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Evaluation of Non-Volatile PM Emissions Characteristics of an Aircraft Auxiliary Power Unit with Varying Alternative Jet Fuel Blend Ratios

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ABSTRACT

The aviation industry is increasingly focused on the development of sustainable alternative fuels to augment and diversify fuel supplies while simultaneously reducing its environmental impact. The impact of airport operations on local air quality and aviation related greenhouse

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gas emissions on a life cycle basis have been shown to be reduced with the use of alternative fuels. However, the evaluation of incremental variations in fuel composition of a single alternative fuel on the production of non-volatile particulate matter (nvPM) emissions has not been explored. This is critical to understanding the emissions profile for aircraft engines burning alternative fuels and their impact on air quality and climate change. A systematic evaluation of nvPM emissions from a GTCP85 aircraft auxiliary power unit (APU) burning a 16 different blends of Used Cooking Oil (UCO) derived Hydroprocessed Esters and Fatty Acids (HEFA) type alternative fuel with a conventional Jet A-1 baseline fuel was performed. The nvPM number- and mass-based emission indices for the 16 fuel blends and neat 100% UCO-HEFA were compared against those for the baseline Jet A-1 at the three APU operating conditions. Fuel composition was found to influence nvPM production. The reductions in nvPM were found to be greater with increasing fuel hydrogen content (higher proportion of UCO-HEFA in the fuel blend). For a 50:50 blend of UCO-HEFA and Jet A-1, which would meet current ASTM specifications, the average reduction in nvPM number-based emissions was ~35%, while that for mass-based emissions was ~60%. The nvPM size distributions were found to narrow and shift to smaller sizes as the UCO-HEFA component of the fuel blend increased. This shift has a greater impact on the reduction in nvPM mass compared to the overall decrease in nvPM number, when comparing the blends to the baseline Jet A-1.

INTRODUCTION

In recent years the aviation industry has focused on the development of sustainable alternative fuels to augment and diversify fuel supplies while simultaneously reducing its environmental impact and emissions. Alternative fuels for the aviation sector must be compatible with existing aircraft engines and fuel handling and storage infrastructure to be

considered “drop in” fuels. Several evaluations and flight demonstrations of alternative fuels blended with conventional jet fuel have been undertaken [1], including commercial biofuel flight operations [2] such as the Lufthansa burnFAIR project [3] and KLM’s JFK Green Lane Program [4]. Worldwide there have been more than 1500 commercial flights powered by various blends of alternative fuel with conventional Jet A/Jet A-1, and the technical suitability of drop-in fuel is largely considered proven.

In order for an alternative fuel to become approved for use either as a neat or blended fuel, it must undergo rigorous assessment as detailed in the American Society for Testing and Materials (ASTM) D4054 [5]. ASTM and other fuels specification bodies have established a specification for the manufacture of jet fuel that consists of conventional fuel under D1655 and up to 50% Synthesized Paraffinic Kerosene (SPK) blending components from Fischer-Tropsch (FT) and Hydroprocessed Esters and Fatty Acids (HEFA) under D7566 [6]. ASTM recently approved blending conventional jet fuel with up to 10% of a renewable Synthesized Iso-Paraffinic (SIP) fuel from hydroprocessed fermented sugars as a third annex to D7566 [7].

The potential to reduce both the impact of airport operations on local air quality [8] and aviation related GHG emissions on a life cycle basis [9,10] has provided additional impetus for the development of alternative jet fuels. Studies investigating the emissions of aircraft engines burning either neat FT fuels or 50:50 blends of FT and HEFA fuels with conventional jet fuel have shown that non-volatile particulate matter (nvPM) and sulfur oxides are dramatically reduced [8, 11-15]. However, the systematic evaluation of incremental variations in fuel composition of a single synthetic fuel on the production of nvPM emissions has not been explored. Such insight is critical to understanding the emissions profile for aircraft engines burning alternative fuels, and the engine’s impact on local air quality and climate change.

Conventional aviation jet fuels are a complex mixture of hydrocarbons, typically comprised of normal (n)-paraffins, iso-paraffins, cyclo-paraffins, and aromatics [16]. N- and iso-paraffins typically dominate the class composition of all-fit-for-purpose, petroleum derived fuels [17]. Currently certified alternative jet fuels consist mostly of n- and iso-paraffinic compounds with negligible aromatic and sulfur content [18]. Additionally these fuels typically have an increased H/C ratio and have been shown to have higher energy content when compared to conventional fuels, an important criterion when assessing the viability of these fuels [19].

This paper presents a systematic evaluation of nvPM emissions from an aircraft auxiliary power unit (APU) burning a Used Cooking Oil (UCO) derived HEFA alternative fuel in varying blend ratios with a conventional Jet A-1 baseline fuel to understand the impact of incremental variations in fuel composition on nvPM production. The emissions tests were conducted at the University of Sheffield Low Carbon Combustion Centre, UK in June 2014 using a Garrett Honeywell GTCP85 APU as the test vehicle. In addition to the neat UCO-HEFA and Jet A-1 fuels, 16 different blends of UCO-HEFA with Jet A-1 were used to develop a comprehensive mapping of the relation between fuel composition and the production of nvPM emissions.

