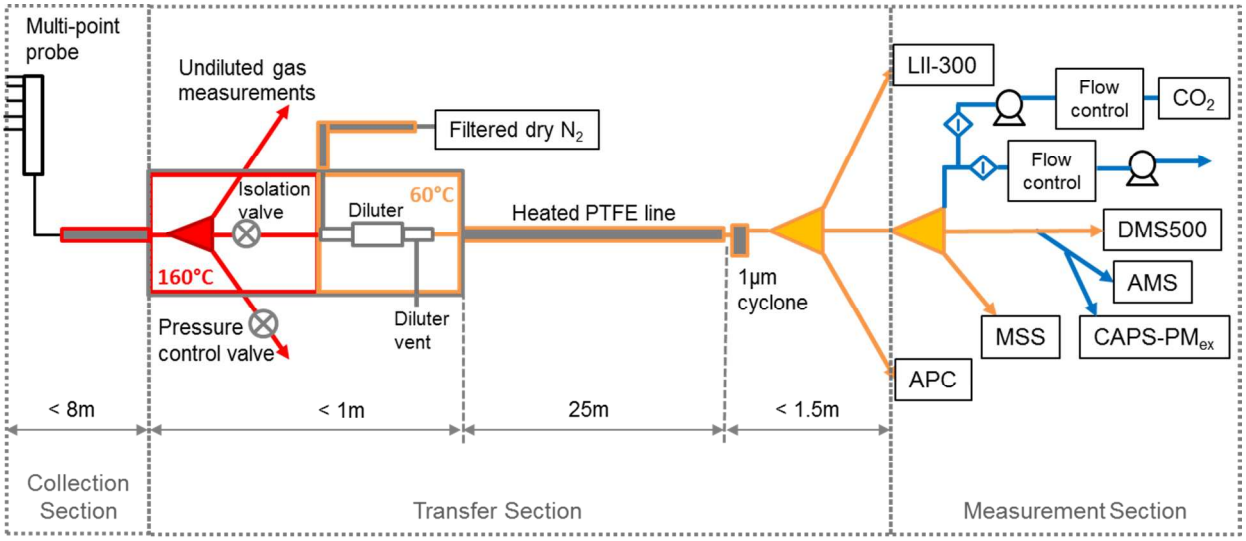

Figure 1: Layout of nvPM sampling and measurement system

Fuel Properties. The Jet A fuel was procured from Avfuel, a global supplier of aviation fuel. The IPK fuel derived from coal was manufactured by Sasol using the Fischer-Tropsch process. The IPK fuel used during this study contained anti-icing and lubricity additives and was delivered to Williams International from Wright-Patterson Air Force Base. Conventional Jet A consists of varying amounts of n-paraffins, iso-paraffins, cyclo-paraffins, and mono-ring alkylated aromatics [24], whereas IPK is composed of iso-paraffinic compounds characterized by a high degree of branching [25, 26]. The fuel properties of the two fuels used during the test (Table 1) are similar to those reported in other emissions tests [9, 10, 13, 23, 26]. The Jet A fuel

also had naphthalenes content that was significantly lower than the maximum allowed under ASTM D1655 [8]. The main difference between the two fuels was that the IPK fuel had very low aromatic content compared to Jet A. Fuels with low aromatic content have been shown to impact seal swell characteristics [27]. Both Jet A and IPK fuels also had very low sulfur content. The IPK fuel does not meet current ASTM specifications for use in the aviation industry in terms of density and aromatic content [28]. However, it can be used as a blending agent (up to 50%) with conventional Jet A/Jet A-1 fuels [6].

Table 1. Fuel Properties‡

Property	ASTM Test	Unit	Jet A	Sasol IPK
Density at 15°C	D4052	kg/m^3	813	760
Kinematic viscosity at –20°C	D445	mm^2/s	4.5	3.5
Distillation temperature	D86			
10% recovered		°C	173	164
End Point		°C	275	222
Flash Point	D56 for Jet A D93 for IPK	°C	44	44
Net heat of combustion	D4809	MJ/kg	43	43.9
Aromatics	D1319	% volume	20	1
Naphthalenes	D1840	% volume	0.8	0
Total Sulfur	D4294 for Jet A D2622 for IPK	% mass	0.02	0.0014
Smoke point, mm	D1322	mm	20	28.5
Hydrogen Content (by NMR)	D7171	% mass	13.7	15.4
Carbon Content (calculated)		% mass	86.3	84.6
H/C ratio (calculated)			1.89	2.17

‡Fuel analyses provided by Air Force Petroleum Agency, Wright-Patterson Air Force Base

Data Processing. The nvPM number and mass concentrations were converted to number- and mass-based emission indices, EIn (#/kg fuel burned) and EIm (mg/kg fuel burned), respectively using the calculation protocol outlined in AIR6241 [3] and described elsewhere [4]. Since the engine used in this study was a mixed turbofan engine and the emissions were sampled from the mixed exhaust flow, the ambient CO_2 concentration was subtracted from that measured in the exhaust flow to determine the emission indices. The emission indices are reported at standard temperature (273.15 K) and pressure (101.325 kPa). The thermophoretic loss in the sample extraction system was negligible for the mixed turbofan engine and hence not considered in the analysis. Since the emissions data are proprietary, the emissions are presented in a normalized form, achieved by dividing the EIn and EIm values by a fixed normalization factor (the maximum respective EI value). Measurement uncertainties in nvPM emissions parameters were calculated using 1σ standard deviation of the average data. In order to compare the nvPM emissions between the Jet A and IPK fuels at the same engine operating condition, the fuel flow rate for the IPK fuel was adjusted to account for the difference in net heat of combustion values to provide a Jet A-equivalent normalized fuel flow rate. This dataset was used to calculate the percent reduction in nvPM number and mass-based emissions at the four engine thrust conditions corresponding to the LTO cycle. The uncertainty in percent reduction was calculated using a method previously used to compare nvPM emissions reduction with alternative fuels [10]. It was estimated by taking the square root of the sum of the squares of the fractional uncertainty in the percent difference and fractional uncertainty for Jet A, multiplied by the percent difference.

