Fight 100: Emission Testing from Auxiliary Power Unit

World's First Net Zero Transatlantic Flight

M. Pourkashanian
I. Ahmed, E. Alborzi, G. Dunderd
Energy Innovation Centre (EIC),
The University of Sheffield, UK

Executive Summary

The University of Sheffield's Energy Innovation Centre (EIC) embarked on a comprehensive study to evaluate the performance of sustainable aviation fuels (SAFs) specifically for Flight-100 project. As the aviation industry seeks environmentally friendly alternatives, understanding the impact of these fuels becomes crucial. This study focused on assessing the gaseous and particulate emissions of two specific fuels: 100% HEFA (Hydroprocessed Esters and Fatty Acids) and an 87.3% HEFA and 12.7% SAK (Synthesized Aromatic Kerosene) blend. These fuels were sourced from Rolls Royce Darby and subjected to rigorous testing alongside a baseline JetA1 fuel obtained from a commercial airport.

Experimental Setup: To simulate real-world engine conditions, a Honeywell 131-9A APU employed. The experimental setup included a sampling system equipped with a single-point probe and an XYZ positioning system. This system facilitated the division of exhaust gases into two streams for parallel analysis. These streams were directed towards the stack emission rack, which housed various analysers for gaseous emission characterization. Additionally, the LII-300 particulate analyser and Dekati ELPI impactor was used in assessing particulate matter emissions.

Key Findings

1. Emission Reductions:
    - Both HEFA and the HEFA/12.7%SAK blend demonstrated significant reductions in both particulate number and mass concentrations compared to the conventional JetA1 baseline. Notably, HEFA emerged as a major contributor to these reductions.
2. Particulate Matter Analysis:
    - The LII300 results indicated that HEFA and the HEFA/12.7%SAK blend particulate matter have an increased active soot surface area compared to those of JetA1.
    - This finding suggests that the alternative fuels may have different combustion characteristics, warranting further investigation.
3. $NO-NO_2$ Ratio Alterations:
    - Intriguingly, alterations in the $NO-NO_2$ ratio within the exhaust emissions were observed which requires further investigation.

Fuel Consumption (by mass): Evidence from the study suggests that when using HEFA and the HEFA/12.7%SAK blend, there was a 2.2%-0.95% improvement in fuel consumption (by mass). This improvement can be attributed to the higher H/C ratio and energy density of 100% HEFA and the HEFA-12.7% SAK blend. These findings underscore the importance of considering not only emissions but also fuel consumption (by mass) when evaluating alternative aviation fuels.

Future Research: Funding has been secured to delve deeper into understanding the impact of H/C ratio and naphthalene on particulate formation and mass flow. Further investigations will shed light on optimizing these sustainable fuel alternatives.

Introduction

As part of a transatlantic flight run entirely on 100% sustainable aviation fuel, the University of Sheffield's Energy Innovation Centre conducted comprehensive tests on the gaseous and particulate emissions of the fuel utilized for Flight 100. Rolls-Royce Darby provided two distinct types of fuels for examination: one composed entirely of 100% HEFA, and the other a blend comprising 87.3% HEFA and 12.7% SAK. Each fuel variant was delivered in two drums, resulting in a total volume of 400 litters for each type.

In contrast, the baseline fuel used for comparison was a standard JetA1, procured from a commercial airport. This baseline fuel was delivered in batches, with each batch comprising four 200-liter drums. The characterization of the baseline fuel was meticulously assessed at the SAF-IC characterization lab.

The primary objective of the testing was to meticulously examine the particulate emission characterization. This examination involved utilizing the LII 300 particulate analyser provided by Rolls-Royce, in conjunction with the University of Sheffield's Dekati ELPI impactor, which facilitated the assessment of size and number distribution of particulate emissions.

Additionally, PM emissions were thoroughly assessed using additional equipment, including SMPS (Scanning Mobility Particle Sizer) and TEM (Transmission Electron Microscopy) analysis and toxicology analysis equipment those were deployed by Imperial College London to conduct. However, the results obtained from those analysis will be provided separately By ICL.

This report exclusively covers the results obtained by the University of Sheffield, focusing on the detailed examination of gaseous and particulate emissions from the sustainable aviation fuels tested.

Experimental Setup

Fuels testing: The experimental setup was designed to ensure the accuracy and reliability of the emissions data collected during the testing process. Honeywell 131_9A APU was deployed to test the fuels at two different loading conditions.

The 131-9 APU, found in Boeing 737-600/-700/-800 aircraft (B variant) and Airbus A319/20/21 models, serves as a versatile self-contained power unit. It offers both shaft and pneumatic power, which are regulated through a system of electronic, hydraulic, and electro-mechanical controls. This APU can provide power while the aircraft is on the ground and during flight. Its functions encompass supplying pneumatic power for main engine starting (MES), cabin air conditioning up to an altitude of 17,000 feet, and electrical power up to 41,000 feet. The APU consists of two main sections: the load section, housing the gearbox and load compressor, and the power section. Each of these components has a specific role in the APU's operation and performance. This is demonstrated in figure 1.

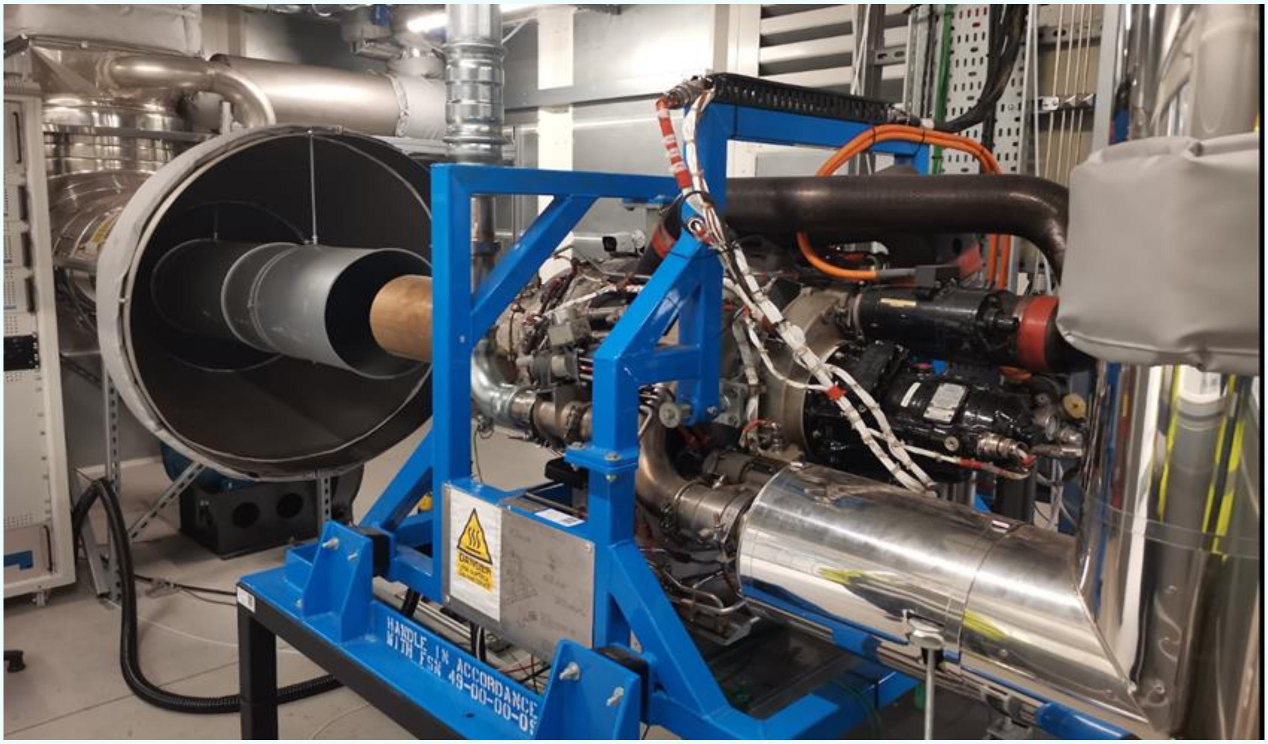


FIGURE 1: HONEYWELL 131_9A APU AT THE TRANSLATIONAL ENERGY RESEARCH CENTRE (TERC).

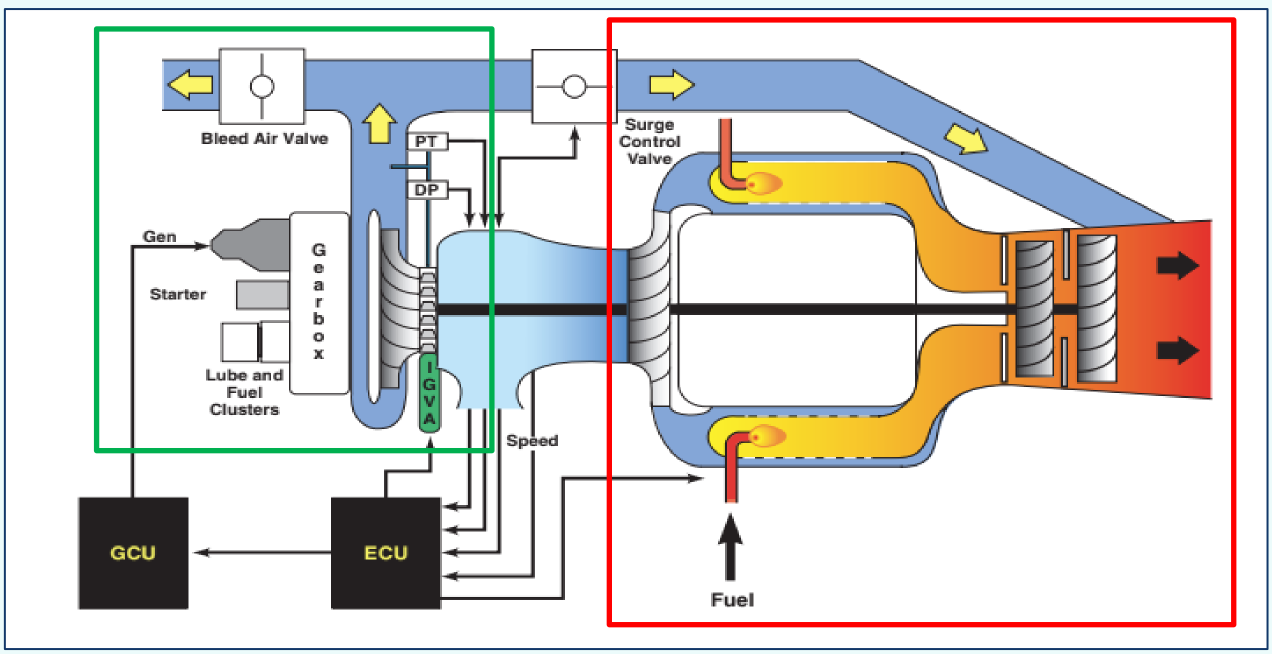


FIGURE 2: APU SCHEMATIC DIAGRAM, THE POWER SECTION FRAMED BY A RED BOX WHILE THE LOAD SECTION IS INDICATED BY GREEN BOX.

