Impact of Alternative Fuels on the PM Emissions Characteristics of Gas Turbine Engines

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ABSTRACT

The growth in the commercial aviation sector has raised concerns about the impact of emissions from aircraft operations on local and regional air quality, climate change, and health-related effects. The lack of Particulate Matter (PM) emissions data from gas turbine engines coupled with the increasing interest in the use of alternative fuels as a potential emissions mitigation strategy are the motivating factors behind this thesis. A total of seven peer-reviewed archival journal publications form the basis of this work. It commences with two field studies that were performed at the Oakland International Airport and the Hartsfield-Jackson Atlanta International Airport to measure the characteristics of aircraft engine specific PM emissions at the engine exit plane and in the near field as the exhaust plume expands and cools. Having characterised the PM emissions from various aircraft gas turbine engine types, the significant impact that alternative fuels can have on the PM emissions characteristics was explored and the results were correlated with fuel properties. A new robust and standardised methodology for the measurement of non-volatile PM emissions is described, and its reproducibility against other systems is demonstrated. Finally this standardized system was used in a detailed examination of the impact of fuel composition on the characteristics of the emitted non-volatile PM from a gas turbine engine. These publications and the resulting data improved the characterisation and quantification of PM emissions for a wide variety of gas turbine engines burning conventional and alternative fuels. PM emissions from aircraft gas turbine engines at airports were found to have bimodal size distributions, consisting of a nucleation mode with volatile PM and an accumulation mode with volatile PM condensed on the surface of non-volatile PM. Fuel properties were found to have a significant impact on the production of PM. The reductions in PM emissions with alternative fuels were best correlated with fuel hydrogen content. The data and analysis from these publications will be used to improve/validate current environmental impact predictive tools with real world aircraft gas turbine engine specific PM emissions inputs and develop effective emissions mitigation strategies.

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LIST OF ACRONYMS AND ABBREVIATIONS

α	Fuel hydrogen to carbon ratio
AAFEX	Alternative Aviation Fuels Experiment
AFR	Air Fuel Ratio
AFRL	Air Force Research Lab
AIR	Aerospace Information Report
AMS	Aerosol Mass Spectrometer
APC	AVL Particle Counter
A-PRIDE	Aviation – Particle Regulatory Instrumentation Demonstration Experiment
APU	Auxiliary Power Unit
ARI	Aerodyne Research Inc.
ARP	Aerospace Recommended Practice
ASTM	American Society for Testing and Materials
ATJ	Alcohol-to-jet
ATL	Hartsfield-Jackson Atlanta International Airport
CAEP	Committee on Aviation Environmental Protection
CO	Carbon monoxide
CO_2	Carbon dioxide
CPC	Condensation Particle Counter
CPMA	Centrifugal Particle Mass Analyzer
CTL	Coal-to-liquid
CToF	Compact Time of Flight
DAC	Dual Annular Combustor
DMA	Differential Mobility Analyzer
DoD	Department of Defense
DMS	Differential Mobility Spectrometer
ECS	Environmental Control Systems
EDB	Emissions DataBank
EGT	Exhaust Gas Temperature
EIn	Number-based emission index
EIm	Mass-based emission index

EIorg	Organic-based emission index
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAME	Fatty Acid Methyl Ester
FID	Flame Ionization Detector
FOA	First Order Approximation
FSFJ	Fully Synthetic Jet Fuel
FT	Fischer-Tropsch
GC	Gas Chromatography
GHG	Green House Gas
GMD	Geometric Mean Diameter
GSD	Geometric Standard Deviation
GTL	Gas-to-liquid
HEFA	Hydroprocessed Esters and Fatty Acids
HRToF	High Resolution Time of Fight
ICAO	International Civil Aviation Organization
LII	Laser Induced Incandescence
LTO	Landing Take-Off
M_c	Molar mass of carbon
M_H	Molar mass of hydrogen
MAAP	Multi Angle Absorption Photometer
MES	Main Engine Start
Missouri S&T	Missouri University of Science and Technology
MMD	Mass-based geometric mean diameter
MOD	Ministry of Defense
MS	Mass spectrum
MSS	Micro Soot Sensor
m/z	Mass to charge ratio
NAAQS	National Ambient Air Quality Standards
NDIR	Non Dispersive Infra-Red
NOx	Nitrogen oxides
NL	No Load
nvPM	Non-volatile Particulate Matter
OAK	Oakland International Airport

PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
PM_n	PM number concentration
PM_m	PM mass concentration
PMP	Particle Measurement Program
PTFE	Polytetrafluoroethylene
PToF	Particle Time of Flight
RME	Rapeseed Methyl Ester
RPM	Revolutions Per Minute
SAE	Society of Automotive Engineers
SAC	Single Annular Combustor
SOx	Sulphur oxides
SPK	Synthetic Paraffinic Kerosene
SSJF	Semi Synthetic Jet Fuel
SN	Smoke Number
ToF	Time of Flight
UCO	Used Cooking Oil
UHC	Unburned hydrocarbons
VPR	Volatile Particle Remover

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CHAPTER 1: INTRODUCTION

The commercial aviation sector has expanded as air travel around the world increases, with most of the growth occurring in emerging markets. Both passenger and cargo traffic is forecast to grow at a rate of 5% per year for the foreseeable future (Airbus, 2015; Boeing, 2015). As air travel increases, concerns about the impact of emissions from aircraft operations have received a lot of attention (Penner et al., 1999).

The emissions from different phases of aircraft operation include carbon dioxide (CO_2), water vapour (H_2O), carbon monoxide (CO), unburned hydrocarbons (UHC), nitrogen oxides (NOx), sulphur oxides (SOx), volatile organic compounds, semi-volatile organic compounds, metals, and particulate matter (PM). Emissions from aircraft operations represent a small percentage ~2-3% of global emissions (Penner et al., 1999). However, they are unique from other sources of anthropogenic combustion in that a significant amount of pollutants are emitted at altitude.

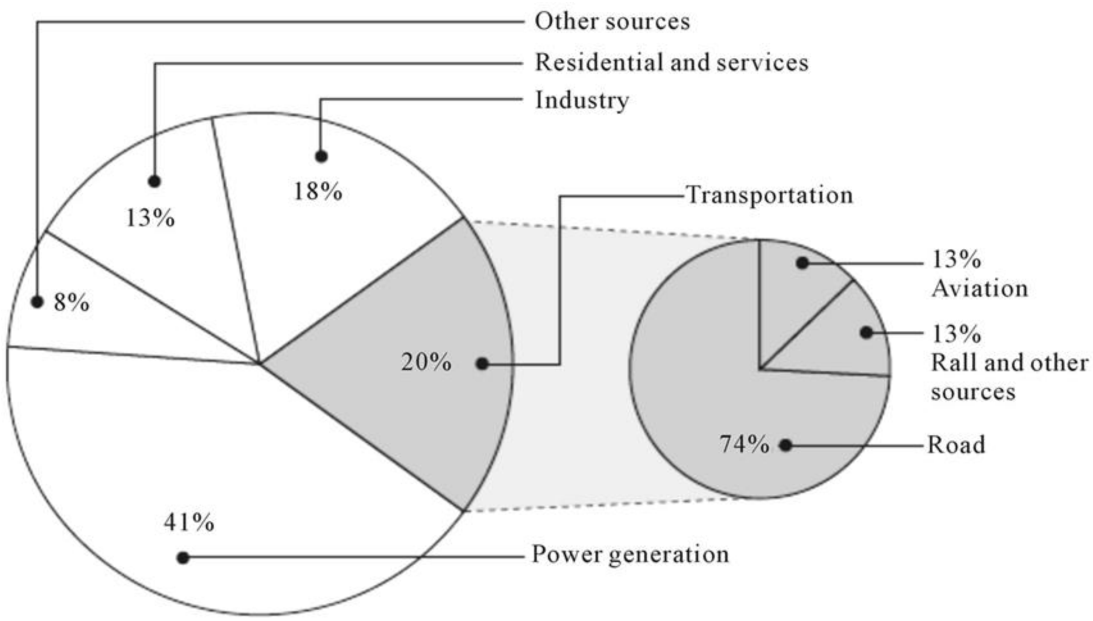

Figure 1: Aviation’s contribution to global carbon dioxide emissions (2004) (US GAO, 2009)

The International Civil Aviation Organization (ICAO) has developed standards for the emissions of NOx, CO, UHC, and smoke number (SN; plume visibility) from aircraft engines whose rated output is greater than 26.7 kN (ICAO, 2008). Data from aircraft engine certification tests for gaseous emissions and smoke number for various aircraft engine types at engine power conditions corresponding to the Landing Take-Off (LTO) Cycle are recorded in the ICAO Aircraft Engine Emissions DataBank (EDB) (EASA, 2015). The LTO cycle encompasses emissions released below an altitude of 3000 feet (915m) which have an impact on local air quality.