RESULTS AND DISCUSSIONS

PM number- and mass-based emissions. The normalized nvPM number and mass-based emission indices as a function of normalized fuel flow rate are presented in Figures 2 and 3,

respectively. For both Jet A and IPK fuels, EIn and EIm generally increased with increasing fuel flowrate. EIn for the 100% normalized fuel flowrate was slightly lower than that at 85% for Jet A. Significant reductions in both EIn and EIm were observed with the IPK fuel across the full spectrum of engine operating conditions. The EIm calculated from the LII, MSS, and CAPS-PM_{ex} data had the same trends and similar reductions with the IPK fuel. The reduction in nvPM emissions can be attributed to the lower aromatic content and higher hydrogen content of the IPK fuel. Higher fuel aromatic content has been shown to enhance the formation of polycyclic aromatic hydrocarbons (PAHs) and produce more precursors that contribute to the formation of soot [29]. The IPK fuel also has a higher smoke point than Jet A, which indicates a lower sooting tendency. In one particular example, within the combustion system of a CFM56 engine, paraffinic fuels have been shown to delay the onset of soot inception compared to fuels containing aromatic compounds, and have a lower fuel-air mixing local equivalence ratio resulting in lower primary particle concentration [30]. This may help to explain the reductions in nvPM emissions observed with the IPK fuel in this study.

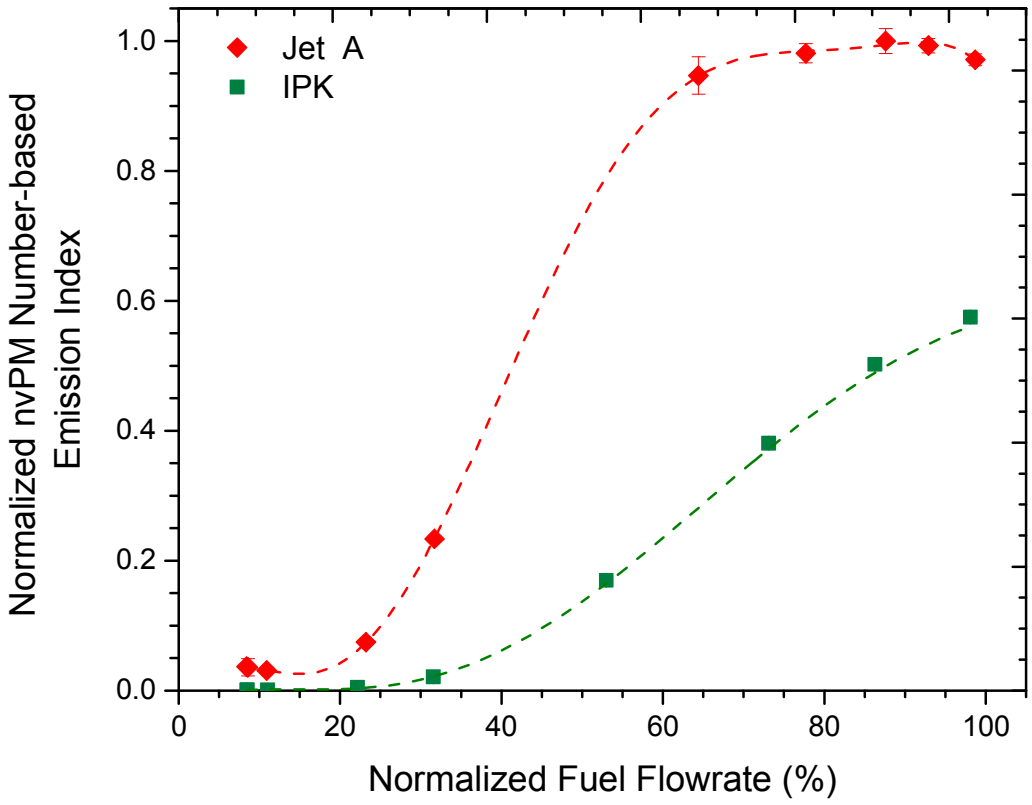

Figure 2: nvPM number-based emission index profile for the mixed turbofan engine burning Jet A and IPK fuels