EXPERIMENTAL METHODS

Fuel Properties. Conventional Jet A-1 used as the baseline fuel in this evaluation was a straight-run kerosene obtained from Air BP (Kingsbury, UK), while the UCO-HEFA fuel was provided by SkyNRG (Amsterdam, NL). This UCO-HEFA fuel was also used in the JFK Green Lane program [3]. Various blend ratios of 2%, 5%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, 60%, 70%, 75%, 80%, 85%, 90%, and 95% by mass were achieved onsite by blending

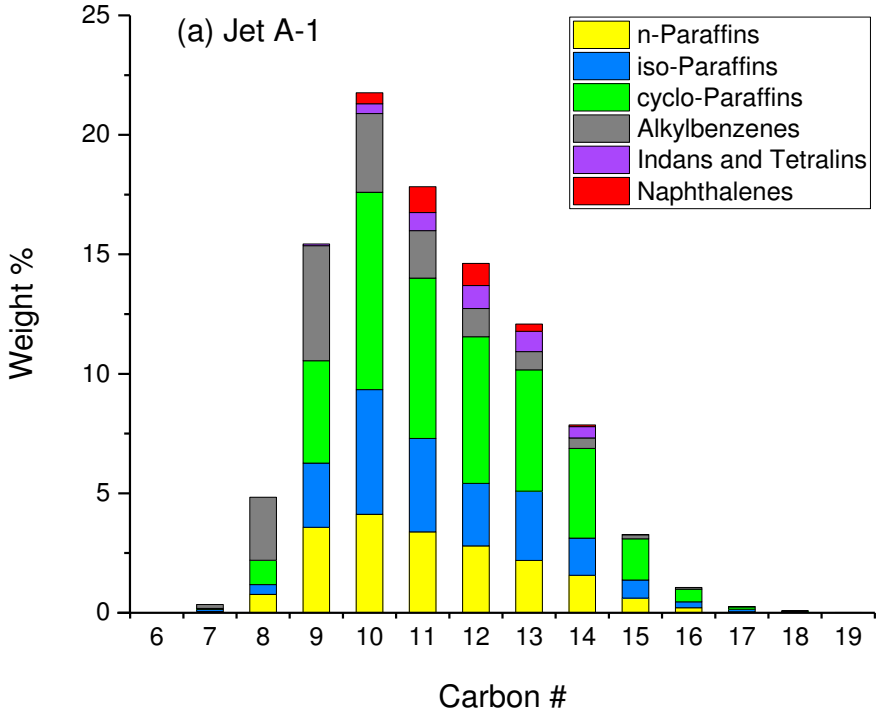
Jet A-1 with the required amount of UCO-HEFA. Neat Jet A-1 and UCO-HEFA were also evaluated. Several of these blends are in excess of current ASTM certification limits for HEFA fuels, however very few studies have characterized emissions from these higher blend ratios, which were essential to develop a robust and complete emissions profile. Selected fuel properties for neat Jet A-1 and UCO-HEFA fuels are listed in Table 1.

Table 1. Selected Fuel Properties[#]

Property	Method	Jet A-1	UCO-HEFA
Density at 15°C, kg/m^3	IP365	805.3	759.6
Distillation temperature, °C	ASTM D86		
10% boiling point		163.8	169.8
90% boiling point		236.4	235.1
Final boiling point		259.1	251.9
Net heat of combustion, MJ/kg	ASTM D3338	43.153	44.023
n-Paraffins, weight %	GCxGC	19.35	19.48
iso-Paraffins, weight %	GCxGC	20.57	71.35
cyclo-Paraffins, weight %	GCxGC	37.65	6.58
Alkylbenzenes, weight %	GCxGC	15.55	1.91
Indans and Tetralins, weight %	GCxGC	3.81	0.6
Naphthalenes, weight %	GCxGC	2.85	0.07
Smoke point, mm	ASTM D1322	23	>50
Carbon, mass %	ASTM D5291	86.2	84.8
Hydrogen, mass %	ASTM D5291	13.7	15.2
H/C ratio	Calculated	1.89	2.14
Sulphur, mass %	ASTM D4294	0.033	<0.018
Kinematic viscosity at –20°C, mm^2/s	IP71	3.521	3.885

[#] Fuel analysis results provided by Intertek Sunbury Technology Centre, UK

The distribution of hydrocarbon groups for the neat Jet A-1 and UCO-HEFA fuels using two-dimensional gas chromatographic separation (GC x GC) analysis is presented in Figure 1. These distributions are similar to those reported elsewhere for conventional and paraffinic fuels [20]. GC x GC analysis has been shown to be in very good agreement with the traditional ASTM D2425 technique for measuring hydrocarbon group types in aviation fuels, and has the added benefit of improved resolution of paraffinic groups [21].