Aircraft operations in the vicinity of airports have increased the inventory of gaseous and PM emissions in the surrounding areas, affecting local and regional air quality (Yu et al., 2004; Unal et al., 2005; Peace et al., 2006; Westerdahl et al., 2008; Hu et al., 2009; Hsu et al., 2013). A study of UK airports found that airport emissions were responsible for 110 premature mortalities each year in the UK (Yim et al., 2013). Another study of simulated emissions from LTO cycle activities from aircraft at 99 airports in the US projected that aviation-related health impacts would increase by a factor of 6.1 from 2005 to 2025 (Levy et al., 2012). Barrett, Britter and Waitz, 2010 investigated the impact of non- LTO emissions and estimated that globally, ~8000 premature mortalities per year could be attributed to aircraft cruise emissions alone.

A recent study estimated that the growth of the aviation sector between 2000 and 2050 would result in increases in the global emissions levels of CO_2 and NOx by a factor 2.0-3.6 and 1.2-2.7, respectively (Owen et al., 2010). Climate impacts through radiative forcing, resulting from changes in trace gases and black carbon PM in the atmosphere, were forecast to increase 3-4 fold between 2000 and 2050 (Lee et al., 2009).

While gaseous emissions from aircraft engines have been extensively characterized in the ICAO EDB as well as several measurement studies (Herndon et al., 2008; Carslaw et al., 2008), limited information on PM emissions is currently available. In the absence of measurement data, the first-order approximation 3.0 (FOA3) (Wayson, Fleming, and Iovinelli, 2009) has been used to estimate mass-based emission indices using SN data reported in the ICAO EDB. However, Stettler et al., 2011 cautioned that FOA3 systematically underestimates mass-based emissions at higher thrust, leading to inaccurate inventory assessments. Environmental and health impact assessments of aircraft engine emissions rely on PM characteristics such as number, size, and composition, which are not readily obtained from SN. Also, FOA3 was developed using emissions data from legacy aircraft gas turbine engines and it remains to be seen whether the correlation is still applicable for newer cleaner burning engines entering the fleet. FOA3 will eventually be phased out as detailed information on PM number and mass-based emissions data for different aircraft gas turbine engine types become available.

Aviation PM emissions are distinct from other emissions sources in the airport complex. They are characterized by mean particle diameters less than 100 nm (Petzold et al., 2003; Lobo, et al., 2007; Mazaheri et al., 2009; Zhu et al., 2011) and are composed primarily of refractory carbon soot with coatings of organic and sulphate compounds (Onasch et al, 2009; Timko et al., 2010). PM emissions characteristics have also been found to evolve as the exhaust plume leaves the engine exit plane and, expands and cools (Lobo et al., 2007; Timko et al., 2010; Kinsey et al. 2010) making characterisation even more challenging.

The first step to mitigating PM emissions from gas turbine engines is to characterise and compare the emissions from different engine types. This provides the basis for a PM emissions inventory that can then be used to develop emissions mitigation strategies. Characterization of aircraft PM emissions during normal activity at airports has been performed in previous studies by employing different techniques such as extractive sampling methods (Herndon et al., 2005), plume capture and analysis techniques (Johnson et al., 2008; Mazaheri et al., 2009; Mazaheri et al., 2011), and optical remote sensing measurements (Bennett et al., 2010). Real-time measurements of aircraft gas turbine engine specific PM emissions are advantageous since spatial and temporal variations in emissions occur as the exhaust plume expands and cools. Likewise, measurements using state-of-the-art, rapid response instruments can provide better characterisation of the PM emissions.

The rising costs of fuel, an increasing desire to enhance the security of energy supply, and potential environmental benefits have driven feasibility and viability assessment studies of alternative fuels for commercial aviation applications. Specifications for aviation gas turbine engine fuels are established by American Society for Testing and Materials (ASTM) and United Kingdom Ministry of Defence (MOD). Other specifications for jet fuel exist but these are similar to those of ASTM and MOD. ASTM D1655 includes specifications for Jet A and Jet A-1 fuels used for commercial aviation within the US. The MOD's DEF STAN 91-91 outlines the specification for Jet A-1 used in Europe. 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 DEF STAN 91-91 and ASTM D1655. ASTM and other fuels specification bodies have established a specification for the manufacture of jet fuel that consists of up to 50% Synthesized Paraffinic Kerosene (SPK) blending components from Fischer-Tropsch (FT) and Hydroprocessed Esters and Fatty Acids (HEFA) under ASTM D7566 (Wilson et al., 2013). 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. The PM emission characteristics of gas turbine engines burning these and other alternative fuels must also be understood to assess the impact of these fuels on emissions mitigation strategies. Both FT and HEFA fuels, although different in origin, have a continuous boiling range and carbon distribution to that found in conventional aviation turbine fuel. However, newer alternative fuels being considered for approval by ASTM, such as Alcohol-to-jet (ATJ) and catalytic conversion of biomass to hydrocarbons, may produce fuels with a limited hydrocarbon distribution which will impact engine performance (Wilson et al., 2013).

The lack of PM emissions data from gas turbine engines coupled with the use of alternative fuels as a potential emissions mitigation strategy are the motivating factors behind this thesis. The thesis address four distinct but related areas of endeavour – 1) PM emissions characteristics of gas turbine engines, 2) PM emissions reductions with alternative fuels, 3) Standardised methodology for aircraft engine non-volatile PM emissions measurements, and 4) Impact of alternative fuels on gas turbine engine PM emissions. A total of seven peer-reviewed archival journal publications form the basis of this thesis. These publications and the resulting data improved the characterization and quantification of PM emissions for a wide variety of gas turbine engines burning conventional and alternative fuels. The data and analysis from these publications will be used to improve/validate current environmental impact predictive tools with real world aircraft engine specific PM emissions inputs and develop effective emissions mitigation strategies.

The following is the list of the seven peer-reviewed archival journal publications with their complete citation:

Publication 1: Lobo, P., Hagen, D.E., Whitefield, P.D., "**Measurement and analysis of Aircraft Engine PM Emissions downwind of an active runway at the Oakland International Airport**", Atmospheric Environment (2012), Vol. 61, 114-123.

Publication 2: Lobo, P., Hagen, D.E., Whitefield, P.D., Raper, D., "**PM Emissions Measurements of In-Service Commercial Aircraft Engines during the Delta-Atlanta Hartsfield Study**", Atmospheric Environment (2015), Vol. 104, 237-245.

Publication 3: Lobo, P., Hagen, D.E., Whitefield, P.D., "**Comparison of PM Emissions from a Commercial Jet Engine burning Conventional, Biomass, and Fischer-Tropsch Fuels**", Environmental Science and Technology (2011), Vol. 45, No. 24, 10744-10749.