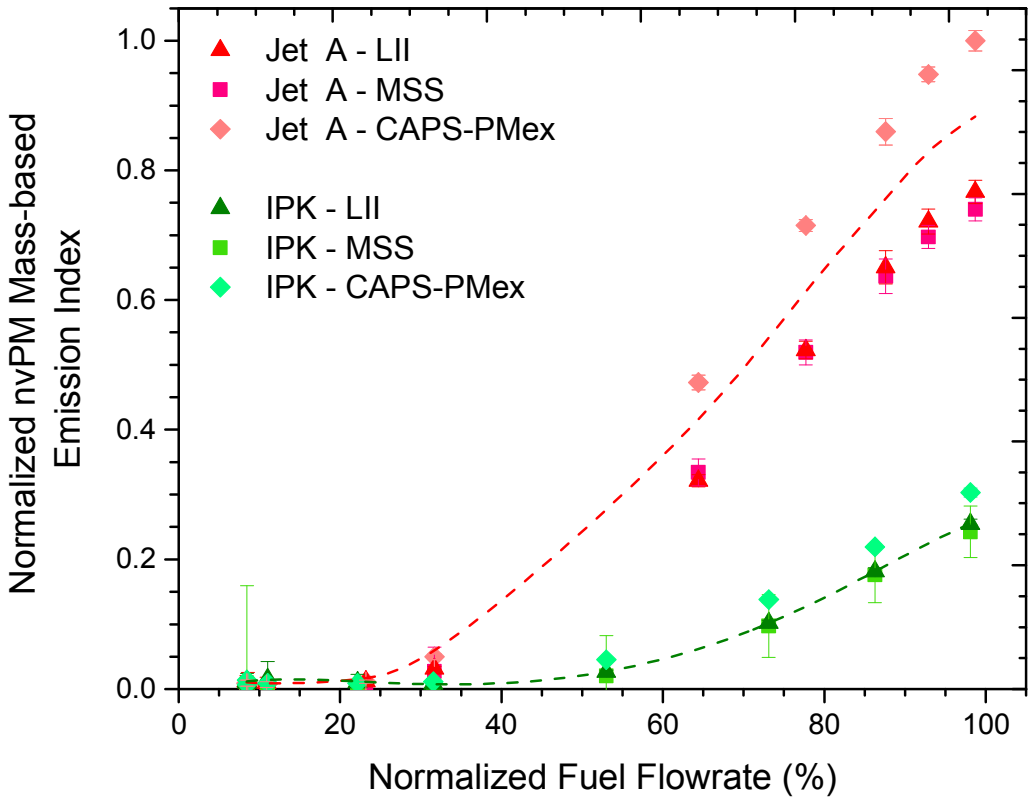

Figure 3: nvPM mass-based emission index profile with the LII, MSS, and CAPS-PM_{ex} for the mixed turbofan engine burning Jet A and IPK fuels

The percent reduction in nvPM EIn for the IPK fuel relative to Jet A and the respective uncertainties at the four LTO cycle conditions is shown in Figure 4. The reductions were greatest at engine thrust settings corresponding to 7% and 30%. Significant yet smaller reductions at 85% and 100% engine thrust settings were also observed. Similar reductions have been reported for larger turbofan engines burning fuels with similar fuel properties [10, 14].

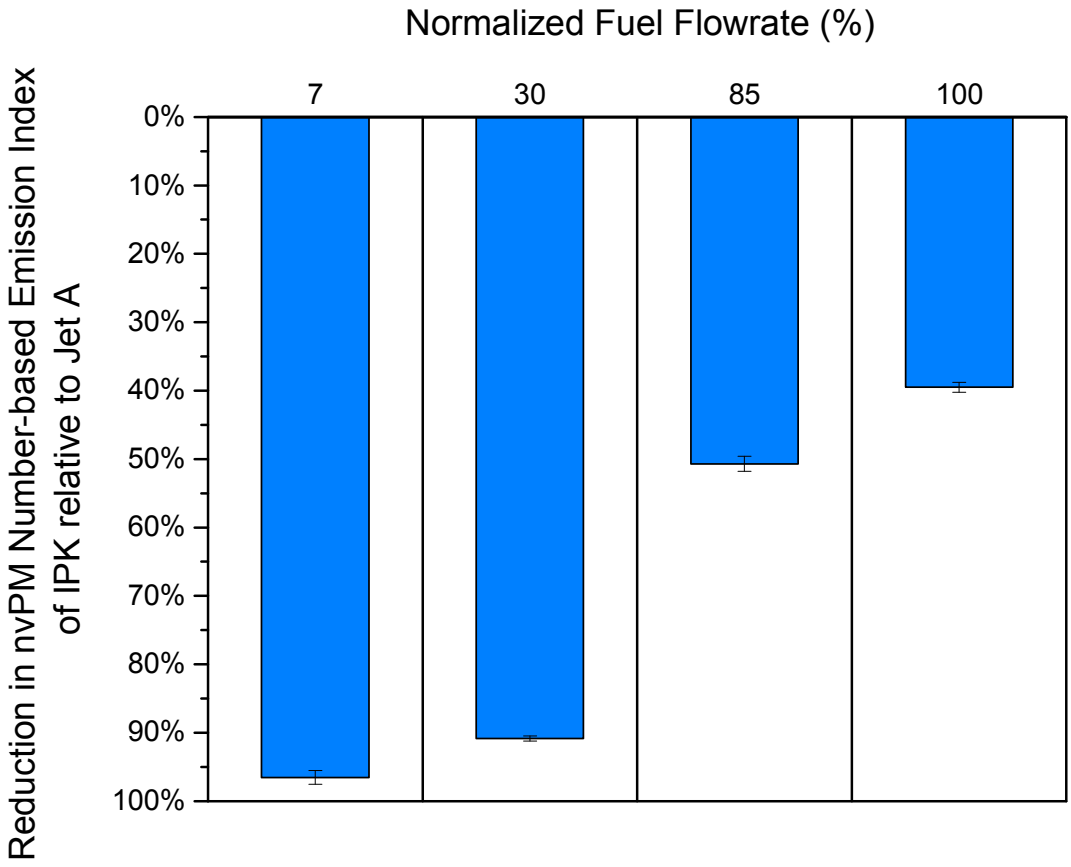

Figure 4: Reduction in nvPM number-based emission index of IPK relative to Jet A at the four LTO cycle conditions