To facilitate emissions sampling, a single-point probe mounted on an XY positioner was strategically deployed. This probe facilitated the division of exhaust gases into two distinct streams for parallel analysis (Figure 3 and Table1).

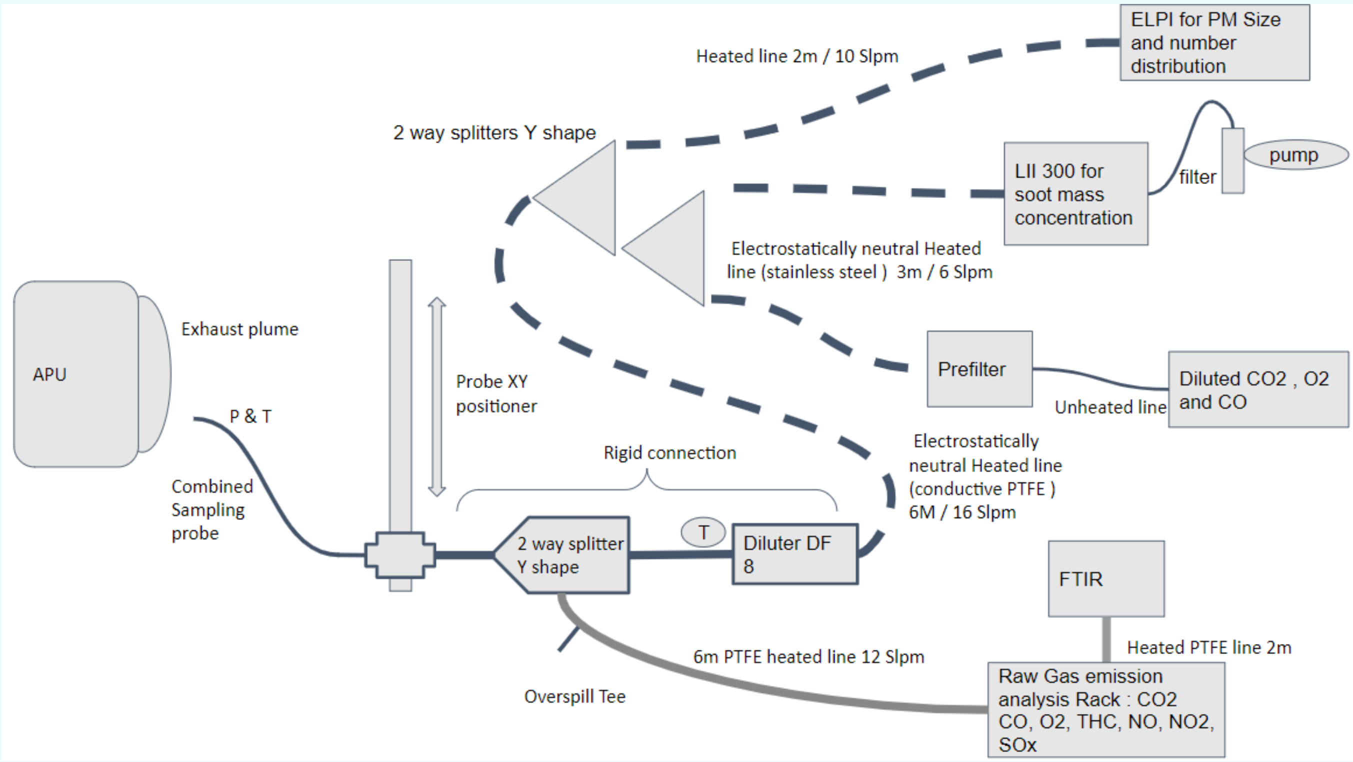


FIGURE 3: SAMPLING SYSTEM.

Method	*Model*	*Measuring Gases*	*Ranges*	*Drift*
CLD NOx Analyser	Quasar192	NO, NO_2, NOx	0-100 ppm to 0-10,000 ppm (with intermediate ranges)	<0.5% FSD/24hrs
FID THC Analyser	Solar272	THC	0-100 ppm to 10% (with intermediate ranges)	+/-0.2ppm or 2% range per week (whichever is greater)
NDIR Analyser	Pulsar293	CO	Channel 1: 0-500ppm, 0-5000ppm, 0-5%, 0-50%	Zero Drift: 1% FS per week; Span Drift: 1% FS per 24 hrs
NDIR Analyser	Pulsar293	SO_2	Channel 2: 0-200ppm, 0-500ppm, 0-1000ppm, 0-2000ppm	Zero Drift: 1% FS per week; Span Drift: 1% FS per 24 hrs
NDIR Analyser	Pulsar293	CO_2	Channel 3: 0-1%, 0-10%, 0-50%, 0-100%	Zero Drift: 1% FS per week; Span Drift: 1% FS per 24 hrs
NDIR Analyser	Pulsar293	CH_4	Channel 4: 0-100ppm, 0-1000ppm, 0-1%, 0-10%	Zero Drift: 1% FS per week; Span Drift: 1% FS per 24 hrs
Paramagnetic Analyser	Pulsar293	O_2	Channel 5: 0-2.5%, 0-5%, 0-10%, 0-21%	Zero Drift: <+/- 0.2% O_2 per 30 days

TABLE 1: STACK EMISSION RACK

One stream was directed towards the stack emission rack, a comprehensive assembly housing various analysers tailored to measure key gaseous pollutants. The stack emission rack, supplied by Signal Group Ltd, featured a Quasar192 NO/NOx analyser, a Pulsar305SP1 analyser for $CO/SO_2/CO_2/CH_4/O_2$, and a Solar273 THC analyser. The inclusion of a Model 361 pre-filter with heated filters and pump, alongside a 203 Cooler Drier, ensured sample integrity and reliability throughout the testing process. The details of the analysers are listed in the table 1.

The inner diameter of the heated sample lines used upstream of the particle measurements (SMPS) is 6mm ID conductive PTFE 6.0m length. On the particulate leg, LII uses 6 lpm, ELPI 10LPM, the Prefilter unit uses 10 -12 lpm. The probe can be considered as a separate section with outlet temperature of 160C (down from 380C probe tip) at RTL load and 210C (down from 500C) at FL before the diluter and then maintained at 60C. The flow rate is 8 for the diluter and 10 to 12 for the gas emission rack. the probe is ID around 7mm.

Concurrently, the second stream was routed to the PM analysis kit utilizing a diluter and a conductive PTFE heated line. Built as close as possible to the AIR6241, this setup facilitated the comprehensive assessment of particulate matter emissions. The Dekati ELPI+ was used to assess the size and number distribution offering real-time measurement capabilities across 14 distinct size fractions, ranging from 6 nm to 10 µm.

LII300 was also deployed to measure the nvPM particulate matter mass concentration by measuring the volume fraction of the particulate matter. It also measures the active soot surface by temporal resolution of the LII fluence. The system is illustrated in the figure 5.

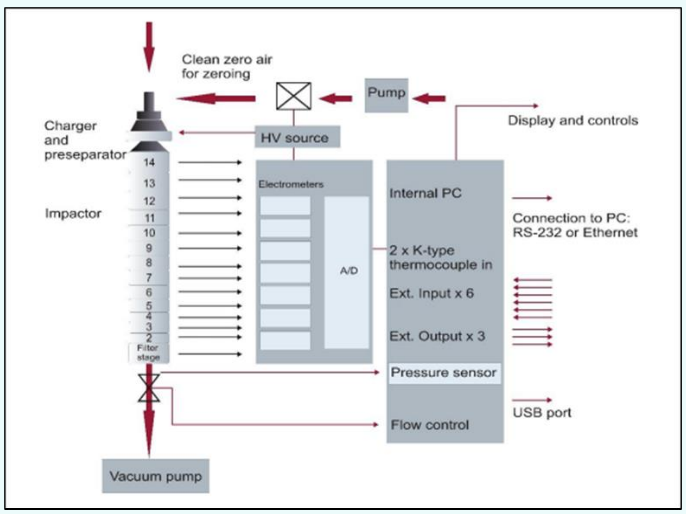


Figure 4: Dekati ELPI PM analyser.

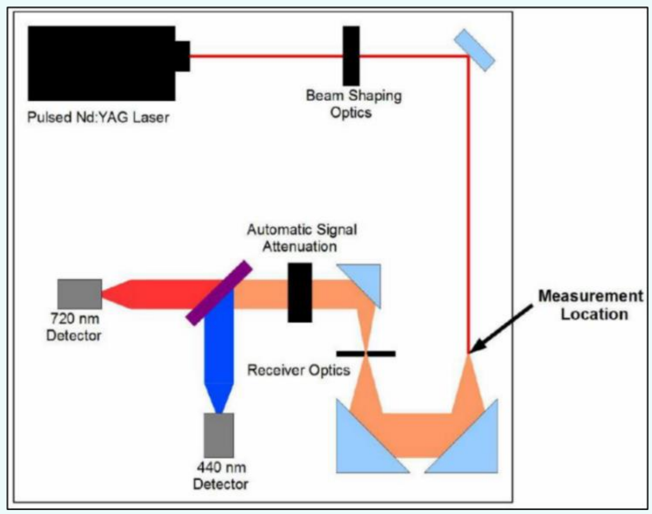


Figure 5: Atrium LII300 schematic diagram.

The PM leg was diluted using Dekati diluter. The Dekati® Diluter is designed for fine particle measurements in conditions of high concentrations, high temperatures, humidity, and long-term sampling. Operating on an ejection type dilution principle, the diluter uses clean, pressurized dilution Nitrogen to draw the sample through a critical orifice into the dilution chamber, where it mixes homogeneously with the dilution air. The dilution factor, determining the ratio of dilution air flow to sample flow, is automatically maintained constant over a wide operational range in this type of diluter. This constant dilution factor, calculated by multiplying the diluted sample concentration by the dilution factor N, relies on a consistent pressure difference between the diluter inlet and outlet the final dilution was measured using the diluted CO_2 and O_2 measurement.

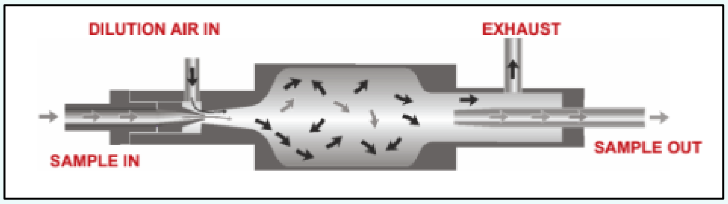


Figure 6: Operating principle of Dekati® Diluter

To enable seamless fuel switching during testing, a carefully designed fuel feed system was employed to minimise cross contaminations and dead volumes. This system facilitated the utilization of both baseline JetA1 fuel and the two test fuels, HEFA and the HEFA/SAK blend. Notably, tank A1 housed the HEFA fuel, while tank A2 contained the HEFA/SAK blend, enabling controlled fuel switching during the testing regimen.

Test Procedure

The testing procedure adhered to a meticulously crafted protocol aimed at ensuring the consistency and reliability of the data obtained. Initial steps involved comprehensive pre-run checks and instrument calibrations to guarantee the accuracy of measurements. Subsequently, the Honeywell 131-9A APU was started and stabilized using the baseline JetA1 fuel, laying the foundation for subsequent testing phases.