Publication 4: Lobo, P., Rye, L., Williams, P. I., Christie, S., Uryga-Bugajska, I., Wilson, C. W., Hagen, D. E., Whitefield, P. D., Blakey, S., Coe, H., Raper, D., Pourkashanian, M., “**Impact of Alternative Fuels on Emissions Characteristics of a Gas Turbine Engine - Part I: Gaseous and PM Emissions**”, Environmental Science and Technology (2012), Vol. 46, No. 19, 10805-10811.

Publication 5: Rye, L., Lobo, P., Williams, P. I., Uryga-Bugajska, I., Christie, S., Wilson, C., Hagen, D., Whitefield, P., Blakey, S., Coe, H., Raper, D., Pourkashanian, M., “**Inadequacy of Optical Smoke Measurements for Characterization of Non-Light Absorbing Particulate Matter Emissions from Gas Turbine Engines**”, Combustion Science and Technology (2012), Vol., 184, No. 12, 2068-2083.

Publication 6: Lobo, P., Durdina, L., Smallwood, G.J., Rindlisbacher, T., Siegerist, F., Black, E.A., Yu, Z., Mensah, A.A., Hagen, D.E., Thomson, K.A., Miake-Lye, R.C., Brem, B.T., Corbin, J.C., Abegglen, M., Sierau, B., Whitefield, P.D., Wang, J., “**Measurement of Aircraft Engine Non-volatile PM Emissions: Results from the Aviation - Particle Regulatory Instrumentation Demonstration Experiment (A-PRIDE) 4 Campaign**”, Aerosol Science and Technology (2015), Vol. 49, No. 7, 472-484.

Publication 7: Lobo, P., Christie, S., Khandelwal, B., Blakey, S.G, Raper, D.W., “**Evaluation of Non-volatile Particulate Matter Emission Characteristics of an Aircraft Auxiliary Power Unit with varying Alternative Jet Fuel Blend Ratios**”, Energy and Fuels (2015), Vol. 29, No.11, 7705 -7711.

CHAPTER 2: Publication 1 - Measurement and analysis of Aircraft Engine PM Emissions downwind of an active runway at the Oakland International Airport

Characterising PM emissions from aircraft engines requires access to different aircraft gas turbine engines as well as a significant commitment of resources. Even if engines and unlimited resources were available, it would take a significant amount of time to develop a database of PM emissions of all the aircraft gas turbine engines operating in the commercial fleet. In the absence of such information, it is important to define the range of PM emissions that can be expected from commercial aircraft gas turbine engines, and where possible to compare the emissions from different engine types. This type of data will help to bound the PM emissions at airports and provide the necessary information to perform environmental impact assessments, and subsequently develop emissions mitigation strategies.

If airport access is made available, then the PM emissions data from a broad mix of commercial aircraft gas turbine engines can be acquired as part of the LTO cycle during normal operations at the airport. The data acquired in this manner would also shed light on how PM emissions from aircraft gas turbine engines evolve in the near field, which is important to assess local air quality and health-related effects.

A number of field measurements have been conducted to characterize the PM emissions of aircraft engines and their contribution to the inventory of emissions around airports. For some of these studies the data collected did not resolve individual aircraft activity (Westerdahl et al., 2008; Dodson et al., 2009; Hsu et al., 2012) and thus aircraft gas turbine engine specific PM emissions at different operational states could not be ascertained. PM emissions have been shown to differ from one engine type to another for exhaust measurements made in the near field plume (Kinsey et al., 2010; Timko et al., 2010), thus it is important to acquire engine specific PM emissions data.

This publication presents the methodology for real-time measurements of aircraft engine specific PM emissions and analysis of the associated high resolution data acquired during normal LTO operations 100-300m downwind of an active taxi-/runway at the Oakland International Airport (OAK). PM emissions characteristics of seven different engine types were measured and reported for the idle/taxi and take-off conditions in terms of size distributions, and number- and mass-based emission indices. The landing and climb-out modes of the LTO cycle were not addressed in this analysis the signal to noise ratio for many of these plumes was low, making it difficult to resolve the aircraft engine component from the ambient background.

The results from this study provided information for better characterizing evolving PM emissions from in-service commercial aircraft under normal LTO operations and assessing their impact on local and regional air quality and health related impacts. PM emissions from aircraft gas turbine engines were found to have bimodal size distributions, consisting of a nucleation mode with volatile PM and an accumulation mode with volatile PM condensed on the surface of non-volatile PM. The characteristics of aircraft gas turbine engine generated PM are explored in greater detail in subsequent publications/chapters. It should be noted that the size distributions were measured with the Cambustion DMS500 during this study utilizing an earlier version of the inversion algorithm. Subsequent studies utilized the inversion algorithms available at the time.

The publication for this chapter can be accessed at the following website:
http://www.sciencedirect.com/science/article/pii/S1352231012007005

CHAPTER 3: Publication 2 - PM Emissions Measurements of In-Service Commercial Aircraft Engines during the Delta-Atlanta Hartsfield Study

This publication follows on from the OAK study and presents the results of the physical characterisation of a different set of aircraft engine specific PM emissions in terms of size distributions, and number- and mass-based emission indices. The data were acquired at the Hartsfield-Jackson Atlanta International Airport (ATL) during a dedicated engine study where emissions measurements were conducted at the engine exit plane through extractive sampling, and an advected plume study where emissions were sampled 100-350m downwind from aircraft operational runways during normal airport operations. Detailed PM emissions characteristics of JT8D-219, PW2037, and CF6-80 engines from the fleet of Delta Airlines were measured during the dedicated engine test. PM emissions from over 300 wind advected take-off plumes over a 3 day period were also characterized for the following engines: BR715, CF34-3B1, CF34-8C1, CF6-80, CFM56-5C, CFM56-7B, JT8D-15A, JT8D-219, PW127, and PW2037. The Cambustion DMS500 was used to measure PM size distributions. Mass-based PM emissions were derived from the DMS500 data assuming particle sphericity and a density of 1 g/cc. In subsequent studies, it has been shown that the PM effective density is size dependent. However, Durdina et al., 2014 have shown that unit density is a reasonable approximation, and the PM mass determined by the integrating the PM size distribution and the real-time black carbon mass measurements are in good agreement.

The data from this study along with that from the OAK study significantly augment the existing database on PM emissions from aircraft operating in the commercial fleet, and will allow the aviation community to better assess the environmental impacts of aircraft engine PM emissions.

The publication for this chapter can be accessed at the following website:
http://www.sciencedirect.com/science/article/pii/S1352231015000321

CHAPTER 4: Publication 3 - Comparison of PM Emissions from a Commercial Jet Engine Burning Conventional, Biomass, and Fischer–Tropsch Fuels

The OAK and ATL studies were instrumental in characterizing the PM emissions for a wide variety of aircraft gas turbine engine types. The real-world dataset from these studies provides information to establish PM emissions inventory estimates for airports. As airports continue to expand, the growth in commercial air traffic, rising costs of fuel, an increasing desire to enhance the security of energy supply, and potential environmental benefits have driven feasibility and viability assessment studies of alternative renewable fuels. The use of alternative fuels as an emissions mitigation strategy for airports is quite promising since the vast majority of emissions on the airport complex can be attributed to aircraft main engines and auxiliary power units. Previous assessments of the emissions profile for gas turbine engines burning alternative fuels were limited to military engines. While this data was useful in determining the extent to which emissions, especially PM emissions, could be reduced, the results could not directly be applied to commercial aircraft engines with different engine technology.

This publication presents the first characterisation of PM emissions from a CFM56-7B commercial gas turbine engine burning conventional and alternative biomass- (fatty acid methyl ester, FAME) and, Fischer Tropsch-based (FT) fuels. The sampling methodology used in this study was similar to that employed during the dedicated engine test of the ATL study. The PM emissions were characterized in terms of size distributions as well as number and mass-based emission indices. Since the emissions data are proprietary, the data are presented in normalized form. Emissions reductions of the various fuels investigated were computed for a LTO cycle and the correlated with fuel properties such as aromatic content and hydrogen/carbon ratio.