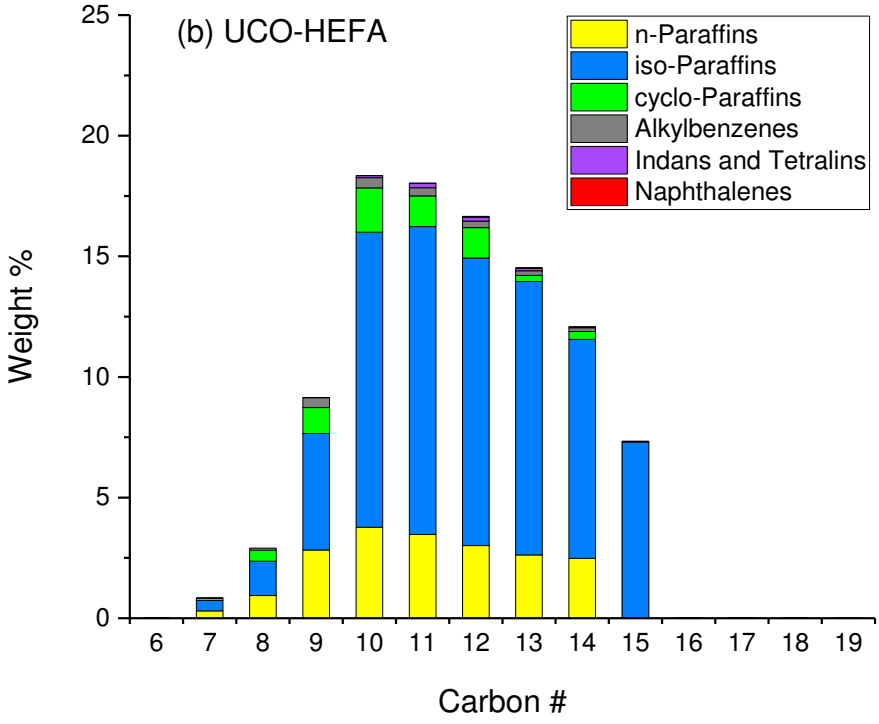


Figure 1: Distribution of hydrocarbon groups for the neat (a) Jet A-1 and (b) UCO-HEFA fuels

APU Operating Conditions. Three operating conditions for the GTCP85 APU were selected to conduct the test – No Load (NL), Environmental Control Systems (ECS), and Main Engine Start (MES). These conditions were chosen since they correspond to the normal operating conditions for an APU. Parameters such as fuel flow rate, RPM, air fuel ratio (AFR), and exhaust gas temperature (EGT) were recorded for each stable APU operating condition. Table 2 presents the parameters for the three APU operating conditions recorded during the Jet A-1 runs. The Jet A-1 runs were conducted at the beginning and end of the study as well as several times in between the biofuel blend runs. Overall, the APU was very stable at each operating condition and the reproducibility of the parameters during the study was very good.

Ambient temperature, ambient pressure, and relative humidity were also recorded throughout the study, and the range of values for these parameters was: 14.0 – 20.6 ºC, 1024.7 – 1031.1 millibar, and 61 – 85%, respectively.

Table 2. APU parameters for the three operating conditions for Jet A-1 runs

Parameter	APU Operating Condition		
	NL	ECS	MES
Fuel flow rate (g/s)	17.7 ± 0.2	25.8 ± 0.3	31.1 ± 1.1
RPM	41435 ± 127	40828 ± 318	40191 ± 742
AFR	135.0 ± 3.9	84.4 ± 0.8	62.2 ± 1.0
EGT (ºC)	324.1 ± 6.0	475.2 ± 5.0	600.0 ± 7.6

Test Matrix. The APU was started and put through a warm up sequence before stabilizing at the first condition. The test matrix followed a stair step down from MES to ECS to NL condition, which represented one test cycle. For each fuel, this test cycle was twice sequenced without APU shutdown. The sequence stepped downward in power in order to minimize differences in APU temperature and hence possible differences in fuel vaporization rate that may then manifest themselves as measurement uncertainties. Emissions data were monitored and recorded over a period of 6 minutes for each condition once the APU was deemed to be stable. The different fuel blends to be tested were selected at random to mitigate possible systematic bias and drift.

Sampling system and Instrumentation. Two identical single-point probes, one for gaseous emissions and smoke measurement and the other for nvPM emissions measurement were place within ½ nozzle diameter of the APU exit plane. The sampling and measurement system employed for nvPM emissions was compliant with the specifications defined in the Society of Automotive Engineers (SAE) Aerospace Information Report (AIR) 6241 [22]. The

description and performance evaluation of the AIR6241 compliant North American mobile reference system operated by the Missouri University of Science and Technology to measure nvPM emissions is presented elsewhere [23]. In this study, the single probe used to extract nvPM emissions samples was connected to a 3-way splitter using a 7.5m long, 7.9mm i.d. thin walled stainless steel tube maintained at 160^0C. The nvPM sample was diluted by particle free dry nitrogen via a Dekati DI-1000 ejector diluter and conveyed to the measurement suite using a 25 m long, 7.9 mm i.d., carbon-loaded, electrically grounded polytetrafluoroethylene (PTFE) tube maintained at 60^0C. Dry gas dilution and heating the sample to 60^0C to the inlet of the instrumentation suppressed the potential for volatile PM formation in the AIR6241 compliant sampling system.