Maintaining Ready-to-load (RTL) conditions for a minimum of 10 minutes served as a preparatory step before commencing the test sequence. This sequence entailed a systematic switching of fuels, with six-minute windows allocated to each fuel type. The sequence commenced with baseline JetA1, followed by HEFA and the HEFA/SAK blend.

The engine then was conditioned to full pneumatic loading (FL) for 6 to 10 minutes using JetA1, ensuring the stabilization of engine condition. Then, the test sequence was repeated for the FL condition.

To validate the repeatability and reliability of our findings, the entire testing regimen was replicated on at least two days, thus mitigating the influence of potential confounding variables. The detailed test procedure is as follow:

1. Pre-run Checks and Instrument Calibration:
    - Thorough pre-run checks were conducted on all equipment and instrumentation.
    - All analysers and instruments were calibrated to ensure accuracy and reliability of measurements.

2. Engine Startup and Stabilization:
    - The startup sequence of the Honeywell 131_9A APU was initiated.
    - The engine was stabilized using JetA1 fuel to establish baseline conditions.

3. Maintained Ready to Load (RTL) Condition:
    - The engine was maintained in the RTL condition for a minimum of 10 minutes to ensure stable operating conditions.

4. JetA1 Test Window:
    - A 6-minute test window was initiated using JetA1 fuel.

5. Switched to HEFA Fuel:
    - After the completion of the JetA1 test window, the fuel supply was switched to HEFA and maintained for 6 minutes.

6. Switched to HEFA/SAK 12.7% Blend:
    - Subsequently, the fuel supply was switched to the HEFA/SAK 12.7% blend and maintained for 6 minutes.

7. Returned to JetA1 and Conditioned to FL:
    - The fuel supply was switched back to JetA1, and the engine was conditioned to full pneumatic loading (FL) state.
    - The engine was kept at FL condition for 6 to 10 minutes to stabilize the operating conditions.

8. Recorded JetA1 Baseline Reading for FL Condition:
    - Once the engine stabilized in the FL condition, baseline readings for JetA1 fuel were recorded.

9. Switched to HEFA Fuel:
    - The fuel supply was transitioned to HEFA and maintained for 6 minutes.

10. Switched to HEFA/SAK 12.7% Blend:
    - Subsequently, the fuel supply was switched to the HEFA/SAK 12.7% blend and maintained for 6 minutes.

11. Data Collection and Analysis:
    - Throughout the test procedure, emissions data were continuously monitored and recorded using the designated instrumentation.
    - A comprehensive analysis of the collected data was conducted to assess the performance and emissions characteristics of each fuel type.

12. Repeated Testing Procedure:
    - The entire testing procedure was repeated on two different days to ensure repeatability and validate the findings.

Results

The testing revealed a marked reduction in both the number and mass of particulate emissions when using the HEFA fuel and its blend compared to conventional JetA1. The average mass concentration of the RTL condition is presented in the figure 7.

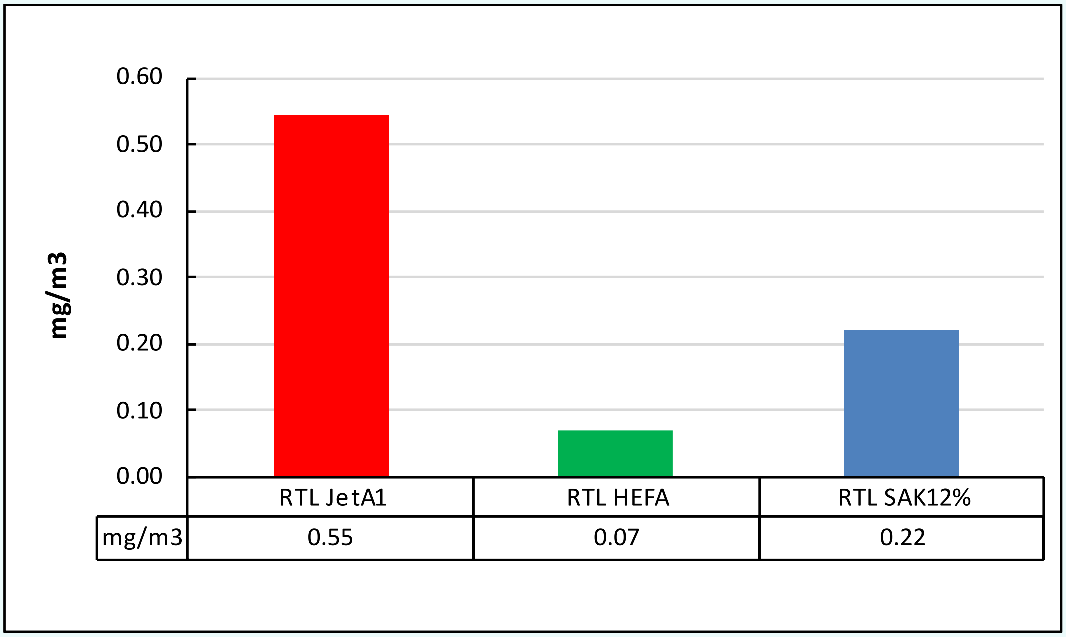


Figure 7: RTL Mass concentration measured using LII 300 for JetA1, HEFA and HEFA/SAK12.7% blend.

The mass concentration detected by the LII 300 at both RTL and FL (figures 7 & 8) conditions is reduced significantly when HEFA is used. This can be attributed to the absence of the aromatic content.

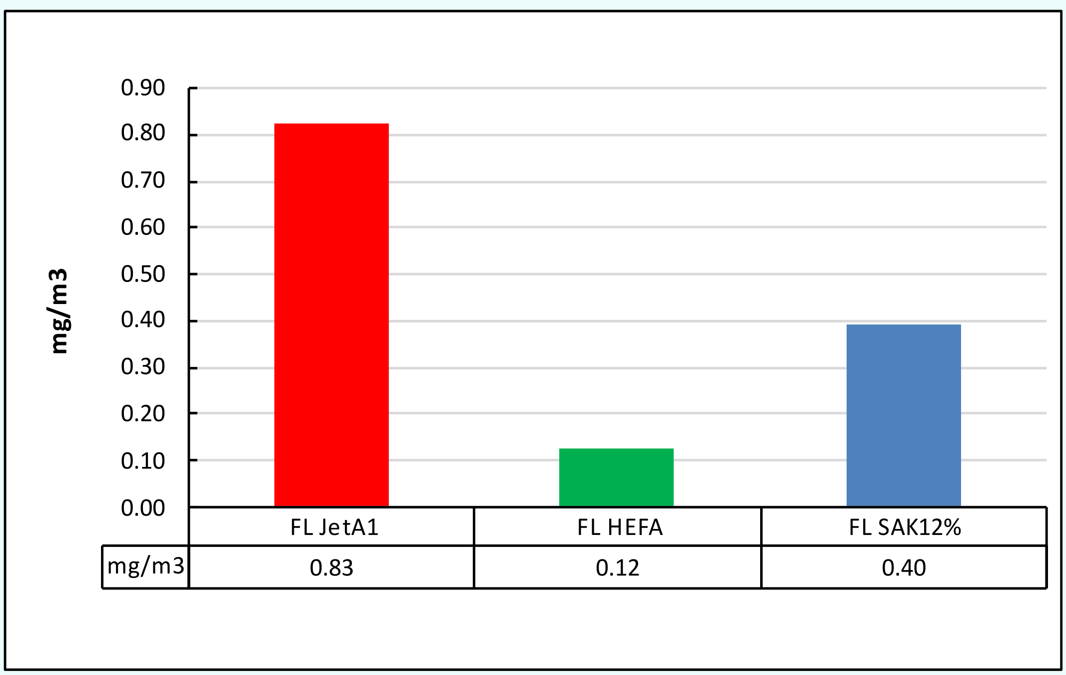


FIGURE 8: FULL LOAD (FL) MASS CONCENTRATION MEASURED USING LII 300 FORJETA1, HEFA AND HEFA/SAK12.7% BLEND.

The SAK 12.7% generated more particulates compared to the pure HEFA, however it is still around 40% of that of JetA1.

On the other hand, by resolving the time it takes for the soot to cool down, the LII can estimate the active soot surface area. This is reported in figures 9 & 10.

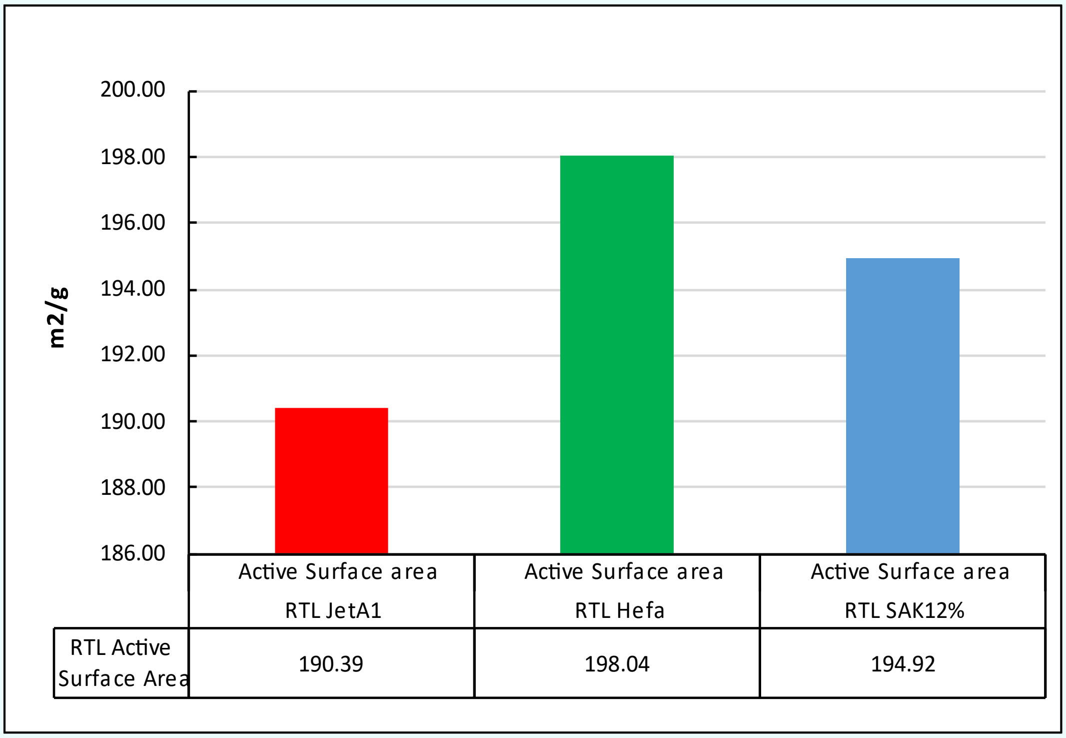


Figure 9: LII300 Active Soot Surface Area at Ready To Load condition.