The data from the LII, MSS and CAPS-PM_{ex} mass instruments were averaged in order to determine the reduction in EIm using IPK relative to Jet A at the four LTO conditions (Figure 5). At the 7% engine thrust setting the AIR6241 compliant system exhibited a high degree of measurement uncertainty for mass-based emissions for the mixed turbofan engine burning Jet A and IPK (Figure 3). Hence the calculation of a percent difference at 7% engine thrust setting could not be resolved to statistically significant values. Significant reductions in EIm, on the order of 70%, were observed at the three other LTO cycle conditions.

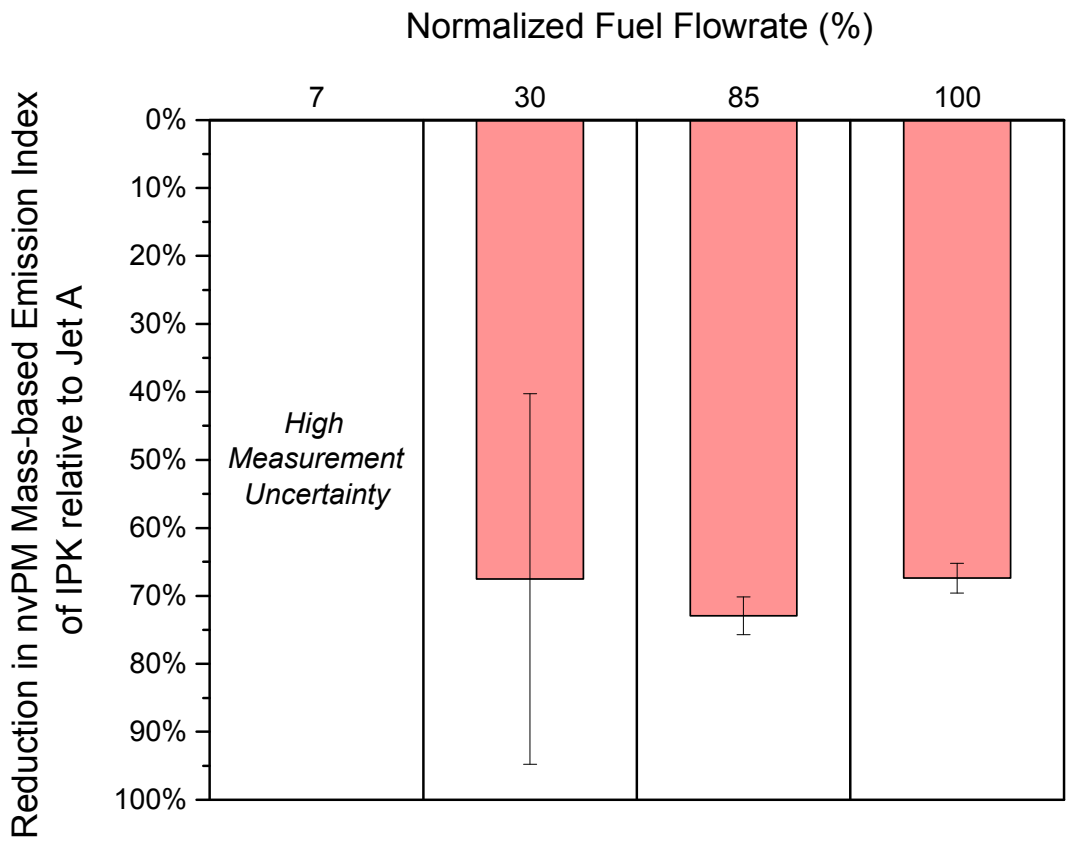

Figure 5: Reduction in nvPM mass-based emission index (based on averages of LII, MSS, and CAPS-PM_{ex}) of IPK relative to Jet A at the four LTO cycle conditions

Comparison of nvPM EIm measured by the LII, MSS, and CAPS-PM_{ex}. The three mass instruments used in this study all measure nvPM mass-based emissions using different methodologies. Figure 6 presents the comparison of the mass instruments to assess their relative differences from data for both Jet A and IPK tests. In Figure 6a, the data from each instrument is plotted against the average of the normalized EIm of the three instruments. The LII and the MSS were ~10% lower, and the CAPS-PM_{ex} was ~20% higher than the average nvPM EIm. Previous studies have shown that linear plots such as those presented in Figure 6a do not accurately

capture the differences at low EIm values [4]. The ratio of the individual instrument EIm to the average nvPM EIm was computed and compared against the average normalized EIm (Figure 6b). The majority of the data lies within 20% of the average normalized EIm. Larger variations are observed at very low EIm values. This trend and the general magnitude of variation have also been reported for larger turbofans engines [4]. A limitation of the standard AIR6241 compliant system is that the instruments used to measure nvPM mass-based emissions currently have neither the precision nor the resolution required to measure mass at very low levels.

