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SUSTAINABLE ENERGY

Influence of Fuel Hydrogen Content and Atomisation Quality on Ultrafine Non-volatile Particulate Matter Emissions in RQL Gas Turbine Technology

Aircraft engines are a source of harmful non-volatile Particulate Matter (nvPM) emissions, negatively affecting human health and the global environment. To mitigate this, new sources of fuel are being assessed for the commercial aviation sector. Sustainable Aviation Fuels (SAF) show significant promise as replacements to conventional aviation fuels, with the potential to reduce lifecycle CO_2 and nvPM emissions because of lower aromatic contents and higher hydrogen content. Towards better understanding of the nvPM emissions from aircraft combustors operating with SAF, this work outlines results from the RAPTOR experimental test campaigns performed at Cardiff University's Gas Turbine Research Centre (GTRC). Several aviation fuels of varying physiochemical properties were burned in a non-proprietary Rich-Quench-Lean (RQL) combustor rig. The nvPM emissions were measured using the European nvPM reference system, with data corrected for particle loss in the sampling and measurement system using additional particle size measurement. nvPM emission reductions were achieved for fuels of higher hydrogen content, and system loss correction was required to accurately quantify those reductions. Additionally, independent control of the air supply to the combustor rig allowed the impact of fuel spray quality to be decoupled from AFR, demonstrating that small improvements in spray droplet atomisation predicted from benchmarking fuel spray experiments (~5% reduction in SMD) consistently yielded significant reductions in nvPM emissions, ranging from 5-72% for nvPM EI_{mass}, 11-89% for nvPM EI_{number}, and 1-7% for GMD.

Keywords:
Rich-quench-lean combustor, particulate matter emissions, sustainable aviation fuel, atomisation, particle loss correction.

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INTRODUCTION

Commercial aviation is currently responsible for around 2-3% of anthropogenic CO_2 emissions, with its global contribution expected to rise owing to predicted increases in flights and the challenges associated with decarbonising aircrafts compared to other sectors (e.g., Automotive) [1], [2].

Aircraft engines also produce other harmful emissions including NOx and non-volatile Particulate Matter (nvPM). The production of nvPM is widely attributed to the presence of aromatic compounds in conventional Jet fuels, which are a carryover from the crude oil refinement process and have minimum requirements in current fuel specs [3]. The nvPM size from aviation gas turbines typically ranges between 10-100 nm [4]–[7], small enough to be absorbed by the lungs, resulting in cardiovascular and respiratory issues [8], [9]. Most commercial gas turbine engines use Rich-Quench-Lean (RQL) combustors, which were originally developed to mitigate NOx emissions, however nvPM emissions are produced in fuel-rich primary zone [10]Gas Turbine Combustion: Alternative Fuels and Emissions, Third Edition provides an up-to-date design manual and research reference on the design, manufacture, and operation of gas turbine combustors in applications ranging from aeronautical to power generation. Essentially self-contained, the book only requires a moderate amount of prior knowledge of physics and chemistry. In response to the fluctuating cost and environmental effects of petroleum fuel, this third edition includes a new chapter on alternative fuels. This chapter presents the physical and chemical properties of conventional (petroleum-based with their burn out competing with NOx reduction in the secondary lean zone.

Both CO_2 and nvPM emissions can be reduced using Sustainable Aviation Fuels (SAF). SAFs produce CO_2 during combustion but have the potential to offer reduced lifecycle CO_2 emissions through carbon capture at their feedstocks. Many SAF also allow for reductions in nvPM emissions due to the lower aromatic (higher hydrogen) content they typically exhibit [4], [11].

SAFs also have the potential to be used as drop-in fuels, meaning that they resemble conventional aviation kerosene closely enough to be used in existing aircraft with minimal modifications. This makes them promising to replace existing Jet-A fuels, with numerous pathways already approved to allow their use when blended with conventional Jet Fuel [12].

Towards better understanding the potential benefits of implementing SAF, the emissions of six Jet fuels of varying physiochemical properties were assessed using a non-proprietary RQL representative combustor as part of the RAPTOR (Research of Aviation PM Technologies, mOdelling and Regulation) research program. The RQL combustor is representative of a small aircraft combustor operating at low thrust conditions, such as idle on a runway. The nvPM and gaseous emissions were measured using the regulatory compliant European nvPM reference [13]and rigorous testing. Three reference systems for aircraft engine nvPM emissions measurement, compliant with the specifications for the standardized methodology, were independently developed. This paper reports the results of the first inter-comparison of these three reference systems using a CFM56-7B26/3 aircraft engine to establish repeatability and intermediate precision of the sampling and measurement systems as part of the multi-agency international collaborative projects: Aviation-Particle Regulatory Instrumentation Demonstration Experiment (A-PRIDE, with additional particle size measurement performed for both particle loss correction, and to investigate the impact of fuel properties on particle size (i.e., Geometric Mean Diameter (GMD)). Additionally, the impact of atomisation quality on emissions was assessed via independent control of the air supplies to the fuel atomiser and primary zone cooling plate, affording maintenance of the primary and global Air to Fuel Ratios (AFR) whilst changing atomisation quality. As such, the results of this work facilitate better understanding of the impact of both fuel composition and atomisation properties on nvPM emissions, towards improving local air quality.