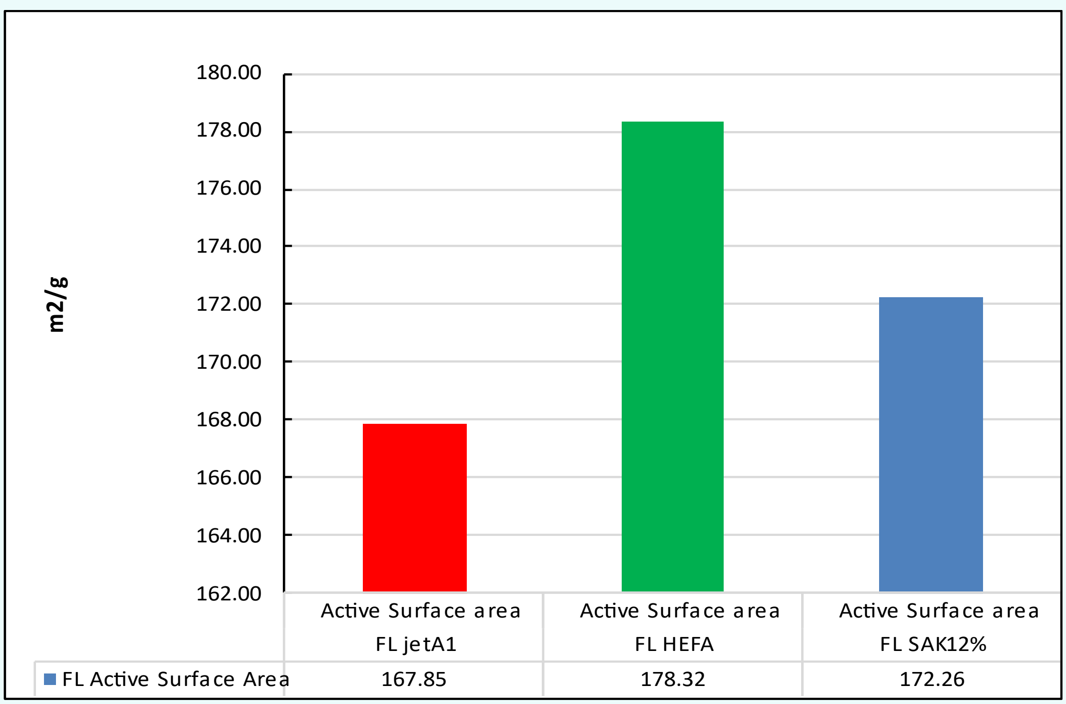


FIGURE 10: ACTIVE SOOT SURFACE AREA AT FULL LOAD CONDITION.

The mass concentration as well as the number density was also estimated using the ELPI impactor. Figure 11 demonstrate the number concentration at both RTL and FL conditions for the three tested fuels, JetA1, HEFA and SAK12.7% blend.

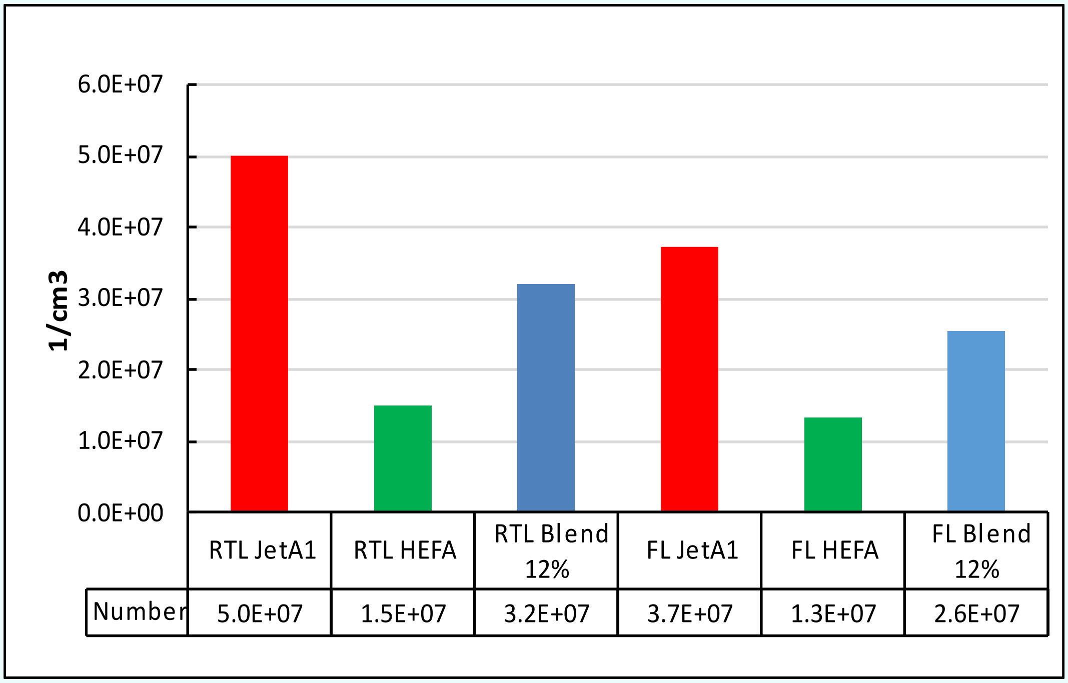


FIGURE 11: ELPI MASS CONCENTRATION AT BOTH RTL AND FL CONDITIONS OF ALL THE TESTED FUELS.

Similar trends can be seen in both test conditions. Significant reduction in number concentration when HEFA or the SAK 12.7% blend are used.

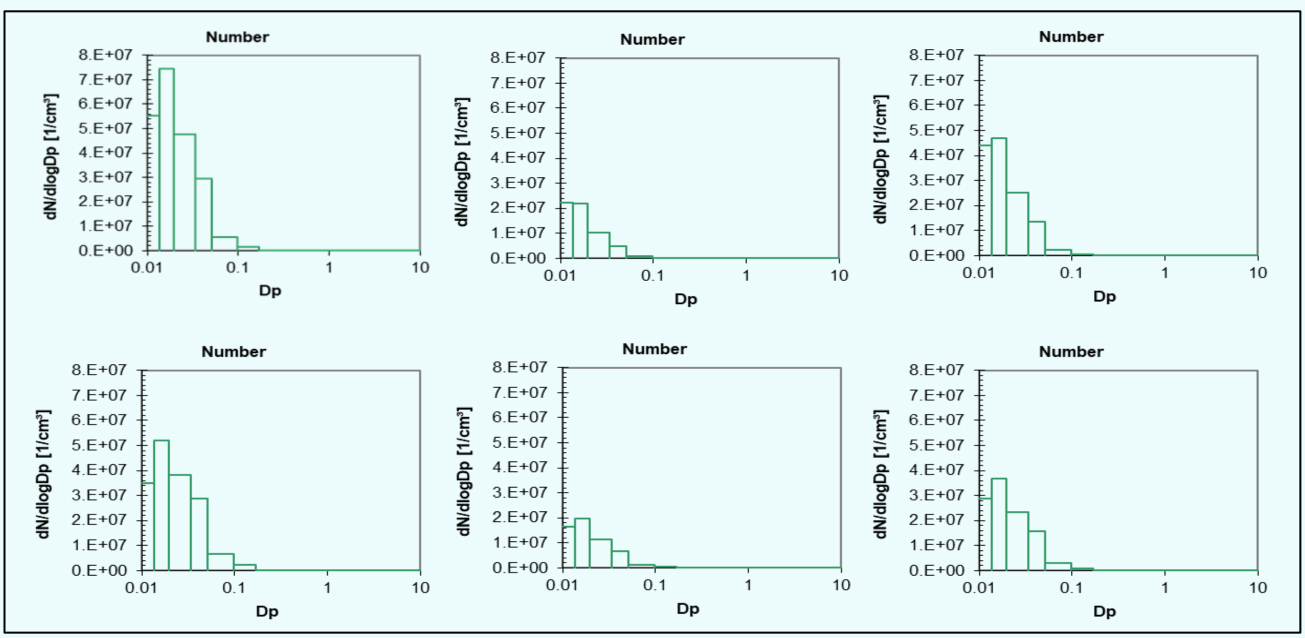


FIGURE 12: ELPI NUMBER CONCENTRATION AT BOTH RTL AND FL CONDITION.

The ELPI has also the capability to estimate the Particle size distribution (PSD) using the current from the 14 impactor stages. The graph below shows the PSD of the three fuels (JetA1, HEFA and SAK12.7% at to different loads (RTL top three and FL bottom three graphs).

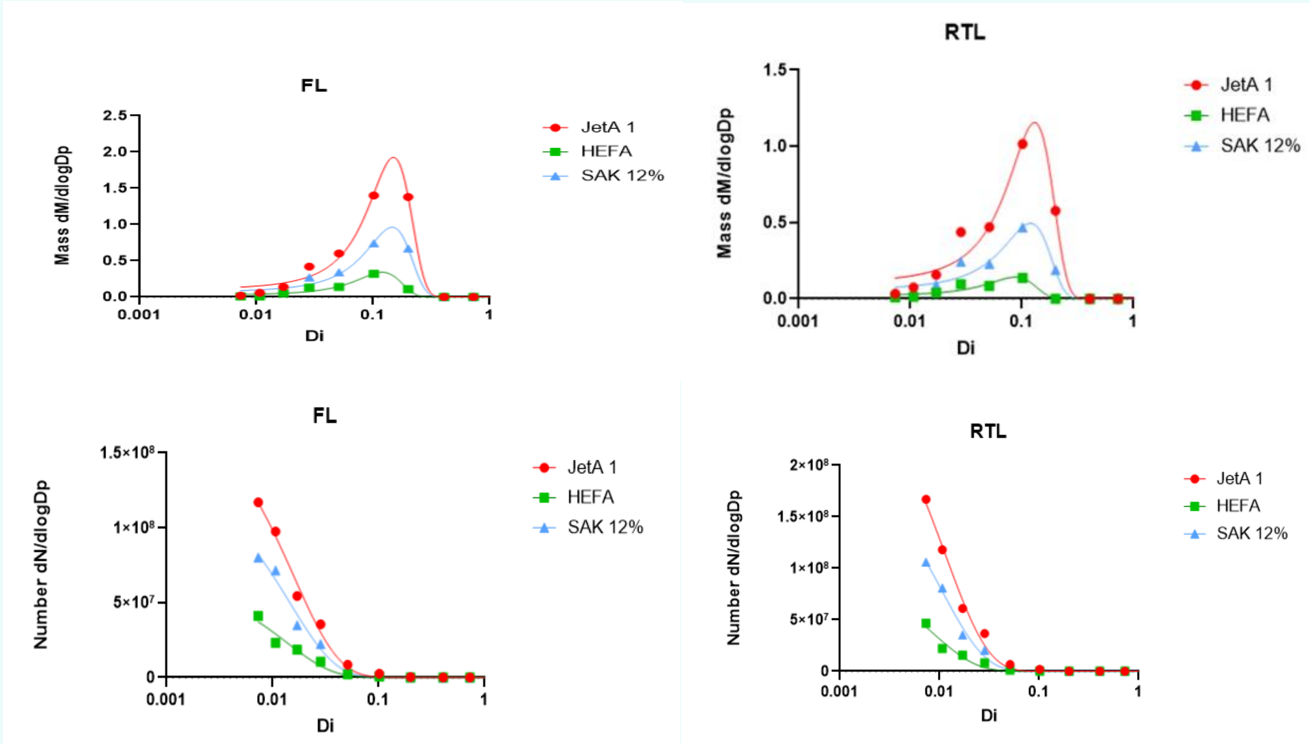
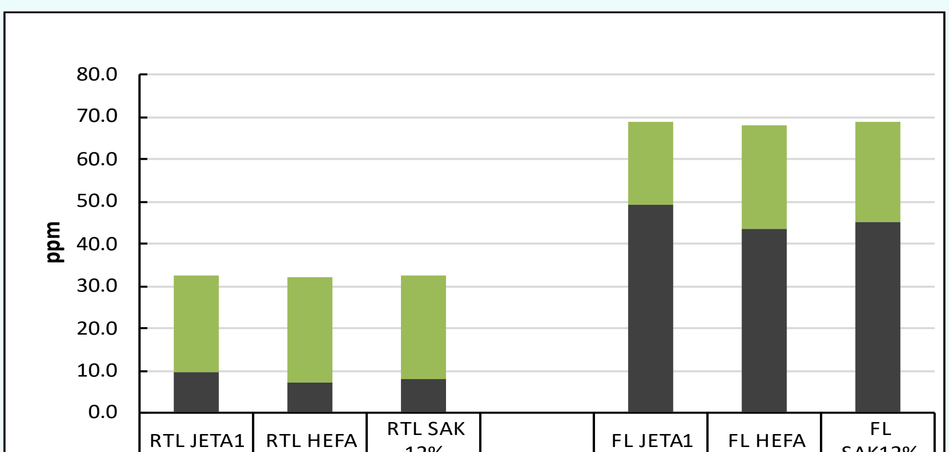