The publication for this chapter can be accessed at the following website:
http://pubs.acs.org/doi/abs/10.1021/es201902e

CHAPTER 5: Publication 4 - Impact of Alternative Fuels on Emissions Characteristics of a Gas Turbine Engine - Part I: Gaseous and PM Emissions

PM emissions reductions with alternative fuels for the CFM56-7B engine were established in the Lobo et al., 2011 study. The CFM56-7B engine is widely used in the commercial aviation sector and this engine type represents a significant fraction of the current commercial fleet operations. In addition to aircraft main engines, aircraft auxiliary power units (APUs) are the next biggest source of emissions in the airport complex. APUs have a different operational cycle at airports when compared to aircraft main engines which follow the LTO cycle. It is important to characterize the PM emissions from APUs and to understand the impact of alternative fuels on their emissions characteristics. As is the case with aircraft main engines, it is hard to find APUs that are available for emissions test, however, the fuel consumed by an APU is much lower than a main engine, making it attractive for use as a test bed for alternative fuel evaluations.

In this publication, the gaseous and PM emissions of a recommissioned Artouste Mk113 APU were investigated at the APU exit plane as well as 10m downstream to assess the properties of the evolving plume as was done during the ATL study. The fuels used in this study included a baseline Jet A-1, gas-to-liquid (GTL), 50:50 GTL:Jet A-1, and coal-to-liquid (CTL). In addition to the first characterization of PM emissions on this type of APU, it was also the first time that evolving emission plumes from an APU burning alternative fuels were measured. The Cambustion DMS500 was used to measure particle size distributions in mobility diameter space and the HR-ToF-AMS was used to characterise the volatile component of PM in aerodynamic diameter space.

The publication for this chapter can be accessed at the following website:
http://pubs.acs.org/doi/abs/10.1021/es301898u

CHAPTER 6: Publication 5 - Inadequacy of Optical Smoke Measurements for Characterisation of Non Light Absorbing Particulate Matter Emissions from Gas Turbine Engines

SN is a legacy metric whose original purpose was to measure smoke visibility. It was appropriate at the time as gas turbine engines had significant visible soot emissions, but SN does not quantify PM characteristics such as morphology, chemical composition, size distribution, or number and mass concentration, which are important from the perspective of local air quality and health effect concerns. Also, SN was never designed as a technique to measure volatile matter. However, emissions from gas turbine engines include both volatile and non-volatile PM, and both are inherently captured with some degree of efficiency on the filter paper used in SN technique.

Lobo et al., 2012b and Williams et al., 2012 have shown that the ratio of volatile to non-volatile PM concentration can change for different fuels. The purpose of this study was to quantify these differences and highlight the failings in the SN technique for certain fuels which produced a large proportion of volatile PM. In addition, the volatile component of the exhaust deposits on the surface of nvPM and changes it reflectivity in the SN measurement.

In this publication, the effect of volatile PM emissions on SN measurements was further explored using the same Artouste Mk113 APU as that used in Lobo et al., 2012b. SN and PM emission characteristics were compared for the APU burning Jet A-1 and a neat Biodiesel produced from a rapeseed oil feedstock. The main objective of this study was to compare SN measurements with measurement data from number, mass, differential mobility and mass spectrometry analysis to highlight the inadequacy of optical smoke measurements in characterising volatile or non-light absorbing PM emissions from gas turbine engines.

The publication for this chapter can be accessed at the following website: http://www.tandfonline.com/doi/abs/10.1080/00102202.2012.697499#.VnL7wNA2ZS8

CHAPTER 7: Publication 6 - Measurement of Aircraft Engine Non-volatile PM Emissions: Results from the Aviation - Particle Regulatory Instrumentation Demonstration Experiment (A-PRIDE) 4 Campaign

Although the PM characteristics of different gas turbine engine types at various operational have been reported (Herndon et al., 2005; Lobo, et al., 2007; Mazaheri et al., 2008; Kinsey et al., 2010; Timko et al., 2010; Mazaheri et al., 2011; Lobo et al., 2012a, b; Lobo et al., 2015a), these data cannot be directly compared because the various measurement studies employed different sampling methodologies and instruments. A standardised sampling and measurement system for PM emission must be developed in order to directly compare data from different studies.

This publication presents the standardised sampling and measurement methodology for nvPM emissions defined in the Aerospace Information Report (AIR) 6241 developed by the Society of Automotive Engineers (SAE) Aircraft Exhaust Emissions Measurement Committee (E-31) (SAE, 2013). It also describes the first evaluation of two AIR6241 compliant sampling and measurement systems, operated by Missouri University of Science and Technology and Empa, in terms of nvPM number- and mass-based emissions. The nvPM number-based emissions were characterised using AVL Particle Counters (APCs), while nvPM mass-based emissions were measured using LII-300 and MSS. It should be noted that the MSSs used in this study were normalized to the LII-300 since only the LII-300 had been calibrated to the NIOSH 5040 protocol prior to the campaign.

Additional characterisation of nvPM size distributions, chemical composition, and effective density are also discussed. The main objectives of the study were to ascertain whether the AIR6241 compliant systems as defined were suitable and adequate for the measurement of aircraft engine nvPM emissions, and to compare the performance and repeatability of the two compliant systems.

The publication for this chapter can be accessed at the following website:
http://www.tandfonline.com/doi/abs/10.1080/02786826.2015.1047012

CHAPTER 8: Publication 7 - Evaluation of non-volatile PM Emissions Characteristics of an Aircraft Gas Turbine Engine with varying Alternative Jet Fuel Blend Ratios

Following the successful evaluation and comparison of the standardised system for the measurement of aircraft gas turbine engine nvPM emissions, the sampling methodology and instruments were employed to emissions from a Garrett Honeywell GTCP85 aircraft APU. APUs represent a different class of gas turbine engine, < 26.7 kN thrust, and their emissions have not previously been characterised using the standardised system. The impact of alternative fuels with varying fuel properties on the emissions characteristics of the APU was also of interest as this would provide additional information on the robustness of the standardised nvPM system.

In this publication the standardised sampling and measurement system defined for nvPM emissions measurements, was used to characterise emissions from a Garrett Honeywell GTCP85 aircraft APU burning conventional and alternative fuel blends. While a number of studies have reported nvPM emissions reductions with the use of alternative fuels (Lobo et al., 2011; Lobo et al., 2012; Beyersdorf et al., 2014), the incremental variations in fuel composition of a single alternative fuel on the production of nvPM has not been explored. In this study, a systematic evaluation of nvPM emissions from an APU burning a Used Cooking Oil (UCO) derived HEFA alternative fuel in varying blend ratios with a conventional Jet A-1 baseline fuel was performed. In addition to employing the standardised system to measure nvPM emissions from the APU, this study also investigated the impact of incremental variations in fuel composition on nvPM production. This was the first study to characterise nvPM emissions from an APU using the standardized system and will add to the data on the nvPM emission characteristics of different gas turbine engines.

Volatile PM emissions were not measured during this study. At the APU exit plane, it is expected that the PM emissions are mostly non-volatile based on results from previous studies (Lobo et al., 2012b, Lobo et al., 2015b). However, as the exhaust plume expands and cool, the nucleation and condensation of volatile PM will contribute to the overall increase in total PM. Since the UCO-HEFA fuel and blends have very low fuel sulphur content, it is anticipated the majority of volatile PM will be organic in nature as has been observed previously (Lobo et al., 2012b).