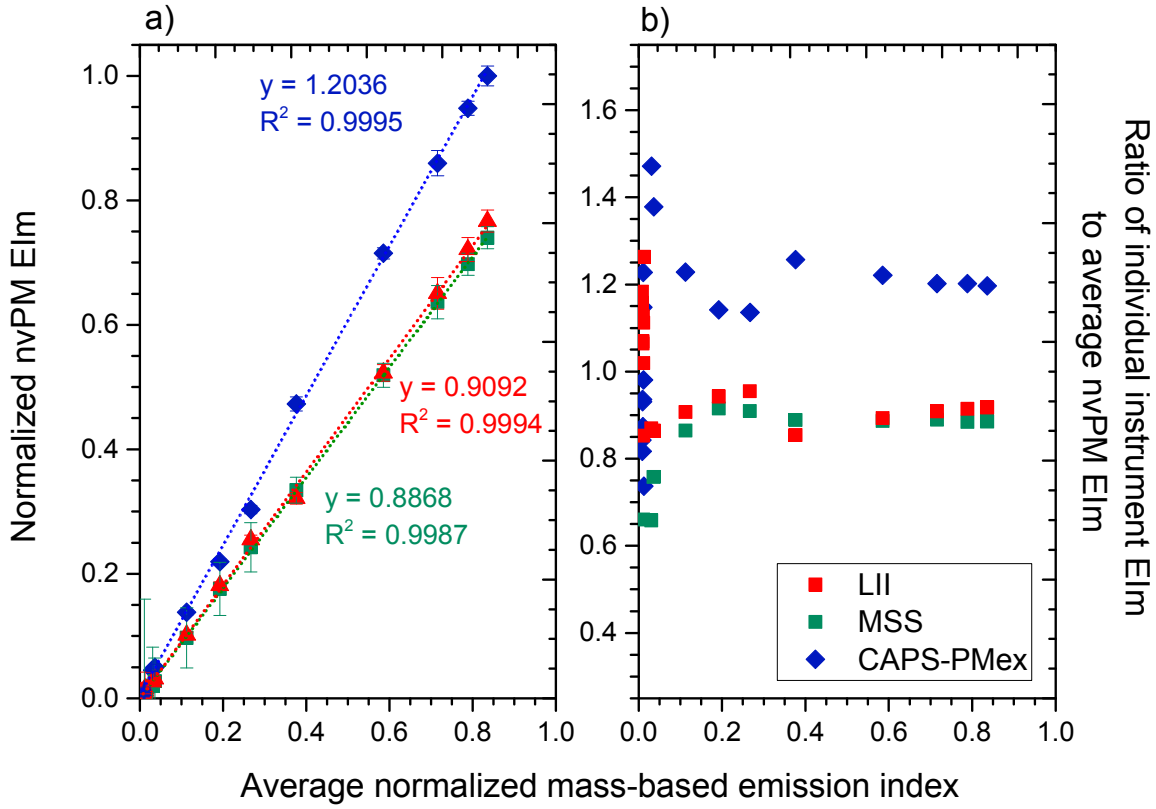

Figure 6: Comparison of nvPM EIm between the LII, MSS, and CAPS-PM$_{ex}$ instruments

Correlation of nvPM mass with FOA3. The nvPM mass-based emission index for Jet A was compared to that obtained from the First Order Approximation version 3.0 (FOA3) [31]. The FOA3 methodology for nvPM estimation is based on a historical data set which showed that smoke number correlated well with nvPM mass-based emissions. FOA3 uses this correlation with smoke number and engine AFR values for turbofan engines as inputs. During this study smoke number was not measured in parallel with nvPM emissions. Hence smoke number data measured during engine type certification was used to represent the smoke number produced by this particular engine type. It is reasonable to use the certification smoke number in this comparison since a representative exhaust sample was acquired and the gaseous emissions were consistent with those recorded (but not reported) during the certification test.

In this analysis, FOA3 based non-volatile EIm was calculated using the overall engine AFR measured during the test for a particular engine thrust setting along with the associated certification SN data. The engine AFR was calculated by directly measured values of airflow and fuel flow. Specifically, a bell-mouth inlet, mounted forward of the engine fan casing and in compliance with industry standard practice, was equipped with instrumentation that enables direct measurement of engine airflow with high accuracy and precision. The fuel flow was measured by a flow controller, downstream of the fuel supply, which had been individually calibrated to the specific gravity of the fuel batch used to test. Thus, the AFR reported was simply the ratio of these direct test measurements.

FOA3 recommends that “representative AFR” values be used only when the AFR values are not known. Generally, exact AFR values for a given engine are proprietary and therefore FOA3 assumes an average AFR per engine thrust setting for all certified commercial aircraft engines.

The representative AFR values for FOA3 were not used in this analysis since measured AFR values were readily available, and therefore a more accurate correlation could be obtained.

Figure 7 presents the results of the comparison of the FOA3 "best estimates" of non-volatile EIm computed FOA3 with that measured by the average of the mass instruments with the AIR6241 compliant system for the engine thrust settings where corresponding smoke number data was available. The mass-based emissions using FOA3 "best estimates" was found to be greater than that measured by the AIR6241 compliant system by ~ 34%. This analysis shows that FOA3 can overestimate the nvPM mass-based emissions for a mixed turbofan engine when measured AFR values are used in the analysis.