FIGURE 12: PSD FOR ALL THE THREE FUELS, JETA1 (LEFT), HEFA (CENTRE) AND BLEND SAK 12.7% (RIGHT) AT RTL LOAD (TOP THREE) AND FL CONDITION (BOTTOM THREE)

As indicated by FIGURE 12 (a & b), the vast majority of particles are in the sub-micron region. Specifically, in the 30nm to 50 nm range. This is in line with the literature for gas turbine PM emissions. It can also be noticed that for the HEFA and the SAK12.7% blend, the PM Peak is shifted slightly to the left, again. This is in line with literature, and it might be attributed to the reduction in the aromatic content and the types of aromatics used in the blend. Finaly ELPI soot particle size and number distribution for both RTL and FL conditions are shown below.
The gaseous emission from the fuel testing is reported in the below graphs. The total nitric oxides (NOx), and Nitrogen Oxide (NO) as well as Nitrogen Dioxide (NO_2) were all measured simultaneously.



	RTL JETA1	RTL HEFA	RTL SAK 12%		FL JETA1	FL HEFA	FL SAK12%
NO2	22.7	24.8	24.7		19.8	24.6	23.7
NO	9.8	7.2	7.8		49.1	43.4	45.1

FIGURE 13 TOTAL NOX, (NO & NO_2) EMISSION FROM JETA1, HEFA AND SAK12.7% BLEND AT BOTH OPERATING CONDITIONS.

It can be noticed from figure 14 that, although the overall NOx level remains unchanged when the fuel is switched, the ratio of NO2 to NO changes when HEFA or the blend is used. A higher NO2 fraction is observed at both loads with the use of HEFA and the blend. The root cause of this phenomenon is not clear, and further work is needed to determine if it is caused by the interaction with CO or fuel atomization, which can impact pockets of local peak temperature within the combustion zone.

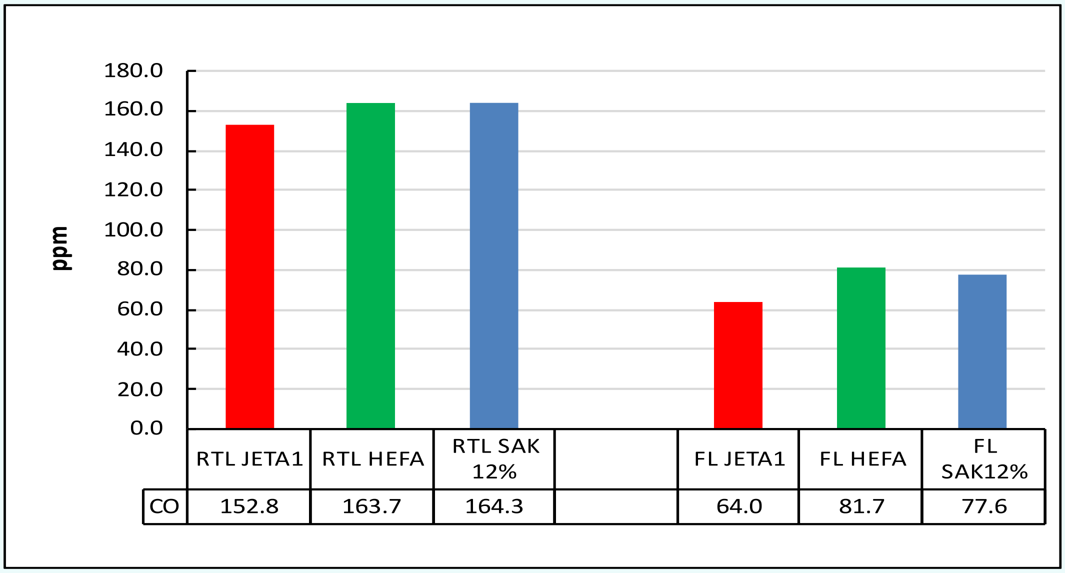


FIGURE 14: CO FOR ALL THE FUELS FROM THE TWO TEST CONDITIONS.

An increase of around 11-13 ppm for RTL and 12-17 ppm for FL conditions has been recorded, when both HEFA and the blend is used. Overall HEFA-12.7% SAK fuel mixture had no discernible effect on CO emission (showing small increase which was within the measuring devices' uncertainty interval).

Similar trend has been observed for the total hydrocarbon emission indicating 2-3 ppm increase in FL runs. This small increase (2-3 ppm) is within the measuring devices' uncertainty interval.

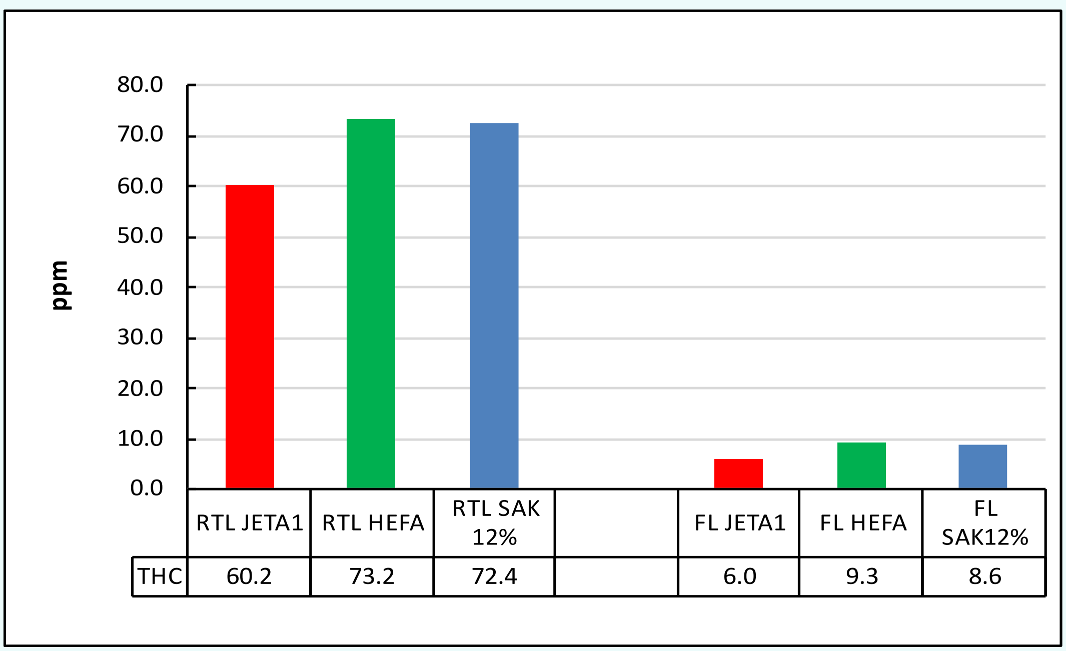
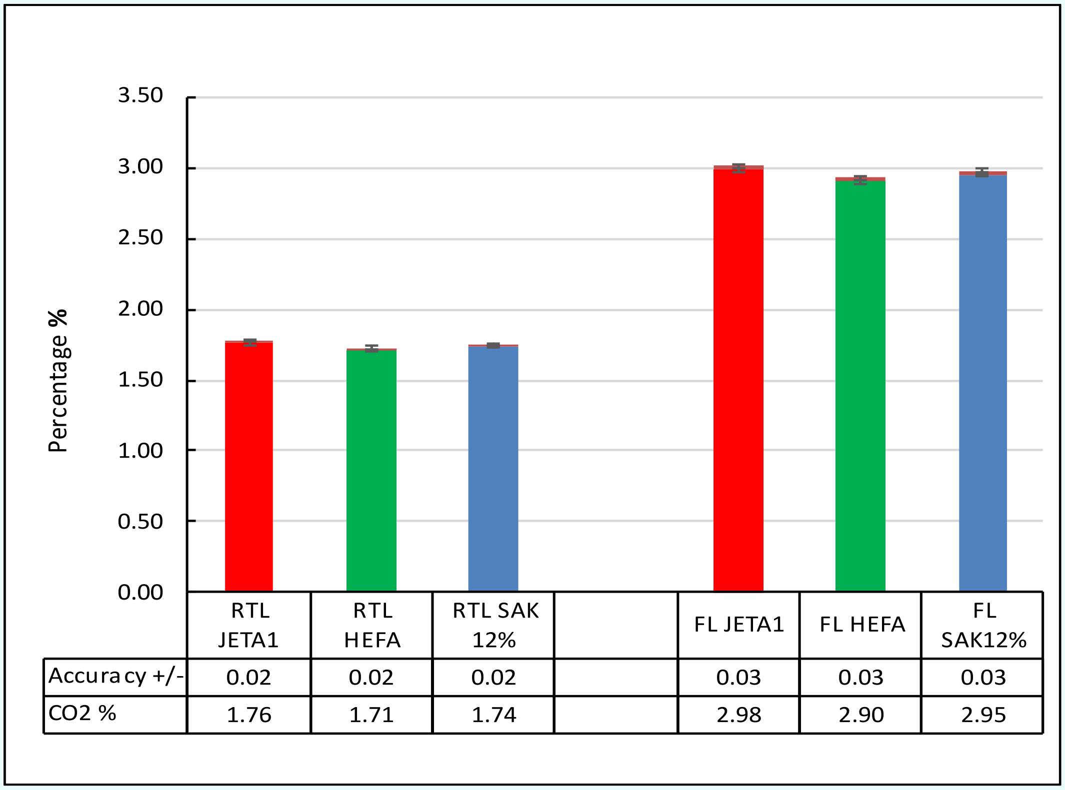


FIGURE 15: TOTAL HYDROCARBON ON THE EXHAUST FOR ALL THE FUELS AT BOTH LOAD CONDITIONS.