The nvPM number-based emissions were measured using an AVL Particle Counter Advanced (APC) while nvPM mass-based emissions measurements were performed using an Artium Laser Induced Incandescence LII-300 (LII) [24] and an AVL Micro Soot Sensor (MSS) [25]. Non-volatile particle size distributions, which are not specified in AIR6241, were measured using the Cambustion DMS500 [26, 27]. The CO_2 concentration in the diluted nvPM line was measured using a LiCor 840A NDIR detector. These instruments have been used previously to measure nvPM emissions from main aircraft engines [23].

Data Analysis. The nvPM instrumentation recorded number and mass concentrations which were converted to number- and mass-based emission indices, EIn (#/kg fuel burned) and EIm (mg/kg fuel burned), respectively, using the equations outlined in AIR6241 [22]. The EIn values were calculated from the APC data, while the MSS data was used to compute EIm. Data from the LII was not used in this analysis since it has been reported that there is greater uncertainty in its quantification of nvPM mass if the chemical structure of the exhaust sample is different from that of the calibration source [28]. The emission indices are reported at standard temperature (273.15 K) and pressure (101.325 kPa). Measurement uncertainties in

nvPM emissions parameters were calculated using 1σ standard deviation of the average data. The nvPM emissions data was corrected for thermophoretic loss in the sample extraction system, as described in Lobo et al., 2015 [23]. The thermophoretic loss correction factors determined for the NL, ECS and MES conditions were 1.12, 1.23, and 1.30, respectively. The fuel flow rate for the UCO-HEFA fuel blends was adjusted to account for the difference in net heat of combustion values to provide a Jet A-1 equivalent fuel flow rate for comparison of emissions at the three APU operating conditions for all fuel blends evaluated. This dataset was then used to calculate the percent reduction in nvPM emissions at the three APU operating conditions for the different fuel blend ratios evaluated. The uncertainty in percent reduction was calculated using a method previously used to compare nvPM emissions reduction with alternative fuels [8].

RESULTS AND DISCUSSIONS

nvPM number- and mass-based emissions using Jet A-1. The GTCP85 APU while burning Jet A-1 was characterized in terms of its nvPM number- and mass-based emissions to establish a basis for comparing the emissions of the various test fuel blends. The nvPM EIn and EIm values as a function of fuel flow rate for the GTCP85 APU burning Jet A-1 are presented in Table 3. For both EIn and EIm, the emissions were found to decrease linearly with increasing fuel flow rate. The highest nvPM emissions were observed at the NL condition. The emissions trends and magnitudes agree well with GTCP85 APU emissions reported in another study [29] with similar fuel hydrogen and aromatic content over the same range of operating conditions, albeit with different sampling and measurement systems. The nvPM EIn and EIm data when APU was burning Jet A-1 at the MES condition during this study is similar to that reported for main aircraft engine nvPM emissions data [23, 30, 31].

This permits the current dataset to be used to estimate nvPM emissions reductions when alternative fuels are burned in main aircraft engines.

Table 3. nvPM number- and mass-based emission indices as a function of fuel flow rate for the GTCP85 APU burning Jet A-1

APU Operating Condition	Fuel flow rate (g/s)	EIn (#/kg fuel burned)	EIm (mg/kg fuel burned)
NL	17.7	$(4.72 \pm 0.24) \times 10^{15}$	745.81 ± 36.98
ECS	25.8	$(3.27 \pm 0.19) \times 10^{15}$	468.79 ± 15.36
MES	31.1	$(2.33 \pm 0.15) \times 10^{15}$	271.73 ± 15.25

Comparison of nvPM emissions of UCO-HEFA fuel blends vs. Jet A-1. The nvPM EIn and EIm for the various fuel blends and neat UCO-HEFA were compared against those for the baseline Jet A-1 at the three APU operating conditions. The percent reduction observed in nvPM EIn and EIm as a function of fuel hydrogen content are presented in Figures 2 and 3, respectively. Fuel hydrogen content or H/C ratio has been shown to be a better parameter than fuel aromatic content for predicting sooting behavior and to evaluate differences in emission levels [13, 8]. The reductions in blend fuel nvPM EIn and EIm correlated well with fuel hydrogen content using a second order polynomial function fit to the experimental data in Figures 2 and 3. For both EIn and EIm, the functional fits were similar for the three APU operating conditions. It was observed that the larger the fuel hydrogen content (higher proportion of UCO-HEFA in the fuel blend), the greater the reductions in EIn and EIm. For all fuel blends investigated, the percentage reductions in nvPM EIn and EIm were generally highest at the MES condition followed by the ECS condition and then the NL condition. For the neat UCO-HEFA fuel, the percent reductions in EIn were 74% (MES) > 66% (ECS) > 61% (NL) and those for EIm were 93% (MES) > 91% (ECS) > 88% (NL). The magnitude of

these reductions in nvPM EIn and EIm are comparable to those reported for other gas turbine engines burning paraffinic fuels [8, 12, 17]. The reduction in EIm is greater than EIn for the corresponding fuel hydrogen content. This trend has also been observed for larger gas turbine engines at high thrust conditions [8, 14] and a turboshaft engine [13] burning paraffinic and surrogate fuels. The average UCO-HEFA/Jet A-1 EIm ratios for the three APU operating conditions in the case of the neat UCO-HEFA and 50% UCO-HEFA fuels were 0.09 ± 0.02 and 0.40 ± 0.02, respectively. These values compare well with those reported for a CFM56-2C1 turbofan engine burning a pure FT fuel (0.14 ± 0.05) and a 50:50 blend of FT and JP-8 fuels (0.34 ± 0.15) [14].

