Local Air Quality and Sustainable Aviation Fuels (SAF)

By Theo Rindlisbacher (Swiss Federal Office of Civil Aviation) and Richard C. Miake Lye (Aerodyne Research)

Introduction

Commercial aviation is making great strides in employing Sustainable Aviation Fuel (SAF) to counter the global environmental impacts of the growth of aviation traffic. The primary purpose of SAF usage is to limit aviation's contribution to the increases in global CO_2 from the burning of fossil fuels. However, numerous measurement campaigns quantifying the emissions from aircraft gas turbines have demonstrated additional emissions benefits from the use of SAF. One benefit that has become well-documented over the past decade or two is the reduction of non-volatile particle matter (nvPM) emissions on top of the CO_2 emissions reduction.

This reduction in nvPM emissions has received much attention in the context of contrail formation and potential reductions in the impact from the commercial fleet's contrail effective radiative forcing as a "non-CO_2" climate impact. nvPM, often classified as ulftra-fine particles or soot, are primary pollutants but they are also related to cloud formation. The use of SAF during aircraft cruise has the potential to contribute to optically thinner contrail cirrus with reduced warming effect. But nvPM emissions also contribute particles to the airport environment and thus contribute to Local Air Quality (LAQ) degradation and the associated negative health impacts.

For both climate and LAQ, it is important to recognize that non-CO_2 impacts are due to changes in emissions from corresponding changes in fuel composition. Research on various SAFs has allowed, and even forced, research on how fuel composition changes can affect emissions and the resulting impacts. But the changes in fuel components such as Fuel Sulfur Content (FSC) and hydrogen content (usually associated with changes in aromatic content and naphthalenic content) are not unique to SAFs. A fossil fuel refined or processed to provide the same fuel composition would have the same non-CO_2 advantages as the corresponding SAF. Of course, any fossil jet fuel with an ideal composition might have all the desired non-CO_2 benefits, but would never have the CO_2 reduction of a SAF. But non-CO_2 benefits do not necessarily need to await sufficient SAF to power the entire commercial fleet.

SAF and PM emissions

SAF, and blends of SAF with fossil kerosene, that have been tested to date, reduce the emitted mass and number of emitted nvPM, with the strongest reduction shown at engine idle conditions. Low power engine conditions are particularly relevant for ground level emissions at airports, *e.g.* when aircraft are taxiing or queuing on taxiways and main engines idling. Engine idle is a far-off-optimum running condition for gas turbines with combustion temperatures being low and combustion technology improvements are difficult to achieve in these conditions. The use of SAF and SAF blends therefore is an important measure to reduce particle emissions at airports. For higher than engine idle power, combustion technology improvements are a very strong handle to reduce particle emissions. This is, however, mostly limited to the new future engine designs. The improvements will be visible in future ICAO emission certification data. The use of SAF, however, has the advantage of having an immediate effect in the existing fleet and directly allows for particle emissions reduction in all existing and future gas turbine engines.

Additionally, SAFs are usually sulphur free, apart from contaminations. This offers the prospect of further reduction in particle emissions measured around airports. Recent studies have shown that even small FSCs, a few ppm by mass, still allow the sulfuric acid created from the combustion process to strongly affect the particle processes in the exhaust plume. However, if very pure SAF with vanishingly low FSC is used, as done at a recent test at Gulfstream with RollsRoyce, FAA, NASA, MS&T, Aerodyne, and Colorado State, new particle formation does not occur (Figure 1). This has the potential to dramatically reduce aviation particle emissions around airports, since the vast majority (90% or more) of the total PM number measured around airports is volatile PM (vPM). Whether such dramatic reductions in vPM can also have major impacts on contrail formation has yet to be determined, although recent flight campaigns (ECLIF2/NDMAX, VOLCAN, and ecoDemonstrator2023) suggest possible linkages.