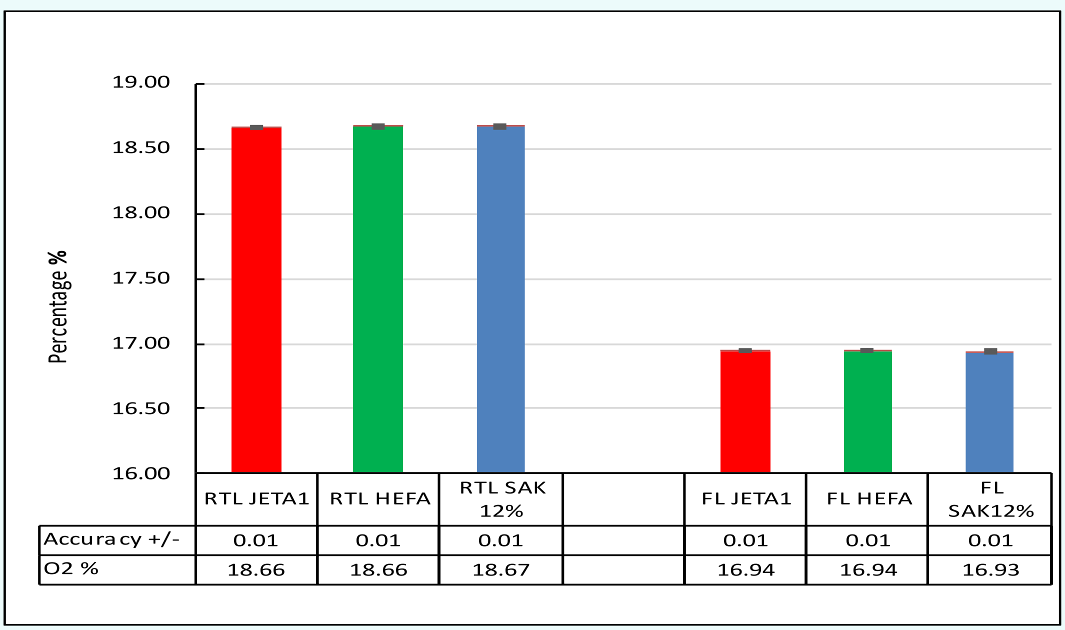
In figure 16 a very slight reduction in CO_2 has been observed when the HEFA and to less extent when the blend is used. This is expected to be due to the variation in the Hydrogen to carbon rations between the fuels.



	RTL JETA1	RTL HEFA	RTL SAK 12%		FL JETA1	FL HEFA	FL SAK12%
Accuracy +/-	0.02	0.02	0.02		0.03	0.03	0.03
CO2 %	1.76	1.71	1.74		2.98	2.90	2.95

FIGURE 16: CO_2 EMISSION FOR FOR ALL THE FUELS AT BOTH RTL AND FL CONDIONS

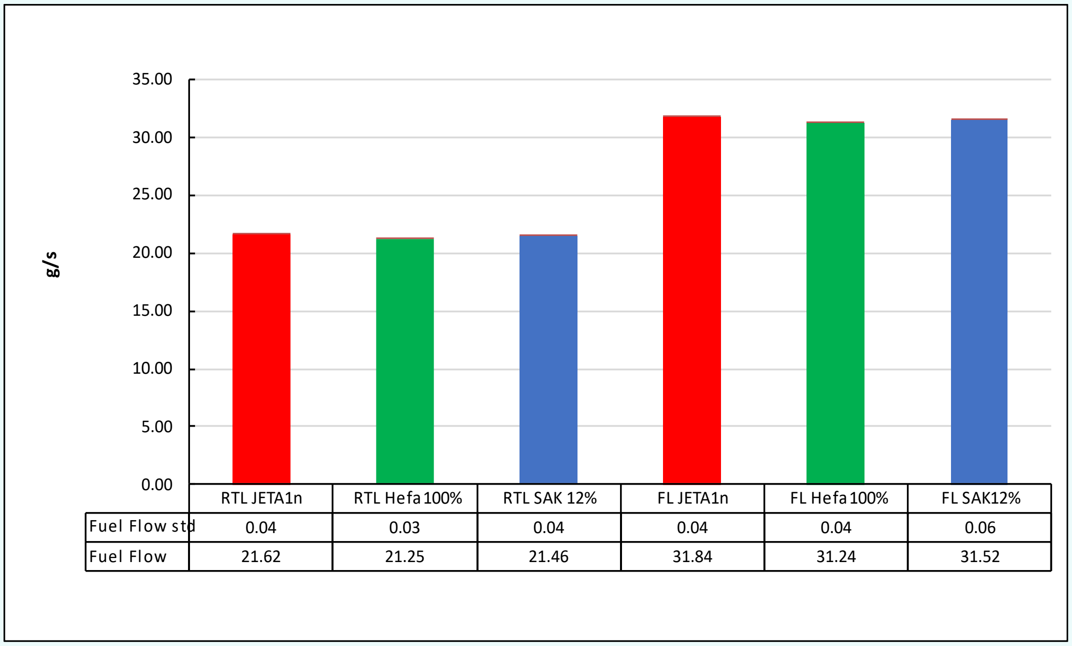
The oxygen level indicated by figure 18 shows very similar values across all the fuels, which is as expected given the same power consumption.



	RTL JETA1	RTL HEFA	RTL SAK 12%		FL JETA1	FL HEFA	FL SAK12%
Accuracy +/-	0.01	0.01	0.01		0.01	0.01	0.01
O2 %	18.66	18.66	18.67		16.94	16.94	16.93

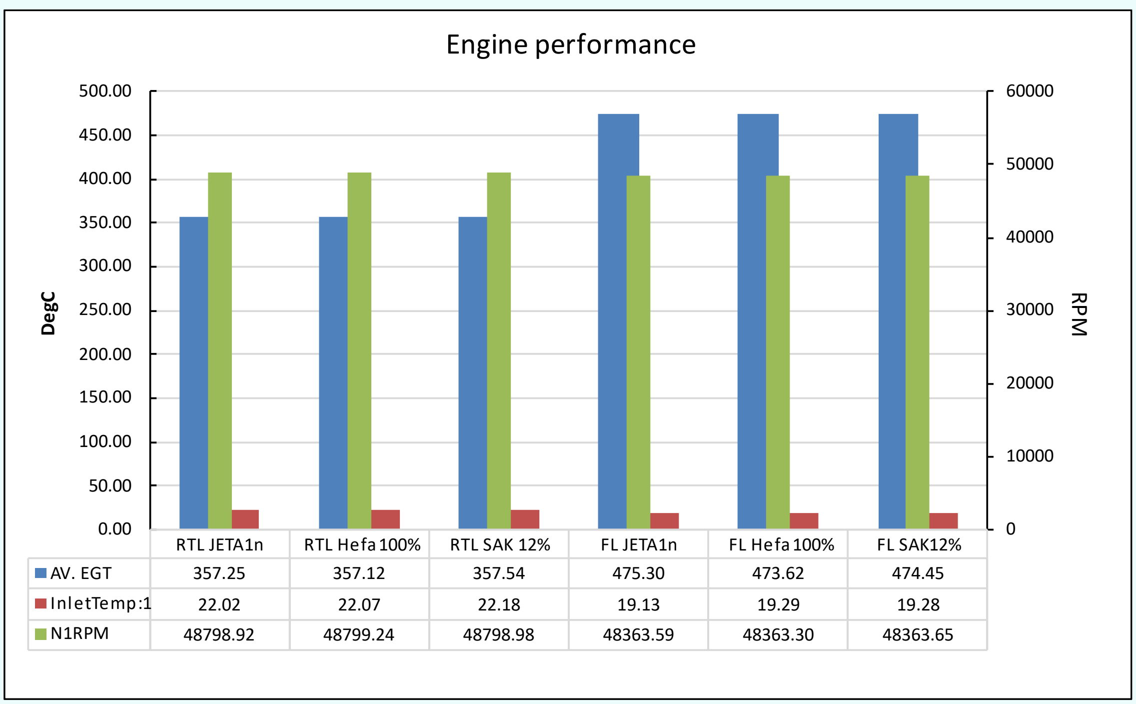
FIGURE 17: O_2 LEVELS IN THE EXHAUST FOR ALL THE FUELS USING BOTH OPERATING CONDITIONS.

The mass fuel flow rate, and the standard deviation, of JetA1, HEFA and SAK12.7% blend for the Ready to load (RTL) and the Full pneumatic Loading (FL) are presented in figure 19. It can be noticed that HEFA demonstrated the least fuel mass flow rate. This is expected from of the increased specific energy (kJ/kg) or higher Hydrogen content of the fuel



	RTL JETA1n	RTL Hefa 100%	RTL SAK 12%	FL JETA1n	FL Hefa 100%	FL SAK12%
Fuel Flow std	0.04	0.03	0.04	0.04	0.04	0.06
Fuel Flow	21.62	21.25	21.46	31.84	31.24	31.52

FIGURE 18: THE FUEL FLOW AND STANDARD DEVIATION FOR THE THREE FUELS, JETA1, HEFA AND SAK 12.7% AT TWO LOADING CONDITIONS (RTL & FL) WITH STANDARD DEVIATION.



	RTL JETA1n	RTL Hefa 100%	RTL SAK 12%	FL JETA1n	FL Hefa 100%	FL SAK12%
AV. EGT	357.25	357.12	357.54	475.30	473.62	474.45
InletTemp:1	22.02	22.07	22.18	19.13	19.29	19.28
N1RPM	48798.92	48799.24	48798.98	48363.59	48363.30	48363.65

FIGURE 19 EGT, INLET TEMP AND RPM FOR THE THREE FUELS, JETA1, HEFA AND SAK 12.7% AT TWO LOADING CONDITIONS (RTL & FL)

Discussion

Impact of Fuel Net Heat of Combustion (Lower heating value, LHV) and Energy Density (ED) on Fuel Mass Flow: High energy density (HED) fuels are specifically blended to fulfil the power and range demands of aircraft. In aviation, the energy density and LHV plays a crucial role by providing crucial information about the properties and performance of fuel. Whereas LHV measures the amount of heat emitted during combustion, energy density concentrates on the amount of energy per unit volume or mass. When assessing a fuel's appropriateness and efficiency for flight, these two attributes are crucial.

Aviation fuels having a higher energy density are very beneficial for volume-constraint aircraft since they allow for longer flights, better fuel consumption, and the capacity to store a significant amount of fuel inside the aircraft's limited volume. Therefore, it is important to measure or calculate energy density of fuel as accurately as possible. The ASTM D4052/IP 365 and ASTM D1298/IP160 are two well-known standard procedures for determining the density of aviation fuel. The LHV, which is the heat, released during whole combustion, is another important element. The flying distance and payload of the aircraft are influenced by the LHV. High gravimetric LHV fuels are recommended for civil aircraft with weight restrictions (high volumetric LHV volume preferred for missiles and rockets).

The main methods for determining the energy density and LHV of aviation fuel are bomb calorimetry and calculations based on fuel composition. Bomb calorimetry provides a direct measurement of energy content by measuring the heat emitted during complete combustion. As an alternative, computation from the fuel composition, which frequently makes use of sophisticated computational techniques such ab initio calculations, calculates the energy density and LHV based on the given chemical composition. These techniques provide important insights by predicting energy changes in combustion reactions using quantum mechanics. A more cost-effective approach is required, even though the experimental and computational methods described above are trustworthy for limited data sets.