The publication for this chapter can be accessed at the following website:
http://pubs.acs.org/doi/abs/10.1021/acs.energyfuels.5b01758

CHAPTER 9: ANALYTICAL COMMENTARY

Prior to the publications included in this thesis, limited information was available on the PM emission characteristics of gas turbine engines. Aircraft main engines and auxiliary power units are significant contributors of PM emissions in the airport complex. Detailed PM emission characterization information was not available for models to assess the impact of airport operations on local and regional air quality.

The data from the Oakland International Airport and Delta-Atlanta Hartsfield studies (publications 1 and 2, Lobo et al., 2012a; 2015a, respectively) improved the characterization and quantification of PM emissions for an important subset of engines operating in the commercial fleet. In these studies, advected plume emissions were sampled downwind from aircraft operational runways during normal airport operations. The seven engine types investigated during the OAK study included: CMF56-3B1 (B737-300), CFM56-7B (B737-700/800), V2500-A5 (A320), JT-8D (MD-80), CF6-80 (A300), CF6-50 (DC-10), and CF34-3B (CRJ-100/200). During the Delta-Atlanta Hartsfield study, PM emissions from eleven different engine types were measured: BR715 (B717), CF34-3B1 (CRJ200), CF34-8C1 (CRJ700), CF6-80 (B767-300/400), CFM56-5C (A340-300), CFM56-7B (B737-700), JT8D-15A (B737-200), JT8D-219 (MD-88), PW127 (ATR72), and PW2037 (B757-200).

The PM emission characteristics were found to be different for different engine types. The range of PM number-based emission index (EIn) observed was 4×10^{15} - 9×10^{17} particles/kg fuel burned, while PM mass-based emission index (EIm) ranged between 0.1 and 0.7 g/kg fuel burned. Overall these ranges for PM EIn and EIm were consistent with those reported in other studies (Herndon et al, 2005; Lobo et al., 2007; Hu et al., 2009; Mazaheri et al., 2009; Zhu et al., 2011; Klapmeyer and Marr, 2012). It was observed that older technology engines such as the CFM56-3B and JT8D engines had as much as 3X higher PM mass-based emissions at take-off compared to newer engine technology such as the CFM56-7B engine. This is an important result for assessing the impact of aircraft engine emissions on local air quality. Aircraft engine technology improvements have resulted in lower NOx emissions and smoke number values (EASA, 2015), and it appears the same is true for PM emissions.

At the engine exit plane, PM exists as non-volatile soot (primary PM) and is characterized by lognormal size distributions with mean particle diameters ranging from 15nm to 50nm. As the exhaust plume expands and cools, volatile components of the exhaust, present in the gas phase at the engine exit plane, begin to condense creating a bi-modal distribution with a nucleation mode consisting of freshly nucleated particles and an accumulation mode consisting of non-volatile PM (nvPM) with a coating of volatile material (secondary PM). During both the OAK and ATL studies, bi-modal size distributions were observed for measurements of aircraft engine exhaust plumes. It was further observed that the secondary PM dominated the mass-based emissions for the CFM56-3B and CFM56-7B engines, but for the JT8D-219 engine primary PM EIm was dominated by primary PM. The rate of formation of secondary PM is influenced by a number of factors such as meteorological conditions, plume age, dilution rate, fuel properties etc., and as a result different studies may come up with different measurements of secondary PM. On the other hand, primary PM emissions are influenced by fuel properties and should therefore be easier to develop emissions mitigation strategies.

Specifications for aviation gas turbine engine fuels are established by American Society for Testing and Materials (ASTM) and United Kingdom Ministry of Defense (MOD). Other specifications for jet fuel exist but these are similar to those of ASTM and MOD. ASTM D1655 includes specifications for Jet A and Jet A-1 fuels used for commercial aviation within the US. The MOD's DEF STAN 91-91 outlines the specification for Jet A-1 used in Europe. ASTM and other fuels specification bodies have established a specification for the manufacture of jet fuel that consists of conventional fuel under D1655. In order for an alternative fuel to become approved for use either as a neat fuel or blended with conventional fuel, it must undergo rigorous assessment as detailed in ASTM D4054. Alternative fuels consisting of up to 50% Synthesized Paraffinic Kerosene (SPK) blending components from Fischer-Tropsch (FT) and Hydroprocessed Esters and Fatty Acids (HEFA) have been approved for use under ASTM D7566. 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.

The anticipated growth in commercial air traffic, rising costs of fuel, an increasing desire to enhance the security of energy supply, and potential environmental benefits have recently driven feasibility and viability assessment studies of alternative renewable fuels. Until recently, almost all of the studies on the performance and emissions characteristics of alternative fuels in gas turbine engines have been limited to military engine applications (Corporan et al., 2005; 2007; 2010). The measurement of nvPM emissions from a CFM56-7B engine burning conventional and alternative biomass- (fatty acid methyl ester, FAME) and, Fischer Tropsch-based (FT) fuels (publication 3; Lobo et al., 2011) was the first such characterisation of emissions from a commercial gas turbine engine.

The study found dramatic reductions in nvPM emissions with the four alternative fuels – 20% FAME, 40% FAME, 50% FT, and 100% FT – compared to conventional Jet A-1 fuel. The measured reductions in PM were greatest at the idle engine operating condition, and smallest at maximum rated thrust. For low engine power conditions, the trend in emissions reduction was: 20% FAME < 40% FAME < 50% F-T < 100% F-T, i.e. the emissions reduction was greater as the relative amount of alternative fuel content in the fuel increased. The reduction in nvPM emissions with alternative fuels has generally been attributed to the low aromatic content of these fuels. Decreasing the aromatic content of a fuel will typically increase the fuel's hydrogen/carbon (H/C) ratio but since aviation fuels are complex mixtures of both aromatic and paraffinic compounds the relationship is not a simple inverse proportionality. Low aromatic content, high H/C ratio, and low viscosity were found to be the drivers for nvPM reduction. While the 20% FAME, 40% FAME, and 100% FT fuels do not meet current ASTM specifications for aviation fuels consisting of conventional and synthetic blending components, these results provide insight into the extent to which PM emission reductions can be achieved.

The lack of availability of aircraft engines for emissions testing using alternative fuels and the costs associated with running such engines make them impractical to use in evaluation studies. Aircraft auxiliary power units (APUs) however, are well suited to perform evaluations of alternative fuels for use in the aviation sector. APU also represent another major source of PM emissions in the airport complex. The PM emissions of an Artouste Mk113 APU were evaluated using several different fuels - Jet A-1, coal-to-liquid (CTL), gas-to-liquid (GTL), 50:50 GTL:Jet A-1 – at two APU operating conditions (publication 4; Lobo et al., 2012b). The impact of the gas turbine engines burning the alternative fuels on the environment as the emissions evolve after combustion was also investigated. As was the case with the main aircraft engines, the greatest reductions in nvPM emissions at the exhaust exit plane were observed at the idle condition. The greatest EIm reductions compared to Jet A-1 were in the order: GTL (90%) > 50:50 GTL:Jet A-1 (78%) > CTL (65%). The reductions in SN for all alternative fuels relative to Jet A-1 followed the same trend as that for EIm. These results were also consistent with those reported for other gas turbine engines burning alternative fuels, with the greatest reduction observed for fuels with the lowest aromatic content (Corporan et al., 2010; Timko et al., 2010; Lobo et al., 2011; Kinsey et al., 2012).