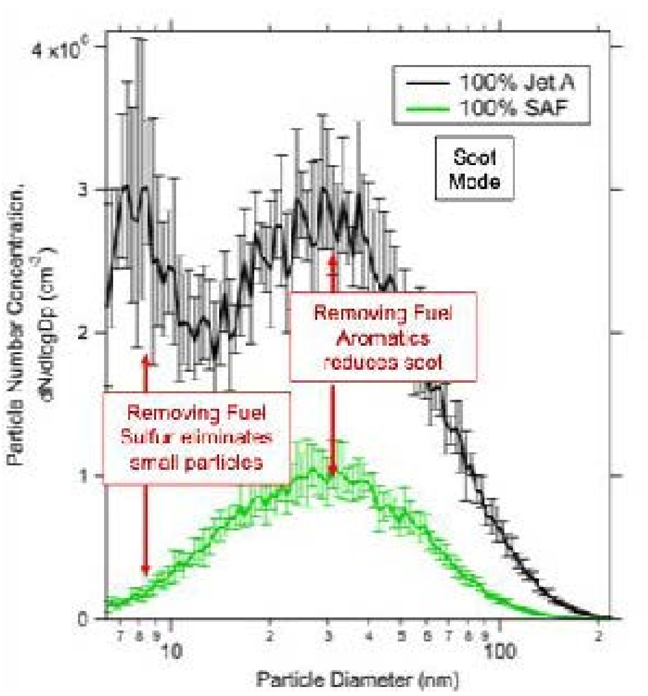

FIGURE 1: Comparison of total particle size distributions with Jet-A and very pure Synthetic Paraffinic Kerosene (SPK) SAF from the Gulfstream G700 test in October 2023.

Oil Aerosol Emissions remain as nvPM decreases due to SAF

Measurements of vPM in aircraft exhaust have shown the vPM mass to have a large contribution from engine lubrication oil[1]. Recent airport studies[2,3] have shown that the aviation contribution to PM downwind of an airport has a major component due to engine oil. As aircraft engine combustor design improves and higher H-content fuels are used, the nvPM emissions are reduced. Yet the oil contribution is affected neither by combustor design, nor by fuel composition and thus oil becomes a larger fraction of the total PM mass contribution. Recent measurements (ecoDemonstrator2022, 2023) have shown that in several modern engines, the mass from oil vPM contributions exceeds that of nvPM. Since oil is not a combustion by-product and the oil system is completely separate from the combustor in aviation gas turbine engines, current regulations do not require the measurement or certification of the emissions of oil. However, as other emissions are decreasing, the oil emissions are becoming an increasingly major contribution to the total PM emissions from aircraft.

SAF and Gaseous Pollutants

In terms of gaseous pollutants, apart from the reduction of sulphur oxides, the use of SAF tested to date has no significant effect on Nitrogen oxides (NO_X), Carbon monoxide (CO) and on the sum of hydrocarbon emissions as measured in emission certification. But what about the composition of hydrocarbon emissions?

Hydrocarbon (HC) emissions are a complex mixture of substances as a result of incomplete combustion. Some may make their way from the fuel directly into the exhaust, others are conversions from fuel HCs into emitted HCs with different chemical structure. They can be non-toxic, more toxic or less toxic than the fuel hydrocarbons. The corelease of nanoparticles together with carcinogenic

1 Timko, M. T.; Onasch, T. B.; Northway, M. J.; Jayne, J. T.; Canagaratna, M. R.; Herndon, S. C.; Wood, E. C.; Miake-Lye, R. C.; Knighton, W. B. Gas turbine engine emissions-Part II: Chemical properties of particulate matter. *J. Eng. Gas Turbine Power.* 2010, *132*, 061505/1-15.

2 Fushimi, A., Saitoh, K., Fujitani, Y., and Takegawa, N.: Identification of jet lubrication oil as a major component of aircraft exhaust nanoparticles, *Atmos. Chem. Phys*., 2019, *19*, 6389–6399, https://doi.org/10.5194/acp-19-6389-2019.

3 Ungeheuer, F., van Pinxteren, D., and Vogel, A. L.: Identification and source attribution of organic compounds in ultrafine particles near Frankfurt International Airport, *Atmos. Chem. Phys*., 2021,*21*, 3763–3775, https://doi.org/10.5194/acp-21-3763-2021.

polycyclic aromatic hydrocarbons (PAHs) affects air quality at airports. For modern gas turbines, incomplete combustion happens especially at engine idle, at very low power. The ICAO emission certification has a means to determine a defined sum of emitted HCs, however, there is no speciation, meaning that the composition of these emissions is not routinely measured.