Calculation of LHV & HHV, Heat of Formation, ED, H/C for Flight-100 and baseline Jet Fuels, H/C calculation: Hydrogen content plays a crucial role in understanding jet fuel properties, and various methods are used to measure it. Hydrogen has a high heat of combustion compared to carbon. When hydrogen-rich fuels are burned, they release more energy per unit mass than carbon-rich fuels. This higher heat of combustion contributes to better overall combustion efficiency. Higher hydrogen content leads to a lower stoichiometric air-fuel ratio and operating closer to the stoichiometric ratio improves combustion efficiency. The H content in mass % can be converted to molar H/C ratio.

$$\frac{H}{C} = \frac{12.0107\ (\text{wt}\%\ H)}{100.794(1 - (\text{wt}\%\ \frac{H}{100})}$$

With the molecular weight for C_aH_b, one can calculate the stoichiometric coefficients:

$$MW\ (C_aH_b) = 12.0107a + 1.008b$$

b/a is the molar H/C ratio as calculated above.
Annex 1 provides detailed explanation of H/C calculation.

Heat of formation: Knowing the heat of formation for aviation fuel is crucial for determining flame attributes in the context of the Flight-100 fuel performance assessment. The calculation of the heat of formation from measured H2 content and heat of combustion is explained in Annex 1.

Table 2 and 3 provides the aviation fuels tested during the Flight-100 project. It is important to note the fuel flow data required to produce the same output power from APU (TBC: subject to confirmation from DfT to share).

Table 2

Sample name	Fuel Flow (PL) (g/s)	Fuel Flow (FL) (g/s)	Fuel Saving (%)	Viscosity -20C,cST	Freezing point (C)	Density (kg/m3)
Jet Fuel (JF)	21.55	31.49	-	4.072	-48.1	801.7
HEFA	21.07	30.92	2.2-1.8	6.841	-43.1	765.0
Flight -100 (HEFA + 12.7% SAK)	21.26	31.21	1.4-0.91	5.279	-46.0	777.3
Sample B (HEFA + 9% SAK)	TBC	TBC	TBC	5.632	-44.8	774.1
Sample C (HEFA + 6% SAK)	TBC	TBC	TBC	TBC	TBC	TBC
Sample D (HEFA + 3% SAK)	TBC	TBC	TBC	6.382	-43.5	767.9
Sample E (JF + HEFA 20%)	TBC	TBC	TBC	TBC	TBC	TBC
Sample F (JF + HEFA 50%)	TBC	TBC	TBC	TBC	TBC	TBC

Table 3

Sample name	MW, kg/kmol	Aromatics %	Density	H/C	Composition, mass% (n/iso/cyclo/aro/alkene)	HHV-LHV, MJ/kg (ASTM D4809)
Jet Fuel (JF) (Local Airport)	TBC	14.55	801.7	1.97	TBC	**45.78 - 43.07**
HEFA	TBC		765.0	2.19	TBC	**TBC**
SAK	TBC			2.17	TBC	**TBC**
Flight -100 (HEFA + 12.7% SAK)	TBC	12.40	777.3	2 .16	TBC	**46.49 - 44.05**
Sample B (HEFA + 9% SAK)	TBC	TBC	TBC	TBC	(n/iso/cyclo/aro/alkene)	**TBC**
Sample C (HEFA + 6% SAK)	TBC	TBC	TBC	TBC	(n/iso/cyclo/aro/alkene)	**TBC**
Sample D (HEFA + 3% SAK)	TBC	TBC	TBC	TBC	(n/iso/cyclo/aro/alkene)	**TBC**
Sample E (JF + HEFA 20%)	TBC	TBC	TBC	TBC	(n/iso/cyclo/aro/alkene)	**TBC**
Sample F (JF + HEFA 50%)	TBC	TBC	TBC	TBC	(n/iso/cyclo/aro/alkene)	TBC

A series of engine ground runs were conducted on Honeywell 131-9B APU including a switch of fuel at various power load settings using two different fuels (i) fossil sourced Jet Fuel A1 and (ii) 100% SAF (HEFA + SAK). The engine showed no change in behaviour from an operational perspective. The results from these runs were presented in previous section showed reduction of 0.95 (FL) and 2.2% (RTL) lower fuel flow that was observed on the engine run of the Flight-100 fuel (HEFA+ 12.7% SAK) is consistent with the higher energy density per unit mass of the SAF. To reach designated or nominal temperature levels, the fuel mass flow rate directly depends on the fuel's energy content, or the heat of combustion. In this sense, the reduced fuel consumption and higher energy content by mass of SAF have a beneficial impact on the pollutant emissions such as CO_2, H_2O, and SOx. These emissions are proportional to the fuel mass flow rate. In this regard, the higher energy content by mass of SAK and thus the reduced fuel consumption has a positive effect on the CO_2, H_2O and SOx emissions.

However, the chemistry of pollutant generation is extremely non-linear and sensitive to even minute variations in the fuel's chemical makeup. For example, viscosity affects the spray quality, particle size, and combustion process. A fuel mixture with high viscosity will worsen the atomization process and promote the formation of higher soot precursors. In addition, it may result in marginally larger droplets for the same primary zone size would result in longer overall times for the physical and chemical reactions, which would raise the production of CO. The precursor for the particulate formation is one of the key components that relates the fuel composition.

Overall flight efficiency (CO_2 and non-CO_2 species produced per passenger per kilometre, all under similar condition) will depend on Take-off weight and thrust needs for a flying which affect the trip's overall energy consumption and emissions. A fraction of emissions is correlated with the mass flow rate of fuel. Thus, the emissions can be immediately decreased by reducing the amount of fuel burned. In addition to energy content, the H content—which was higher for Flight-100 SAF—also contributes to lower CO_2 emissions or EI_{CO2}. Conversely, the water emission per kilogramme of fuel, or EI_{H2O}, tends to rise in direct proportion to the fuel's H concentration. APU studies employing Flight-100 SAF confirmed that NOx emissions range from a minor reduction (within the measuring devices' uncertainty interval) to indifferent effects in APU rig tests. Overall, there was insufficient evidence of either a favourable or negative effect in the experimental results from the APU test. The flight-100 fuel mixtures had no discernible effect on carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions (showing small increase which was within the measuring devices' uncertainty interval).

On the other hand, there is substantial proof that Flight-100 SAF reduce nVPM emissions. Volatile aerosol (vPM) emissions were also investigated, and results will be published at a later date. The results obtained in flight-100 project initiated new funding to investigate the impact of two-ring or bicyclic aromatics or di-aromatics in the naphthalene on the mass and volume of EI_{soot}, and non-volatile number density.

Another important finding is related when HEFA-12.7% SAK results was combined with previously published data on the relationship between fuel's hydrogen concentration and the measurement of nvPM (in mass) emissions a strongest association was found. APU measurement results confirmed that mass emissions and particle count were reduced by 55%-47% with 100% SAF (HEFA-12.7%SAK). The results obtained from APU test are shown in figure 19. Results from ground-based studies by Moore et al. (2017), who demonstrated that blending biofuel (HEFA-SPK) decreased an aircraft's in-flight mass emissions and particle count by 50% to 70%.

The evidence mounted in the ensuing years. For example, Schripp et al. (2018) examined the particle emission indices behind an Airbus A320 equipped with V2527-A5 engines and showed that for two different jet fuel blends, the reductions may reach 50% (number) and 70% (mass).

They verified that the particle emissions correlated more strongly with the H content than with the aromatics content.

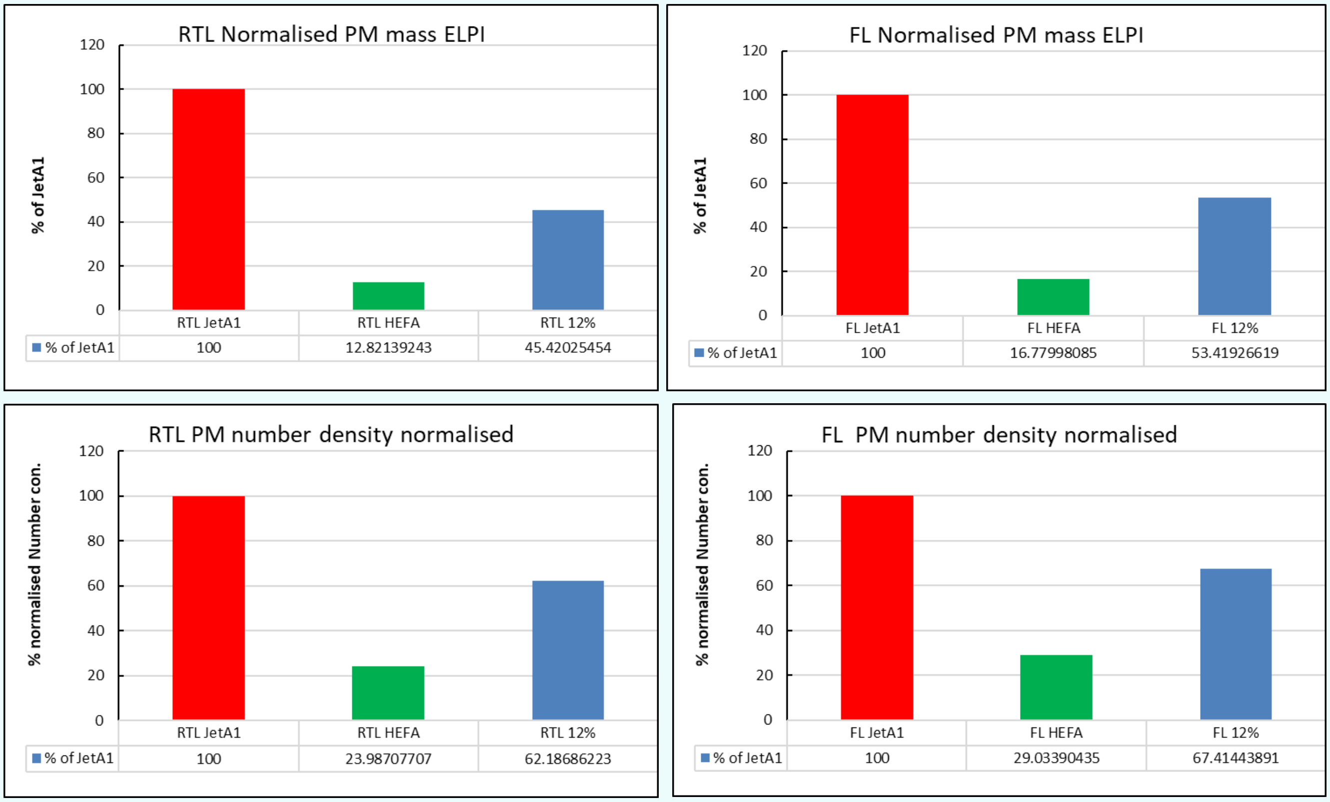


FIGURE 20: NORMALISED DATA FROM THE LII-300 AND ELPI REPRESENTING % REDUCTION OF nvPM (MASS AND NUMBER) FROM APU TEST AT RTL AND FL CONDITIONS.