For a 50:50 blend of UCO-HEFA and Jet A-1, which would meet current ASTM specifications, the average reduction in nvPM number-based emissions was ~35%, while that for mass-based emissions was ~60%. However, the 2% and 5% UCO-HEFA fuel blend ratios are also of interest since they are representative of possible near to midterm 'real world' situation under a flightpath 2020 comingled supply scenario. A slight decrease in nvPM EIn and EIm was observed with these low fuel blend ratios, however, the differences relative to Jet A-1 were not statistically significant. This implies that the use of low fuel blend ratios is not advantageous in terms of nvPM emissions reduction.

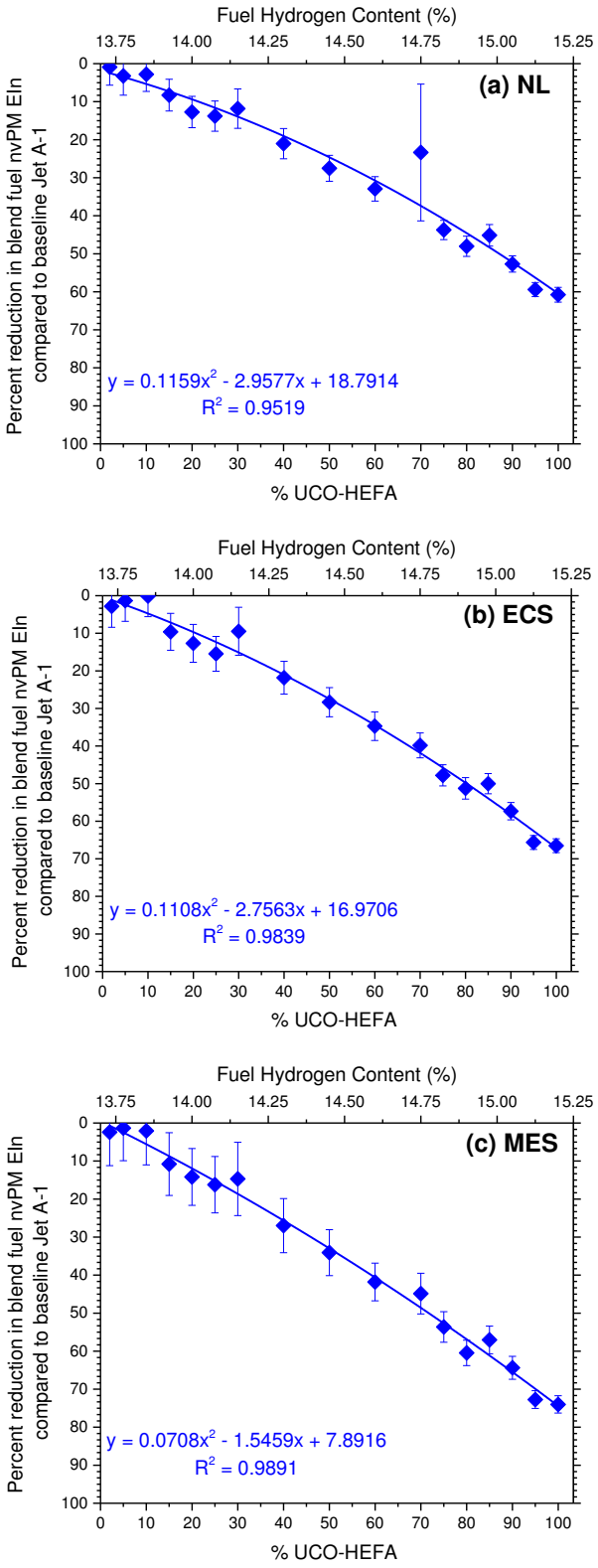


Figure 2: Percent reduction in nvPM number-based emission index for the fuel blend compared to Jet A-1 as a function of fuel hydrogen content for the (a) NL, (b) ECS, and (c) MES operating conditions