Lobo et al., 2012b was also the first study to examine the evolution of PM emissions downstream of a gas turbine engine. It was found that the organic-based PM emission index (EIorg) varied by a factor of 100 while EIn remained constant, when the emissions were measured 10m downstream of the APU. A small change in EIn was observed between the idle and full power conditions, whereas a very significant variation in EIorg over the same conditions was observed, implying that the condensation of organic species was the dominant process occurring as the plume evolves. A strong correlation between EIorg and EIm confirmed that the increase in mass was a consequence of an organic coating on the surface of the PM. This is an important result to consider. The reduction of nvPM emissions could potentially improve local air quality around airports; however, studies have demonstrated that the fraction of volatile PM from gas turbine engines increases in the evolving plume (Onasch et al., 2009; Presto et al., 2011). Therefore, for local air quality assessments, both non-volatile and volatile emissions need to be considered when developing PM emissions inventories. From measurements at the OAK (Lobo et al., 2012a) and ATL (Lobo et al., 2015a) airports it was evident that volatile material in the form of secondary PM dominated the total PM measured in some cases. The contribution of non-volatile and volatile emissions is essential to understand the impact of alternative fuels on the environment and to develop emissions mitigation and control strategies.

The effect of volatile PM emissions on SN measurements was further explored in publication 5 (Rye et al., 2012). The same Artouste Mk113 APU was used as the emissions source to compare SN measurements with those from number, mass, differential mobility and mass spectrometry analysis and to highlight the inadequacy of optical smoke measurements in characterising volatile or non-light absorbing PM emissions from gas turbine engines. The SN technique was intended to be used to measure plume visibility, and it does not quantify PM characteristics such as morphology, chemical composition, size distribution, or number and mass concentration, which are important from the perspective of local air quality and health effect concerns. FOA3 has been used to estimate mass-based emission indices using the SN data reported in the ICAO EDB (Wayson, Fleming, and Iovinelli, 2009). However, SN is not sensitive to volatile PM emissions and this could lead to underestimation of total PM emissions when the combustion products of a gas turbine engine include a large fraction of volatile or non-light absorbing PM. In this study, the SN and PM emission characteristics were compared for the Artouste Mk113 APU burning Jet A-1 and a neat Biodiesel produced from a rapeseed oil feedstock. The set up and instrumentation for PM emissions measurements was the same as that employed in Lobo et al., 2012b. For SN measurements, a separate probe was used to extract the emissions sample. SN was established using a Richard Oliver Smoke Meter, Whatman no. 4 filter paper, and a reflectometer per ARP1179 (SAE, 2011). It was found that less visible or light absorbing material was deposited on the Whatman no. 4 filter paper while sampling emissions from APU burning Biodiesel compared to Jet A-1. The comparison between Jet A-1 and Biodiesel in terms of total PM number and mass concentrations revealed that higher concentrations were observed with Biodiesel than Jet A-1. However, when only non-volatile PM emissions were considered, Biodiesel emissions at idle and full power were significantly lower than those for Jet A-1. Simultaneous chemical speciation measurements established that the volatile material (difference between total and non-volatile PM) was organic in composition and had a strong propensity to condense despite probe tip dilutions typically exceeding 20:1. This study showed that using the SN measurements to derive PM mass via the FOA3 method does not adequately capture the total PM emissions for some fuel types.

To develop better inventories of PM emissions at airports, a database of PM emission factors from a wide range of engine types must be developed together with an understanding of how fuel properties may affect PM characteristics. This is not a trivial task, since the methods used to characterise PM emissions could differ from one measurement campaign to another, thereby leading to inconsistent results. A standardised sampling and measurement system for PM emission must be developed before a database of PM number and mass-based emission indices, similar to that already in existence for gaseous emissions in the ICAO EDB, can be realised.

The Society of Automotive Engineers (SAE) Aircraft Exhaust Emissions Measurement Committee (E-31) developed a standardised sampling and measurement methodology, defined in the Aerospace Information Report (AIR) 6241, that will be used for future nvPM certification measurements (SAE, 2013). ICAO's Committee on Aviation Environmental Protection (CAEP) is currently developing a regulatory standard for nvPM number and mass-based emissions from civil aviation aircraft engines. The system defined in AIR6241 is designed to operate in parallel with existing sampling systems for gaseous emissions and smoke certification defined in ICAO Annex 16 (ICAO, 2008). The system specifications in AIR6241 build upon the work conducted in previous studies to evaluate sampling and measurement methodologies for aircraft engine nvPM emissions measurements (Lobo et al., 2007; Petzold et al., 2011; Lobo et al., 2011; Lobo et al., 2012 a, b; Crayford et al., 2012; Lobo et al., 2015). Publication 6 (Lobo et al., 2015b) reports the first of a kind data on aircraft engine nvPM number- and mass-based emissions using two standardized systems. Two compliant sampling and measurement systems operated by Missouri University of Science and Technology (Missouri S&T) and Empa were evaluated during the Aviation - Particle Regulatory Instrumentation Demonstration Experiment (A-PRIDE) 4 campaign. The main objectives of the study were to ascertain whether the AIR6241 compliant systems as defined were suitable and adequate for the measurement of aircraft engine nvPM emissions and to compare the performance and repeatability of the two compliant systems.

The standardised sampling system consists of a probe connected to a Y-splitter using a 7.5 m long, 8 mm ID thin walled stainless steel tubing which was heat traced to maintain a temperature of 160 ^{0}C ± 15 ^{0}C in the sample line. The Y-splitter provided exhaust samples to the Missouri S&T and Empa systems. Each system had a 3-way splitter to distribute sample among the nvPM, pressure control, and Annex 16 lines. The Annex16 line was used to measure undiluted gaseous emissions such as NOx, CO, UHC and CO_2. The sample in the nvPM line was diluted by particle free dry nitrogen (ultra-high purity 5.0 grade) via a Dekati DI-1000 ejector diluter to suppress the potential for water condensation, particle coagulation, gas-to-particle conversion, and volatile particle formation in the sampling lines. The dilution factor for the nvPM sample was determined by calculating the ratio of the CO_2 concentration in the undiluted Annex 16 line to that measured in the nvPM line. Dilution factors for both systems were maintained in the range 8–13, as specified by AIR6241, by regulating the inlet pressure to the ejector diluter to be slightly sub-atmospheric using a control valve in the pressure control line. The diluted sample was then conveyed to the measurement suite by a 25m long, carbon-loaded, electrically grounded polytetrafluoroethylene (PTFE) tube (Missouri S&T line: 7.87 mm ID, Dekoron Unitherm, USA; Empa line: 8 mm ID, Hillesheim GmbH, Germany) maintained at 60 ± 15^{0}C. The sample flow rate in this line was maintained within the AIR6241 stipulated 25 ± 2slpm. The construction of the two systems was very similar and the sample lines from the splitter to the individual instruments were of similar length and inner diameter.

The primary instruments in the AIR6241 systems report nvPM number and mass-based emissions. The nvPM number was measured using an AVL Particle Counter (APC) Advanced. The APC includes a volatile particle remover (VPR) consisting of a two stage dilution with a rotary diluter and a catalytic stripper, and an n-butanol based condensation particle counter (CPC) TSI 3790E which has a 50% cut-off diameter, D_{50}, at 10 nm. For nvPM mass measurements, two real-time, high resolution instruments that satisfied the performance specifications were used – an Artium Laser Induced Incandescence LII-300 (LII; Snelling et al., 2005) and an AVL Micro Soot Sensor (MSS; Schindler et al., 2004). The CO_2 concentrations in the diluted nvPM lines were measured using a LiCor 840A and Thermo Scientific 410i NDIR detectors on the Missouri S&T and Empa systems, respectively. Additional ancillary instruments which are not prescribed by AIR6241 were deployed to further characterize the physical and chemical properties of the nvPM emissions. Particle size distributions were measured using the Cambustion DMS500 (Reavell, Hands, and Collings, 2002). A compact Time of Flight Aerosol Mass Spectrometer (CToF-AMS) (Drewnick et al., 2005) and a high resolution Time of Flight Aerosol Mass Spectrometer (HRToF-AMS) (DeCarlo et al., 2006) were used to evaluate semi-volatile PM emissions. Tandem mass-mobility measurements using a differential mobility analyzer (DMA; TSI 3081A), a Centrifugal Particle Mass Analyzer (CPMA; Cambustion) and a CPC (TSI 3776) in series were taken to determine particle effective density and the mass-mobility exponent (Olfert and Collings, 2005).