There are extensive previous detailed research investigating the impact of hydrogen content in fuel on mass and number emissions of non-volatile particulate matter (nvPM) has been published. Notably, data obtained from APU using HEFA-12.7%SAK closely aligns with published results. These findings have significant implications for aviation emissions reduction strategies, particularly in terms of improving fuel mass consumption and minimizing environmental impact.

The Flight-100 project provided valuable insights into the relationship between hydrogen concentration and nvPM emissions. As the aviation industry seeks to transition toward more sustainable fuels, understanding the effects of hydrogen content becomes crucial. The comparison with conventional fuels and alternative blends highlights the potential benefits of adopting cleaner options.

Furthermore, the agreement between APU data and published results validates the reliability of the study. Researchers can confidently use these findings to inform policy decisions, aircraft design, and fuel selection. As we await the formal publication of this research, it’s exciting to anticipate its impact on the future of aviation.

Conclusion

Disclaimer: This test was conducted using an Auxiliary Power Unit (APU). While the results are indicative of this specific type of engine, they may not necessarily reflect the performance of the main aeroengine.

Testing HEFA and HEFA-SAK12.7% blends against standard JetA1 fuel in a Honeywell 131-9A APU showed clear environmental advantages for these Sustainable Aviation Fuels (SAFs). The reduction in particulate emissions highlights the potential of SAFs to significantly contribute to the aviation industry's sustainability goals.

Flight-100 Fuel (HEFA+ 12.7%SAK) having a higher energy density than conventional jet fuel, an increase of 0.92% to 2.2% in fuel consumption (by mass) was observed during APU ground engine test. If this finding confirmed in aircraft engine, not only will this increase the range of an aircraft, but it will also decrease its hourly fuel burn figure. This, in turn, will reduce the emissions produced from an aircraft during its mission.

APU test results confirmed that concerning CO and NOx emissions there were no significant change (slight increase of CO within the uncertainty interval of the measurement devices) using Flight-100 fuel. Overall, APU test measurement did not show clear evidence of neither a positive nor negative effect on CO and NOx affected by the different fuel compositions.

These findings indicate that reduced aromatic content of SAFs, or the type of Aromatics used, can substantially reduce particulate air pollution from aviation. The observed shift in NO-NO_2 ratio highlights the need for further research on NOx emissions, a major contributor to air quality issues and climate change.

The successful use of 100% SAFs in this study marks a critical milestone on the path to net-zero emissions in aviation. However, further research is needed to understand the reasoning behind highlighted outcomes. This includes understanding the relation between the physical and chemical properties of the fuel and their impact on emission species.

ANNEX 1

Gross Heat of Combustion (Higher heating value, HHV): Energy released per unit mass of fuel. The product includes CO2 (gas) + other gases + H20 (L) @ Standard T (25C) and constant volume.

Net Heat of Combustion (Lower heating value, LHV): Energy released per unit mass of fuel. The product includes CO2 + H2O (gas) + other gases @ Standard T (25C) and constant pressure (1 atm.)

Gross Vs Net Heat of Combustion: GT combustor operates at constant pressure (first approximation), product all gaseous phase, therefore “heat of combustion” to be used for calculating engine performance.

Net Specific Energy = Net Heat of Combustion

Cautionary Note: *Calculation and uncertainty of the lower heating value of conventional and sustainable aviation fuels, from hydrocarbon class concentration measurements, reference molecular heats of formation, and the uncertainties of these reference heats of formation (estimations using ASTM D3338 or ASTM D4809 measurements).*

- $HHV = Q_{bomb} + 0.006145 * H_{\%m}$ &
- LHV = $Q_{bomb} - 0.2122 * H_{\%m}$ therefore
- $HHV - LHV = 0.218345 * H_{\%m}$ (1)

Where Q_{bomb} = Heat of combustion at constant volume, and H = Mass fraction of hydrogen

Neat Heat of Combustion based on chemical compositions.

Eqs	Correlations	r^2	References
1	$-0.017C_n + 0.0039C_{ar} + 0.5977T_{10} - 1.9372T_{90} + 46.04$	0.6861	[35]
2	$2.18C_n - 2.04C_{iso} - 1.07C_{cycl} - 0.80C_{ar} + 41.76$	0.8238	[4]
3	$1.36C_n + 1.23C_{iso} + 0.25C_{cycl} - 0.43C_{ar} + 0.0059T_{10} + 0.0021T_{90} + 44.32$	0.8932	[4]
4	$7.1645163.10^{-2}Cv_{n+iso} + 6.0442816.10^{-2}Cv_{cycl} + 3.9693211.10^{-2}Cv_{ar} - 2.965279.10^{-3}T_{10} + 1.808345.10^{-3}T_{90} + 36.89985097$	0.8222	This work
5	$2.15947.10^{-2}C_n + 2.28206.10^{-2}C_{iso} + 1.42693.10^{-2}C_{cycl} + 5.638.10^{-3}C_{ar} - 1.7777.10^{-3}T_{10} - 5.0576.10^{-3}T_{90} + 43.3481491$	0.8990	This work

With C_n being the mass fraction of n-paraffins, C_{ar} of aromatics, C_{iso} of iso-paraffins, C_{cycl} of cycloparaffins, T_{10} the distillation temperature at which 10% of volume was recovered, T_{90} for 90% of volume recovered and Cv the respective volume fractions.

Energy Density (Per Unit Mass) = Net Heat of Combustion. Energy per unit volume is calculated using the density of the fuel.

E_d = H/M (or Ed_{-v} = H/V) (**UNITS:** Heat of combustion J/kg (MJ/kg))

- (H) is the total energy released (in joules).
- (V) is the volume of the fuel (in cubic meters or other appropriate units).

- Specific Energy (E_s): Specific energy is the energy per unit mass of the fuel (in joules per kilogram or other appropriate units).
- (M) is the mass of the fuel (in kilograms or other appropriate units).

Heat Of Combustion Requirements Within Fuel Specifications: net heat of combustion to be measured and meet minimum requirements (ASTM, IP)

Jet fuel simplified combustion reaction: $C_{12}H_{22}+18O_2 \rightarrow 12CO_2+12H_2O$

Hydrogen Content Measurement and calculation: Jet fuels are predominantly hydrocarbons. The H/C ratio of jet fuels can be calculated from the measured hydrogen content. Here are some relevant points:

- The hydrogen content is an optional specification test for most jet fuels. Two common methods for measuring hydrogen content are ASTM D3701 (Low Resolution Nuclear Magnetic Resonance Spectrometry, LR-NMR) and ASTM D7171 (Low-Resolution Pulsed Nuclear Magnetic Resonance Spectroscopy, LRP-NMR). Hydrogen content can also be inferred from GCxGC (comprehensive two-dimensional gas chromatography) composition data.

- The JP-8 specification (MIL-DTL-83133) includes a minimum hydrogen content of 13.8% by mass, while ASTM D1655 does not specify a minimum. The World Fuel Survey includes hydrogen content data obtained using ASTM D3701.

Reliability and Bias: The D3701 data in the World Survey appears to be biased higher than the GCxGC data. This bias may affect the correlation with heat of combustion. It suggests that the World Survey D3701 data is indeed biased high, rather than the fuels themselves being unusual.

In summary, hydrogen content plays a crucial role in understanding jet fuel properties, and various methods are used to measure it. Keep in mind that oxygenate-free jet fuels allow direct conversion of hydrogen content to H/C ratio by assuming that the non-hydrogen portion of the fuel consists entirely of carbon.
The H content in mass % can be converted to molar H/C ratio.

$$\frac{H}{C} = \frac{12.0107\ (\text{wt\%}\ H)}{100.794(1 - (\text{wt\%}\,\frac{H}{100})}$$

With the molecular weight for C_aH_b, one can calculate the stoichiometric coefficients:

$MW\ (C_aH_b) = 12.0107a+1.008b$

b/a is the molar H/C ratio as calculated above.

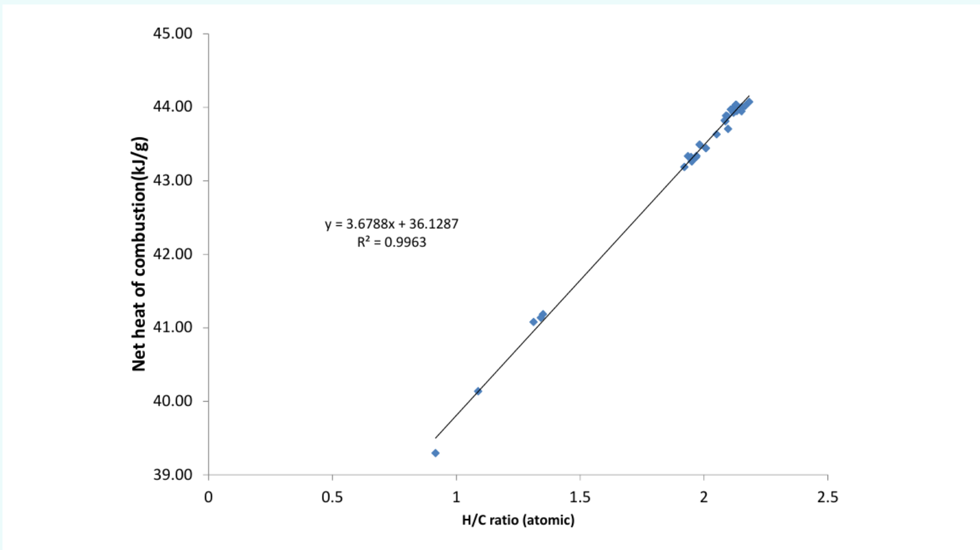
Heat of Formation: Knowing the heat of formation is crucial for determining flame attributes in the context of the Flight-100 fuel performance assessment. The measured heat of combustion and hydrogen content can be used to (back) calculate the heat of formation.

$$CaHb + \left(a + \left(\frac{b}{4}\right)\right) O2 \longrightarrow aCO2 + \left(\frac{b}{2}\right) H2O$$

$$Heat\ of\ Combustion\ \left(\frac{KJ}{mole}\right) = a(\Delta HfCO2) + \left(\frac{b}{2}\right)\left(\Delta HfH2O(gas)\right) - (\Delta HfFuel) - (a + \left(\frac{b}{4}\right))(\Delta HfO2)$$

where the heat of fuel formation is the only unknown in the second equation (because b/a=H/C and the heats of formation of CO_2 and water are known). The fuel H/C ratio is utilised in the calculation below to artificially define the fuel, such as $CH_{1.9818}$. Heat of formation is usually expressed as J/g since a mole of fuel, or the fuel equivalent molecular weight, is an abstraction.

It is more practical to obtain the heat of formation in terms of kJ/mol using an equivalent molecular weight determined by GC-GC or another method rather than characterising the fuel as CH1.9818.



IMPACT OF FUEL C/H RATIO ON NET HEAT OF COMBUSTION

The diffusional particulate loses (or penetration transport efficiency) is shown in figure below. The calculation based on the AIR6241 procedure (SAE Aerospace Information Report). The AIR6241 methods represent a means of determining particle mass concentration, particle number concentration, and reporting of emissions indices using an appropriate sampling system and instrumentation. Initial calculations show that by applying the correction value result in a shift slightly to the left toward smaller particles (smaller than 15nm).