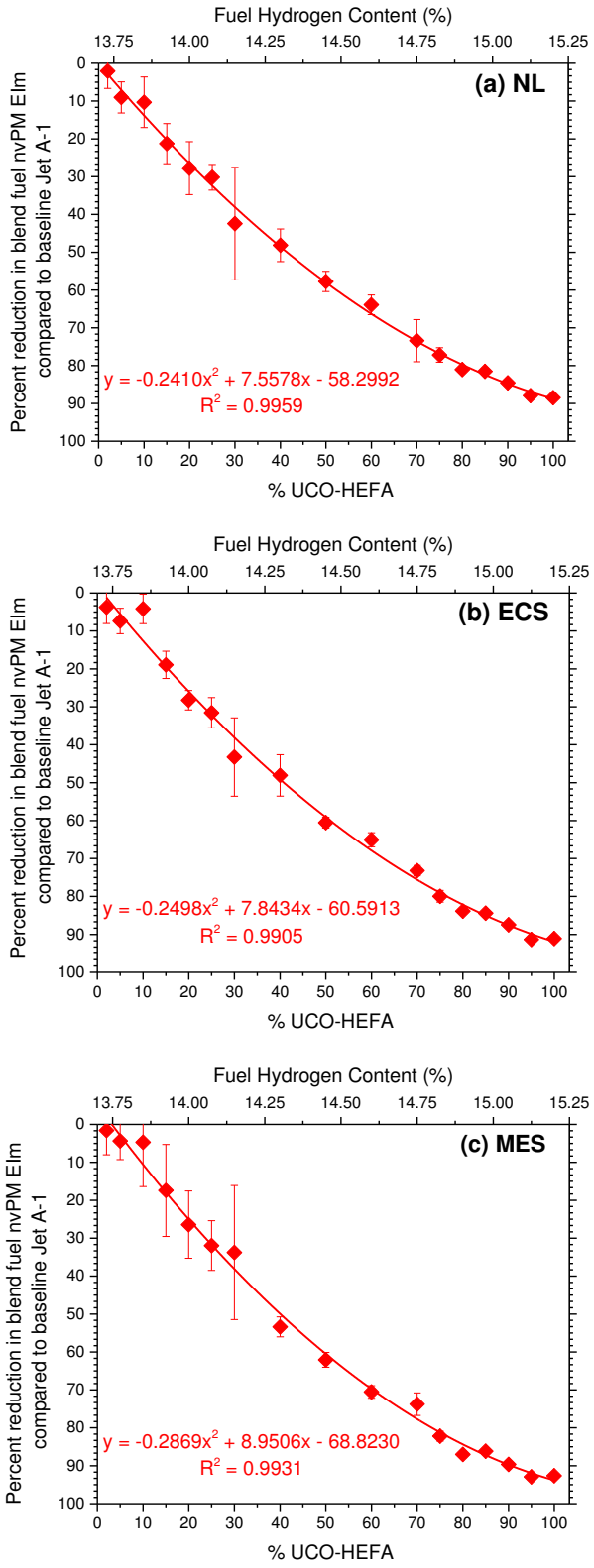
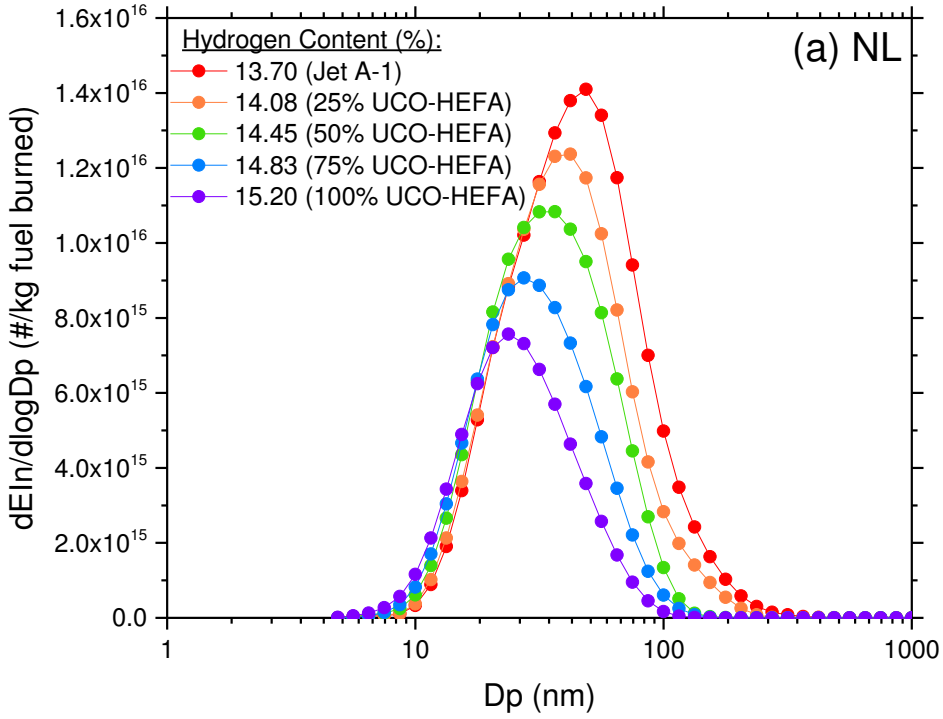
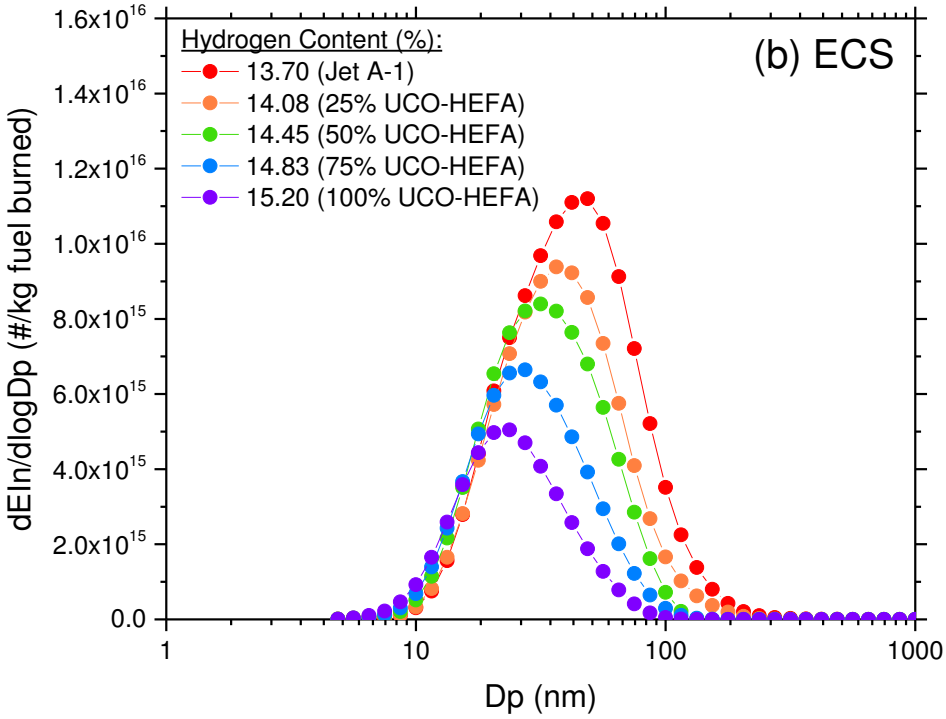