The performance of the Missouri S&T and Empa AIR6241 compliant systems was compared during dedicated engine testing on a CFM56-5B4/2P engine source and maintenance engine testing using CFM56-7B24/3 and PW4168A engine sources at a range of engine operating conditions. Overall, these two compliant systems were found to be within 6% of each other in terms of nvPM number-based emissions and within 15% for nvPM mass-based emissions. This study successfully demonstrated that the systems built to the AIR6241 specifications are suitable for the measurement of aircraft engine nvPM emissions. However, for the three engine sources studied, at several engine power conditions the mass instruments approached their limit of detection, resulting in high measurement uncertainties. As with smoke number, for modern cleaner burning and fuel efficient engines, accurately measuring nvPM mass at certain engine power conditions will continue to be a challenge with current instrumentation. This will have to be taken into consideration by ICAO/CAEP when the regulatory limit for nvPM mass is defined.

While the regulatory limit will be established for only number- and mass-based emissions, it is useful for environmental impact assessments to have further characterisation of nvPM in terms of size distributions, chemical composition, and effective density. With the standardised AIR6241 compliant system, it was found that particle geometric mean diameter ranged 20 - 45 nm and geometric standard deviation varied 1.55 - 1.9 for the three engine types studied consistent with previous studies (Lobo et al., 2007; Lobo et al., 2015a). PM organic emissions observed for CFM56-5B4/2P engine was similar in magnitude to that measured for other aircraft engines. The size-dependent particle effective density was parameterized from mass-mobility measurements using the DMA-CPMA technique with a mass-mobility exponent of 2.57 and a pre-factor of 0.606.

With the standardised sampling and measurement system defined for nvPM emissions measurements, the same methodology can be applied to a gas turbine engine burning alternative fuels. Publication 7 (Lobo et al., 2015c) presents the systematic evaluation of nvPM emissions from a Garrett Honeywell GTCP85 aircraft APU burning a Used Cooking Oil (UCO) derived HEFA alternative fuel in varying blend ratios with a conventional Jet A-1 baseline fuel to investigate the impact of incremental variations in fuel composition on nvPM production. The nvPM number- and mass-based emissions along with size distributions were measured using the AIR6241 compliant system. This was the first study to characterise nvPM emissions from an APU using the standardized system and will add to the data on the nvPM emission characteristics of different gas turbine engines. Another unique feature of this work is the evaluation of incremental variations in fuel composition of a single alternative fuel on the production nvPM emissions.

Conventional Jet A-1 was used as the baseline fuel in this evaluation. Various blend ratios - 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. Three operating conditions, corresponding to the normal operating conditions for the GTCP85 APU, were selected to conduct the test – No Load (NL), Environmental Control Systems (ECS), and Main Engine Start (MES). APU operating parameters such as fuel flow rate, RPM, air fuel ratio (AFR), and exhaust gas temperature (EGT) were recorded for each stable APU operating condition. 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 evaluated, this test cycle was twice sequenced without APU shutdown. The different fuel blends to be evaluated were selected at random to mitigate possible systematic bias and drift.

The nvPM number- and mass-based emission characteristics of the APU while burning Jet A-1 were found to decrease linearly with increasing fuel flow rate. The emissions trends and magnitudes agree well with GTCP85 APU emissions reported in another study (Kinsey et al., 2012). 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 (Lobo et al., 2007; Lobo et al., 2015a, b). This permits the current dataset to also be used to estimate nvPM emissions reductions when alternative fuels are burned in main aircraft engines.

The reductions in blend fuel nvPM EIn and EIm correlated well with fuel hydrogen content, with higher fuel hydrogen content (higher proportion of UCO-HEFA in the fuel blend) resulting in greater reductions in EIn and EIm. 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 (Lobo et al., 2011; Lobo et al., 2012b; Corporan et al., 2011). 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) (Beyersdorf et al., 2014).

The results from all of these studies will be critical to understanding the PM emissions profile for aircraft engines burning alternative fuels and the impact of emissions on local air quality climate change and health-related effects.

CHAPTER 10: CONCLUSIONS

The seven peer reviewed publications that are contained within this thesis greatly advanced the characterization of gas turbine engine PM emissions. The summary conclusions from each publication are presented below:

Publication 1 – Lobo et al., 2012a – described the methodology for real-time measurements of aircraft engine specific PM emissions via extractive sampling of wind advected plumes and presented the analysis of the associated high resolution data. The aircraft gas turbine engine PM emissions were measured for the following engine-airframe combinations: CMF56-3B1/-3B2 (B737-300), CFM56-7B22/-7B24/-7B26 (B737-700/800), V2500-A5 (A320), JT-8D (MD-80), CF6-80 (A300), CF6-50 (DC-10), and CF34-3B (CRJ-100/200). For all engine types studied, the size distributions were typically bimodal in nature with a nucleation mode comprised of freshly nucleated PM and an accumulation mode comprised mostly of PM soot with a coating of condensed volatile material. The geometric mean diameter (GMD) for the size distributions at idle was found to be 13.1 ± 2.9 nm with a geometric standard deviation (GSD) of 1.47 ± 0.19. At take-off, the GMD was 13.2 ± 5.3 nm with a GSD of 1.58 ± 0.32. Older technology engines such as the CFM56-3B and JT8D engines were observed to have as much as 3X higher PM EIm values at take-off compared to newer engine technology such as the CFM56-7B engine.

Publication 2 – Lobo et al., 2015a – described the results of PM emissions measurements at the engine exit plane, and during an advected plume study where emissions were sampled 100-350m downwind from aircraft operational runways during normal airport operations at the Hartsfield-Jackson Atlanta International Airport. Engines from the fleet of Delta Airlines - JT8D-219 (MD88), PW2037 (B757), and CF6-80 (B767) were sampled during the engine exit plane measurements. An extensive set of engine such as BR715 (B717), CF34-3B1 (CRJ200), CF34-8C1 (CRJ700), CF6-80 (B767-300/400), CFM56-5C (A340-300), CFM56-7B (B737-700), JT8D-15A

(B737-200), JT8D-219 (MD-88), PW127 (ATR72), and PW2037 (B757-200) were sampled during the advected plume study. For engine exit plane measurements it was found that the size distributions were generally lognormal in nature with a single mode, and PM emission indices change as a function of engine power condition and also vary with engine type. For the advected plume measurements, substantial gas-to-particle conversion occurred as the exhaust plume expanded and cooled, leading to the formation of secondary PM. EIn was found to range between 7×10^{15} - 9×10^{17} particles/kg fuel burned, and the range for EIm was 0.1 – 0.6 g/kg fuel burned. The results from this study along with those from the OAK study provided PM characteristics for a broad range of commercial aircraft gas turbine engine emissions at various operational states that were not previously available. The sampling and measurement approaches employed in these studies proved to be robust for the various engine types investigated.

Publication 3 – Lobo et al., 2011 – employed the same methodology for PM emissions measurements as the OAK and ATL studies to characterize the emissions from a CFM56-7B engine burning conventional and alternative fuels. This was the first such characterization of PM emissions from a commercial aircraft gas turbine engine. The PM distributions demonstrated a correlation to both engine operating condition and fuel type. Reductions in both EIn and EIm were observed when burning the alternative fuel compared to the baseline Jet A-1. Generally, the measured reductions in PM were largest at idle, and smallest at maximum rated thrust. The emissions reduction was greater as the relative amount of alternative fuel content in the fuel was increased. It was found that both fuel aromatic content, and H/C ratio (or hydrogen content) can influence PM emissions.