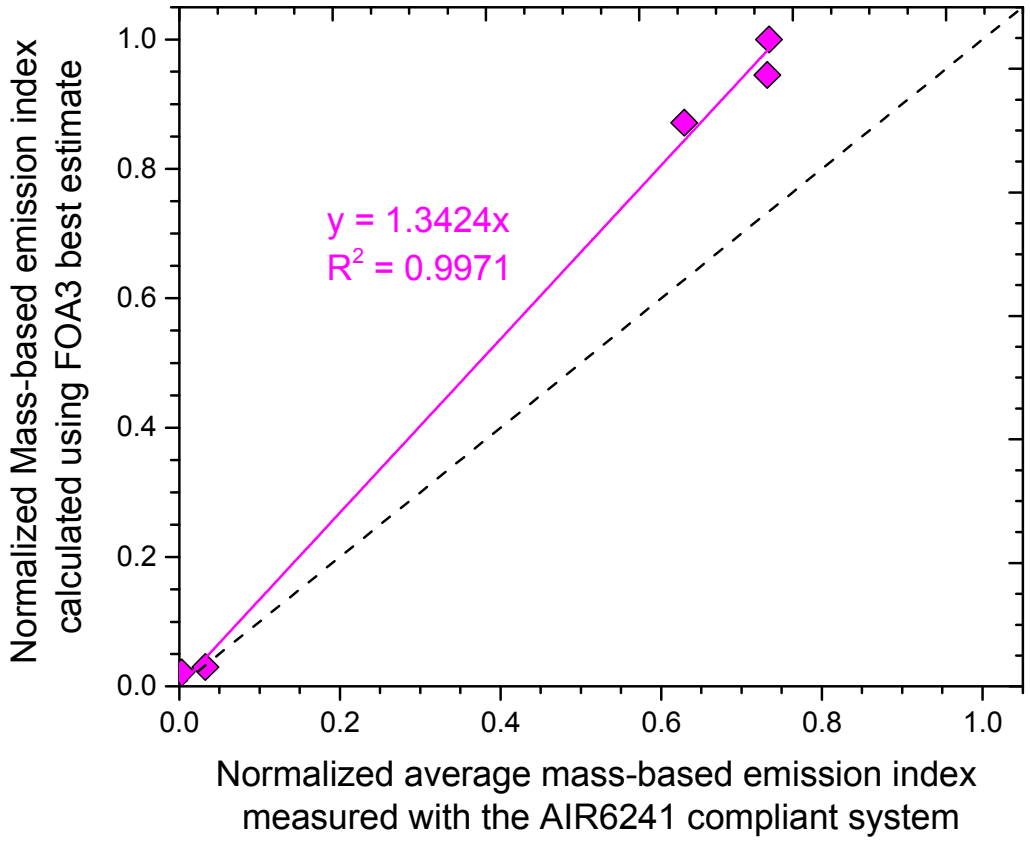

Figure 7: Comparison of mass-based emission index between the FOA3 estimates with that measured with the average EIm with the AIR6241 compliant system

PM Size distributions. PM size distributions at the measurement location were converted to EIn distributions to compare the emissions between the Jet A and IPK fuels. Figures 8 and 9 present the normalized EIn size distributions for the mixed turbofan engine burning Jet A and IPK, respectively, as a function of normalized fuel flowrate for the four LTO cycle conditions. The size distributions were generally lognormal. The geometric mean diameter (GMD) of the distributions was found to increase linearly with increasing fuel flowrate for both Jet A and IPK. The GMD ranged from 15nm to 50nm for Jet A and from 15 nm to 45 nm for IPK. The uncertainty in the reported GMD is ± 5%. The geometric standard deviation (GSD) varied from 1.69 – 1.82 for Jet A and 1.5 – 1.76 for IPK. These values for GMD and GSD are consistent with those reported in other studies for emissions sampled at the engine exit plane with engines burning conventional and alternative fuels [4, 9, 10, 13, 23, 32, 33].