Figure 3: Percent reduction in nvPM mass-based emission index for the fuel blend compared to Jet A-1 as a function of fuel hydrogen content for the (a) NL, (b) ECS, and (c) MES operating conditions

The nvPM EIn size distributions for selected fuels at each of the three APU operating conditions are presented in Figure 4. In all cases, the size distributions were observed to be lognormal, and the geometric mean diameter (GMD) varied from 22.5nm to 49nm and the geometric standard deviation (GSD) ranged 1.58 – 1.99. These results are consistent with those reported for other gas turbine engines burning conventional and alternative fuels [8, 13, 23, 30, 31]. For the three APU operating conditions, GMD decreased linearly with increasing fuel hydrogen content. The size distributions were found to narrow and shift to smaller sizes as the UCO-HEFA component of the fuel blend increased. This has a greater impact on the reduction in nvPM mass compared to the overall decrease in nvPM number, when comparing the blends to the baseline Jet A-1 as seen in Figures 2 and 3. In another study on the emissions of a GTCP85 APU, fuel chemistry was observed to drive the fullerenic nanostructure of soot from a paraffinic fuel, for the combustion conditions encountered in the APU [32]. The timescale for soot formation was found to be accelerated with conventional fuel because it contained a less fullerenic nanostructure compared to the paraffinic fuel.


(a) NL
Hydrogen Content (%):
13.70 (Jet A-1)
14.08 (25% UCO-HEFA)
14.45 (50% UCO-HEFA)
14.83 (75% UCO-HEFA)
15.20 (100% UCO-HEFA)
dEIn/dlogDp (#/kg fuel burned)
1.6x10^16
1.4x10^16
1.2x10^16
1.0x10^16
8.0x10^15
6.0x10^15
4.0x10^15
2.0x10^15
0.0
1
10
100
1000
Dp (nm)


(b) ECS
Hydrogen Content (%):
13.70 (Jet A-1)
14.08 (25% UCO-HEFA)
14.45 (50% UCO-HEFA)
14.83 (75% UCO-HEFA)
15.20 (100% UCO-HEFA)
dEIn/dlogDp (#/kg fuel burned)
1.6x10^16
1.4x10^16
1.2x10^16
1.0x10^16
8.0x10^15
6.0x10^15
4.0x10^15
2.0x10^15
0.0
1
10
100
1000
Dp (nm)