Publication 4 – Lobo et al., 2012b – extended the methodology used for commercial aircraft gas turbine engines and applied it to a recommissioned Artouste Mk113 APU. In addition to studying the impact of alternative fuels (produced using the FT process) on APU combustion, this study was also the first to investigate the evolving PM emissions from an APU at the idle and full power operating conditions. Dramatic reductions in EIn and EIm at both operating conditions were observed. The lower the aromatic content of the alternative fuel, the greater the reduction in PM emissions. At the engine exit plane, both EIorg and EIn were bound within a small range, however, at the downstream location, the EIorg values varied by a factor of 100 while EIn values remained relatively constant. Condensation of organic species was identified as the dominant process occurring as the plume evolves. A strong correlation between EIorg and EIm confirmed that the increase in mass was a consequence of an organic coating on the surface of the PM. The study served to highlight the fact that although nvPM emissions are reduced with alternative fuels, the impact of volatile PM emissions on the environment needs to be better understood.

Publication 5 – Rye et al., 2012 – explored the impact of volatile PM on traditional SN number measurements using the Artouste Mk113 APU as the emissions source burning Jet A-1 and Biodiesel fuels. The total and nvPM emissions were also evaluated using measurement systems employed in the previous 4 publications. The SN results indicated that Biodiesel significantly reduced visible emissions compared to Jet A-1. The nvPM number and mass concentrations of Biodiesel were also found to be significantly lower than those for Jet A-1, consistent with the SN results. However, the total PM concentrations for Biodiesel relative to Jet A-1 were higher. Biodiesel exhaust exhibited a stronger propensity to condense volatile PM which was found to be organic in composition. The SN technique was unable to measure this increased fraction of volatile components and thus significantly underestimated total PM emissions.

Publication 6 – Lobo et al., 2015b – describes the standardised sampling and measurement system developed for the measurement of aircraft gas turbine engine nvPM emission measurements that will be used for nvPM certification measurements. The performance of two independently constructed - Missouri S&T and Empa - AIR6241 compliant systems was successfully compared during the A-PRIDE 4 campaign during dedicated engine testing on a CFM56-5B4/2P engine source and maintenance engine testing using CFM56-7B24/3 and PW4168A engine sources at a range of engine operating conditions. This was the first study to report on aircraft gas turbine engine nvPM number- and mass-based emissions using standardized AIR6241 systems and demonstrated that systems built to the AIR6241 specifications are suitable for the measurement of aircraft engine nvPM emissions.

Publication 7 – Lobo et al., 2015c – utilized the standard sampling and measurement system to characterise the nvPM emissions from a GTCP85 APU burning conventional Jet A-1 as well as a UCO-HEFA fuel and 16 different blends of UCO-HEFA with Jet A-1. This study was the first to measure nvPM emissions from an APU at three operating conditions using the standardised system. EIn and EIm were found to decrease linearly with increasing fuel flow rate when the APU was burning Jet A-1. Fuel composition was found to influence nvPM production. Jet A-1 and UCO-HEFA both 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. The reductions in UCO-HEFA blend fuel nvPM EIn and EIm correlated well with fuel hydrogen content using a second order polynomial function fit to the experimental data. 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. The reduction in EIm was found to be greater than EIn for the corresponding fuel hydrogen content.

Prior to the publication of the seven peer reviewed papers, PM emissions from gas turbine engines such as aircraft main engines and auxiliary power units, significant contributors of PM emissions in the airport complex, were not well characterised. The sampling methodology described in Lobo et al., 2012a, b and Lobo et al., 2015a, demonstrated how PM emissions from gas turbine engines could be sampled, reliably and repeatedly, with a state of the art measurement suite. The characterisation of PM emissions in terms of number- and mass-based emissions, size distributions, and chemical composition provided an extensive dataset from a wide variety of engine types. These publications also provided first of a kind characterisation of expanding exhaust plumes. With a better understanding of PM emissions measured at the exhaust exit plane as well as in the near field, more accurate emissions inventories could be established and emission mitigation strategies developed. One such direct application of the data acquired was in the development of a detailed PM emissions inventory for the Copenhagen Airport in Denmark (Winther et al., 2015).

As alternative fuels started to be considered for the aviation sector, Lobo et al., 2011 was the first study to examine the PM emissions of a CFM56-7B engine, a widely used commercial aircraft gas turbine engine. This study utilised the same sampling system and protocol that was successfully demonstrated in earlier studies. The highlight of this study was the dramatic reduction of PM emissions using alternative fuels. The use of these fuels during normal airport operations can significantly reduce the environmental impacts associated with PM emissions. The emissions were also correlated with fuel properties, and it was found that fuels with lower aromatic content, higher hydrogen content, and lower viscosity significantly reduced emissions. This project and associated data spurred other research activity to investigate effects of fuel composition on primary and secondary PM formation (Miracolo et al., 2012; Timko et al., 2013; Beyersdorf et al., 2014) using a wide variety of alternative fuels.

As the data on PM emissions from gas turbine engines burning conventional and alternative fuels started to be collected, it became apparent that different groups were utilising different sampling and measurement approaches. For emissions certification and comparison purposes, the sampling protocol and methodology for PM emissions characterisation must be standardised. To this end, the Society of Automotive Engineers (SAE) Aircraft Exhaust Emissions Measurement Committee (E-31) developed a standardised procedure for the continuous sampling and measurement of aircraft gas turbine engine nvPM emissions. The standardised methodology defined in the Aerospace Information Report (AIR) 6241 (SAE, 2013) was informed in large part by the PM emission characterisation studies described in this thesis.

Once the standard methodology was developed, the robustness and repeatability of the system had to be evaluated before it could be adopted for use by engine manufacturers. Lobo et al., 2015b was the first study to report on the performance evaluation of two AIR6241 compliant systems. The study successfully demonstrated that the nvPM emissions measurement methodology was sound and the specifications outlined AIR6241 were robust to allow engine manufacturers to either build or purchase their own AIR6241 compliant systems. Subsequently, the ICAO/CAEP/Working Group 3/Particulate Matter Task Group took up the work project to develop a regulatory standard for aircraft gas turbine engine nvPM emissions. This new regulation, the first for aircraft gas turbine engine PM emissions, will be defined based on the measurement data reported in Lobo et al., 2015b and Lobo et al., 2015c, among others. The nvPM number- and mass-based emissions data will eventually be tabulated for different engine types in the ICAO EDB, similar to gaseous emissions and smoke number. This information can then be used for forecasting the PM emissions impact of aviation operations on local and regional air quality, climate change, and health-related effects with gas turbine engines burning conventional and alternative fuels. It will also provide critical information in the cost-benefit analysis of the use of alternative fuels by airlines and airports.

While the seven peer reviewed publications advanced the understanding of the characteristics of PM emissions with conventional and alternative fuels, a lot more work is still required. PM emission characteristics have been shown to be directly influenced by fuel properties and engine/technology type. New fuels are being developed for the commercial aviation sector as the need to augment and diversify fuel supplies becomes increasingly important. Technological advances in engine design to improve efficiency and reduce fuel consumption coupled with the use of alternative fuels will certainly drive down PM emissions but the extent to which they would do so is not well understood. The following are some recommendations for future work:

1. Characterise PM emissions from different gas turbine engine types burning newer alternative fuels to develop a robust correlation between PM reduction and fuel properties.
2. Develop international standard atmosphere corrections for PM emissions data acquired with the standardized system as has been done for gaseous emissions
3. Develop a correction for fuel properties so that PM emissions data acquired with different fuels can be inter-compared
4. Evaluate system particle losses to develop loss correction factors that can be applied to PM emissions data at the measurement location to determine PM concentrations and emission indices at the engine exit plane to perform environmental impact assessments.

The data and analysis from this thesis will serve as baseline from which PM emissions from newer engines burning various alternative fuels can be compared and assessments of local and regional air quality, climate change, and health related PM impacts can be undertaken.

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