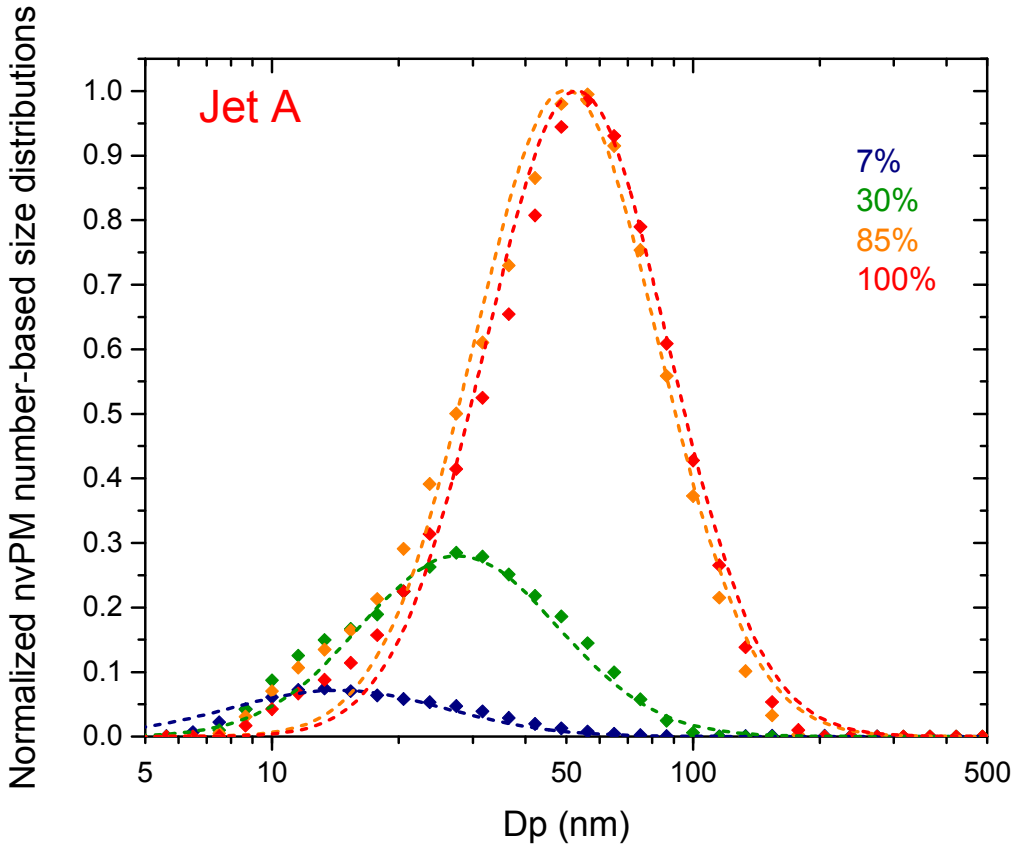

Figure 8: Normalized nvPM number-based size distributions for the engine burning Jet A at normalized fuel flowrates corresponding to the four LTO cycle conditions

For a specific fuel flowrate, the GMD for the IPK fuel was found to be smaller than that for Jet A. Similar reductions have been observed in other engines burning paraffinic fuels [10, 13, 14, 23, 26]. The percent reduction in EIm is higher than the reduction in EIn for the corresponding engine thrust conditions (Figures 4 and 5) because the size distribution shifts towards smaller particle sizes with IPK fuel combustion. In another study with a CFM56-2C1

engine burning conventional and alternative fuels, the primary particle size for paraffinic fuels was reported to decrease with engine thrust setting [30].

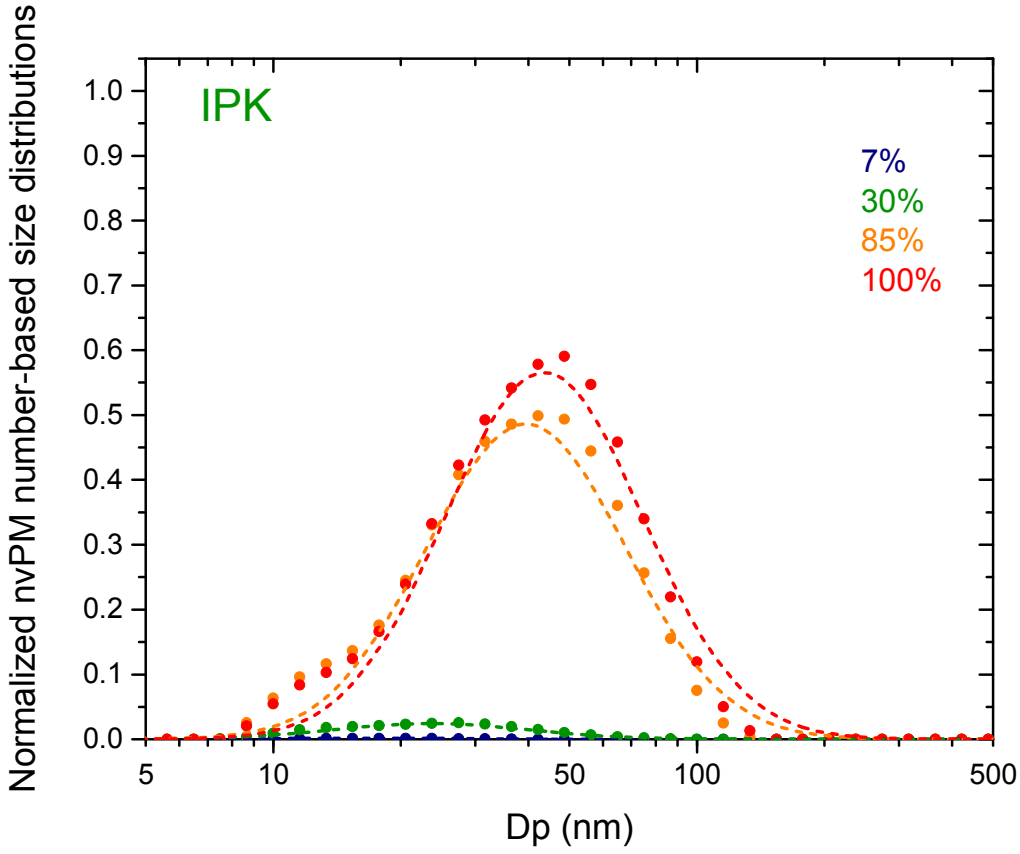

Figure 9: Normalized nvPM number-based size distributions for the engine burning IPK at normalized fuel flowrates corresponding to the four LTO cycle conditions

PM organic-based emissions. The AIR6241 compliant measurement system was designed to measure nvPM. However, aircraft engine exhaust also contains non-refractory PM in the form of organic and sulfate species, which are normally generated from the combustion process [34]. The PM organic-based emission index, calculated from CToF-AMS measurements, as a function of

normalized fuel flowrate had the same profile as that of nvPM mass-based emission index for the Jet A and IPK fuels. PM sulfate-based emissions were not detected due to the low fuel sulfur content for both Jet A and IPK. The average contribution of organic PM to the total mass was ~ 10-15% across the range of engine operating conditions evaluated for this mixed turbofan engine.