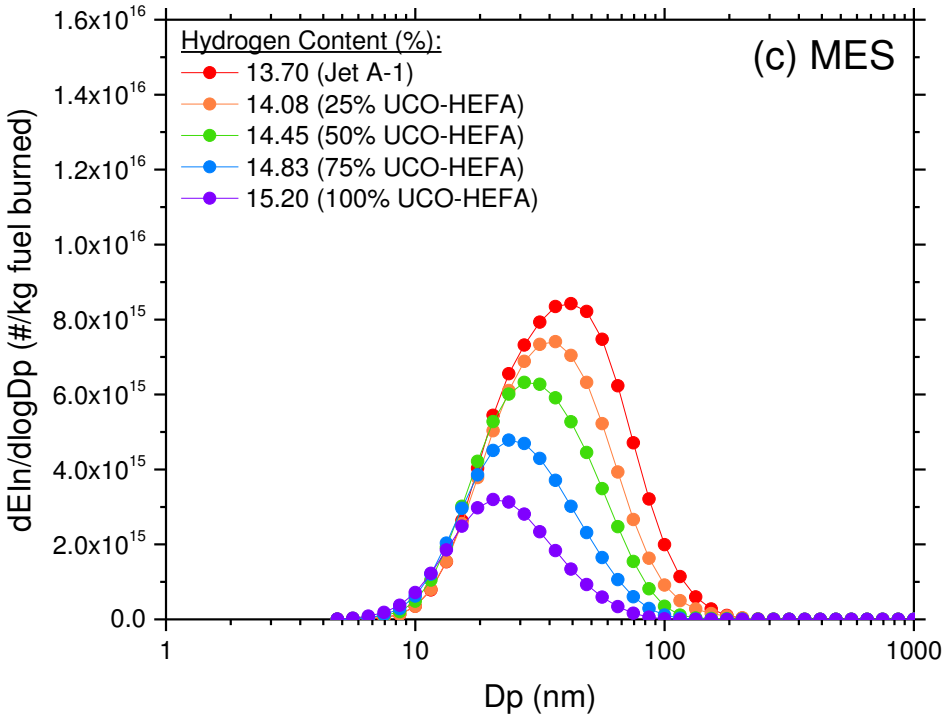


Figure 4: nvPM EIn size distributions for selected fuels at the (a) NL, (b) ECS and (c) MES conditions

Influence of fuel properties on nvPM emissions. The potential to produce nvPM emissions is highly influenced by the underlying properties of the fuel. Smoke point, a lumped fuel composition parameter, has been widely used as general indicator of sooting propensity despite providing little information on the hydrocarbon composition of the fuel [33, 34]. In this study, the UCO-HEFA fuel had a significantly higher smoke point compared to Jet A-1 implying a lower sooting tendency, and was also correlated with lower overall nvPM emissions. In terms of fuel composition, both Jet A-1 and UCO-HEFA had a similar proportion of n-paraffins in the fuel. However, the UCO-HEFA fuel had a higher proportion of iso-paraffins and lower amounts of cyclo-paraffinic and aromatic compounds. N-paraffins

produce lower particle emissions than iso-paraffins, despite having the same H/C ratio [18]. The peak active radical pool produced in the oxidation of each class of compounds present in the fuel is ordered as n-paraffins > iso-paraffins > cyclo-paraffins > aromatics [19]. A comparison of different molecular classes of diesel fuels showed that a high Cetane Number associated with short ignition times was correlated with molecular composition [35]. N-paraffins had the highest Cetane Numbers followed by iso-paraffins, which have a greater degree of branching, and then aromatics. Aromatics have more stable ring structures that require higher temperature and pressure for ignition to occur, and produce more precursors that contribute to the formation of soot nuclei. For gas turbine engine ignition, the formation of a flame kernel is dependent on the fuel vapor pressure which is a function of the individual hydrocarbon groups. At a given temperature for lower carbon numbers, the vapor pressure of paraffins in the fuel is higher [20]. The UCO-HEFA blends which have a higher fraction of paraffins with a higher vapor pressure are more volatile compared to Jet A-1 resulting in shorter ignition delay times. Lack of fullerenic nanostructure for conventional jet fuels with significant aromatic content compared to paraffinic fuels has been shown to accelerate soot formation in an APU [32]. These are some of the factors that contribute to the overall lower nvPM emissions of the UCO-HEFA blends fuels relative to Jet A-1.

SUMMARY

A systematic evaluation of nvPM emissions from a GTCP85 aircraft auxiliary power unit (APU) burning a UCO-HEFA alternative fuel in varying blends with a conventional Jet A-1 baseline fuel was performed. Incremental variations in fuel composition of the UCO-HEFA fuel with Jet A-1 on the production of nvPM emissions were explored. The nvPM number- and mass-based emission indices for 16 fuel blends and neat 100% UCO-HEFA were

compared against those for the baseline Jet A-1 at the three APU operating conditions. - NL, ECS, and MES. Fuel composition was found to influence nvPM production. For both EIn and EIm, the reductions were found to be greater with increasing fuel hydrogen content (higher proportion of UCO-HEFA in the fuel blend). For all fuel blends investigated, the percentage reductions in nvPM EIn and EIm were generally highest at the MES condition followed by the ECS condition and then the NL condition. For a 50:50 blend of UCO-HEFA and Jet A-1, which would meet current ASTM specifications, the average reduction in nvPM number-based emissions was ~35%, while that for mass-based emissions was ~60%. The nvPM size distributions were found to narrow and shift to smaller sizes as the UCO-HEFA component of the fuel blend increased. This has a greater impact on the reduction in nvPM mass compared to the overall decrease in nvPM number, when comparing the UCO-HEFA fuel blends to the baseline Jet A-1. The current dataset can be used to estimate nvPM emissions reductions when alternative fuels are burned in main aircraft engines. The results from this study will be critical to understanding the emissions profile for aircraft engines burning alternative fuels and their impact on local air quality and climate change.

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