MATERIALS AND METHODS

Six fuels were assessed, including high-aromatic conventional Jet fuels (J-HA1 & J-HA2), a high aromatic SAF (A-HA), a low aromatic Gas-To-Liquid fuel (GTL), and blends of GTL and Jet fuels (B-HE & B-LA). In line with recent research in the field [11], [14], emphasis was given to fuel hydrogen content, which was determined using GCxGC-FID compositional data and represents the typical range encountered across Jet fuels meeting the aromatic and di-aromatic specifications prescribed by ASTM D1655 [3].

Fuel	Hydrogen Content (% wt.)	Total Aromatic Content (% wt.)	Di-Aromatic Content (% wt.)
J-HA1	13.43	24.24	1.07
A-HA	13.51	20.57	0.28
J-HA2	13.65	22.75	2.18
B-HE	14.51	12.82	0.14
B-LA	14.90	6.71	0.38
GTL	15.47	0.06	0.00

Table 1. RAPTOR fuel properties.

Experiments were undertaken at Cardiff University's Gas Turbine Research Centre (GTRC) using their bespoke 'Flexis' RQL combustor rig. Fuel and atomisation air were introduced using a purpose developed prefilming airblast atomiser produced using Additive Manufacturing (AM) [15], with secondary combustion air introduced through a fixed geometry combustion liner manufactured by traditional machining techniques. The combustor was housed in a High-Pressure Optical Chamber (HPOC), allowing for elevated temperatures, and pressure.

Two iterations of the combustor were used labelled Mk. II and Mk. II-A, with the MK. II-A designed to afford an additional air supply feed to the primary zone via an internal transply cooling plate. Independent control of the air supplies to the atomiser and cooling plate allowed for variation in atomisation quality whilst maintaining constant primary AFR, thereby decoupling the impact of atomisation quality on emissions.Estimation of the atomisation quality was achieved using spray characterisation experiments carried out prior to combustion testing [15]. Measured droplet size data, over a range of operating conditions, were used to derive empirical constants for the developed AM atomiser, required as inputs for an established atomisation correlation [15]. Droplet sizes were measured for a range of fuels using a Dantec Fiber PDA system.

Fig. 1. RQL combustor atomiser and combustion chamber design.

Measurement of nvPM number and mass emissions was undertaken using the regulatory compliant European nvPM reference sampling and measurement system [16], [17], which contains several instruments used for the traceable determination of nvPM and gaseous emissions [13]and rigorous testing. Three reference systems for aircraft engine nvPM emissions measurement, compliant with the specifications for the standardized methodology, were independently developed. This paper reports the results of the first inter-comparison of these three reference systems using a CFM56-7B26/3 aircraft engine to establish repeatability and intermediate precision of the sampling and measurement systems as part of the multi-agency international collaborative projects: Aviation-Particle Regulatory Instrumentation Demonstration Experiment (A-PRIDE.

As per international standards [16] nvPM number and mass emissions are reported as Emission Indices (EIs) used to assess engine performance by giving emitted pollutants per unit mass of fuel burned. Particle loss correction was performed using a method PSD_B [18] to account for the significant losses of particles in a regulatory nvPM system, with particle size data determined using a Cambustion DMS-500. Each test point corresponds to a stable 30-second condition with error bars representative of ±2 standard deviations of the scatter across the point.

RESULTS AND DISCUSSIONS

The impact of fuel hydrogen content on loss-corrected nvPM EI number and mass emissions are shown in Figure 2 for both combustor iterations. In agreement with the literature [4], [11], nvPM emissions are seen to decrease with increasing fuel hydrogen content, demonstrating a stronger correlation with nvPM emissions than any other single fuel property (e.g., aromatic content) . System loss correction was critical to accurately quantify the nvPM reduction associated with cleaner fuels. This is because higher losses are associated with smaller particle sizes, typically witnessed for fuels of higher hydrogen content. Therefore, engine exit particle number concentrations tend to be underpredicted in the case of SAFs without correction, resulting in an overprediction in the effectiveness of high hydrogen content SAFs in mitigating nvPM. By comparing values of EI number before and after system loss correction, this overprediction was determined empirically as shown in Figure 3. As can be seen, without system loss correction, EI number reductions for higher hydrogen content fuels are overestimated by up to ~13%.