The organic PM mass spectra from the Jet A and IPK fuels were very similar. A plot of the organic mass spectra obtained at the highest normalized fuel flowrate for the two fuels is presented in Figure 10. The correlation coefficient, $r^2 = 0.976$, demonstrates that composition of the organic PM emissions for the two fuels is almost identical. This observation is consistent with previously reported results from another study ($r^2 = 0.97 \pm 0.02$) when the mass spectra for conventional Jet A and several fuels derived from the Fischer-Tropsch process were compared [35]. The organic PM concentration of the IPK fuel was determined to be 26.2% ± 0.2% of Jet A. This value is similar to the ratio of the nvPM mass concentration between the IPK and Jet A fuels (0.32 ± 0.03) measured with the AIR6241 compliant system, implying that organic PM was proportional to the soot concentration.

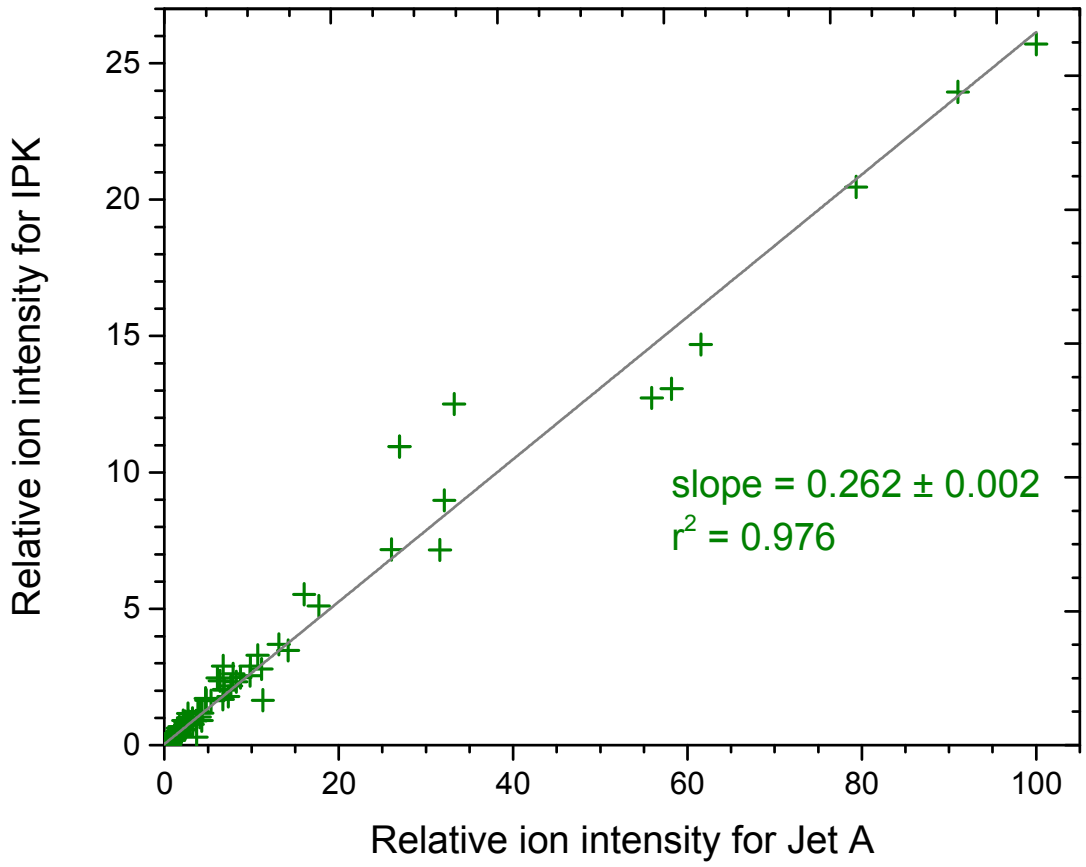

Figure 10: Correlation plot of organic PM mass spectrum for the IPK and Jet A fuels at the highest normalized fuel flowrate

SUMMARY

The nvPM emissions in the exhaust stream of a small (<26.7 kN thrust) mixed turbofan aircraft engine burning a conventional Jet A fuel as well as a Sasol IPK fuel were measured using the AIR6241 compliant North American mobile reference system. Significant reductions in

both number- and mass-based emissions were observed with the IPK fuel over a range of engine operating conditions. The reductions were greatest at engine thrust settings corresponding to 7% and 30%. The reduction in nvPM emissions can be attributed to the lower aromatic content and higher hydrogen content of the IPK fuel relative to Jet A. The non-volatile mass-based PM emissions calculated using FOA3 "best estimates" were found to be greater than that measured by the AIR6241 compliant system by ~ 34%. The percent reduction in EIm was higher than the reduction in EIn for the corresponding engine thrust settings because fewer and smaller particles were generated with IPK fuel combustion. PM size distribution GMDs for the IPK fuel were found to be smaller than that for Jet A. The composition of the organic PM emissions for the two fuels was almost identical and the organic PM was also found to be proportional to the soot concentration. The nvPM mass-based emissions for the mixed turbofan engine measured with AIR6241 compliant system exhibited a high degree of measurement uncertainty at low engine thrust settings. This limitation was not encountered for nvPM number-based emissions. These findings will inform ICAO/CAEP in the development of a regulatory standard for nvPM emissions from aircraft engines. The data will also be used to better assess the impacts of aviation operations on local air quality, global climate, and health, by being able to provide estimates of nvPM emission reductions as measured by a standardized system.

ACKNOWLEDGMENTS

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facility, engine, and fuels) for this project was provided through WI internal research and development funds. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the sponsoring organizations.

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