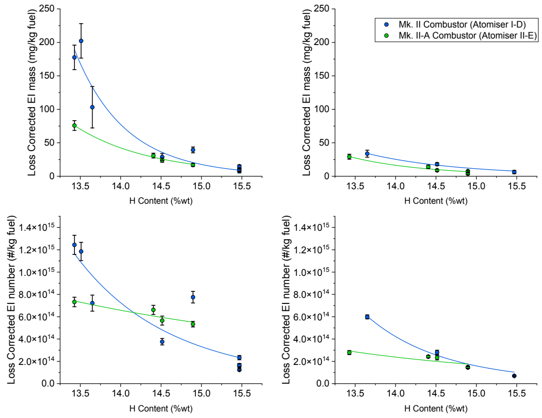

Fig. 2. nvPM EI number and mass emissions Vs fuel hydrogen content at rich (left) and lean (right) conditions.

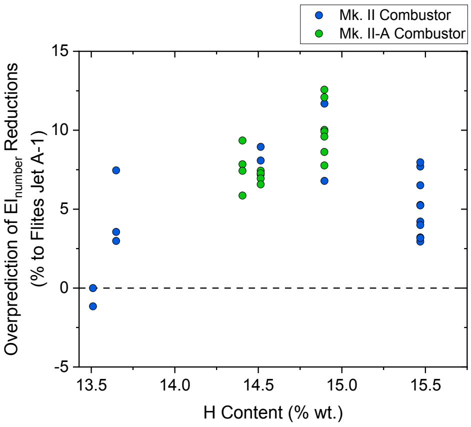

Fig. 3. Percent overprediction of EI number reduction associated with increased fuel hydrogen content without system loss correction.

Additionally, the impact of atomisation quality on nvPM emissions was assessed using the Mk. II-A by holding the primary and global AFRs constant at a given fuel hydrogen content, whilst decreasing the relative proportion of air supplied to the atomiser, resulting in worsened atomization performance (5% in SMD) as estimated using empirically validated correlations [15]. For the rich and lean conditions, switching to the reduced atomisation condition was achieved by reducing the mass flowrate of air through the atomiser by 8.5% and 8.7%, respectively. The results shown in Fig. 4 oveleaf highlight that the reduced atomisation performance corresponds to an increase in nvPM EI number (11-89%), mass (5-72%) and particle size (1-7% for GMD) across all the fuels and AFRs studied.

This finding is in agreement with the literature [19], suggesting improvements in atomisation quality led to higher numbers of smaller particles in the primary zone, which are more easily consumed in the secondary lean zone, leading to overall reduced PM emissions.

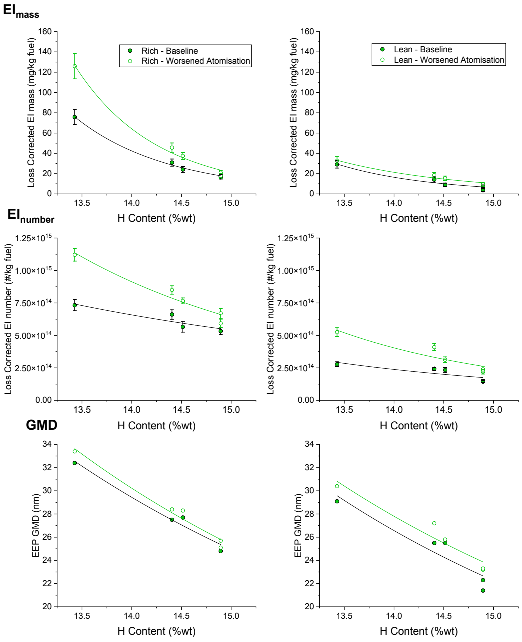

Fig. 4. Impact of reduced worsened atomisation quality on nvPM EI number, mass, and GMD.

Analysis of the gradients of the plotted trendlines in Fig. 4 3 suggests that higher increases in nvPM due to worsened atomisation are expected for fuels of lower hydrogen contents, implying that high aromatic conventional fuels could be more sensitive to changes in atomisation quality. The results also serve to experimentally demonstrate how small changes to atomisation quality can significantly impact nvPM number and mass, at least under the relatively low power conditions used for experimentation in this project.

CONCLUSIONS

- A non-proprietary RQL combustor rig with independent control of inlet air flows, representative of a small-scale aircraft engine operating at low thrust conditions, was successfully developed.
- The nvPM emissions from the RQL combustor were characterised using the European reference nvPM system for a range of Jet fuels with different hydrogen contents.
- System loss correction using particle size measurement was utilised to predict engine exit emissions, allowing for more accurate quantification of nvPM emission reductions achieved with SAFs of higher hydrogen contents.
- The influence of fuel physical properties affecting spray quality may significantly impact nvPM emissions, with small improvements in atomisation quality potentially resulting in significant decreases in nvPM emissions.

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