Since the HC composition of SAF is very different from fossil kerosene, the HC emissions from SAF may also be different – with a prospect of being less toxic, since the most commonly used SAF to date (HEFA-SPK = Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene) is mainly composed of paraffins. A recent investigation concentrated on the amount and types of known genotoxic compounds, measured from combustion of a fossil Jet-A1 and a Jet-A1 30% HEFA-SPK blend. Genotoxic compounds, namely polycyclic aromatic hydrocarbons (PAH) can adsorb on ultrafine soot. If the soot is inhaled, these compounds can get into the body like in a Trojan Horse. It has to be noted, that such compounds are found in very low concentrations in engine exhaust, mainly at low power, but nevertheless it is important to know, whether their concentration changes with the type of fuel.[4]

The emission test referenced in Figure 2 was performed at the engine maintenance facility SR Technics, Switzerland, using the very common CFM56-7B family engine with dedicated tests[4]. Measurements were done at five thrust points, from ground idle to 85% thrust, each test point running for one hour. Blending jet fuel with HEFA-SPK lowered PAH and particle emissions by 7−34% and 65−67% at idle and 7% thrust, respectively, indicating that the use of paraffin-rich biofuels is an effective measure to reduce the exposure to nanoparticles coated with genotoxic PAHs at an airport[4].

A further Swiss emission test campaign was conducted with a small turbofan engine (PW545A) on a Cessna Citation 560XL business jet[5]. It focused again on particulate matter, gaseous pollutants and volatile organic compounds (VOC),

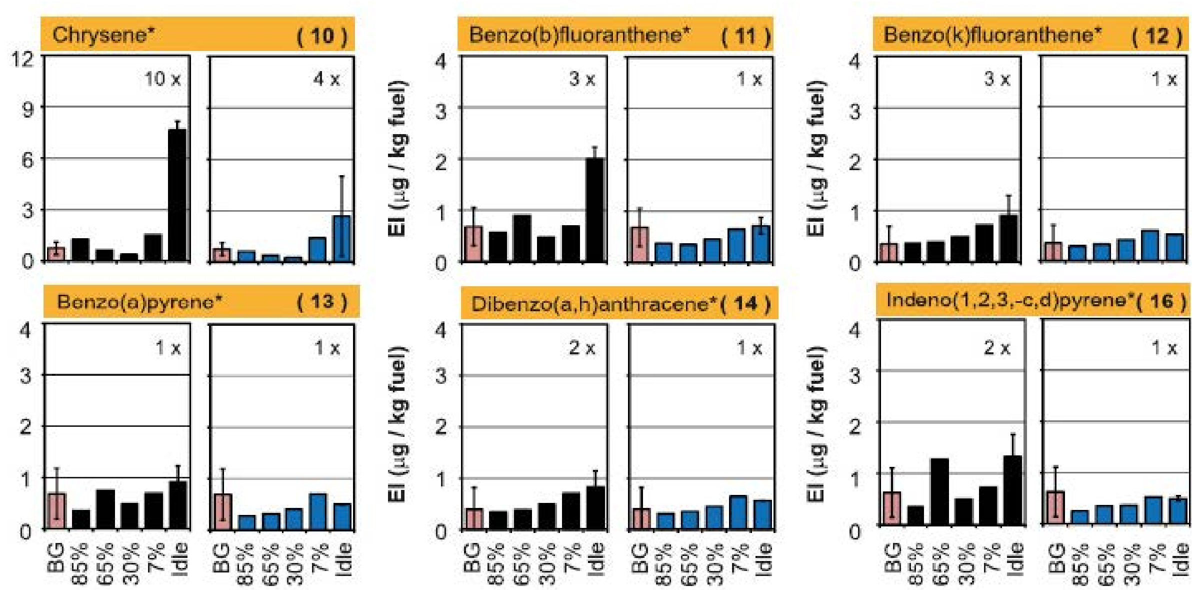

FIGURE 2: Extract of emission indices EI of priority PAH from Heeb et al.[4] The left panel of each pair is Jet-A1 and the right panel is the blend. Black bars are for the fossil kerosene, blue bars for the blend with 32% HEFA-SPK SAF. BG (pink bars) stands for background measurement. The x-axis shows the percent thrust. The numbers (e.g. 10 x) indicate how much higher the EI was measured compared to the background air (Note: the test facility is located at an airport).

4 Heeb et al, Corelease of Genotoxic Polycyclic Aromatic Hydrocarbons and Nanoparticles from a Commercial Aircraft Jet Engine – Dependence on Fuel and Thrust, Environmental Science and Technology, 2024, https://doi.org/10.1021/acs.est.3c08152

5 Durdina et al, Gaseous and Non-Volatile Particulate Emissions from a Private Jet Using Fossil Jet A-1 and a 30% HEFA-SPK Blend, Environmental Science and Technology, 2025, https://doi.org/10.1021/acsestair.5c00053

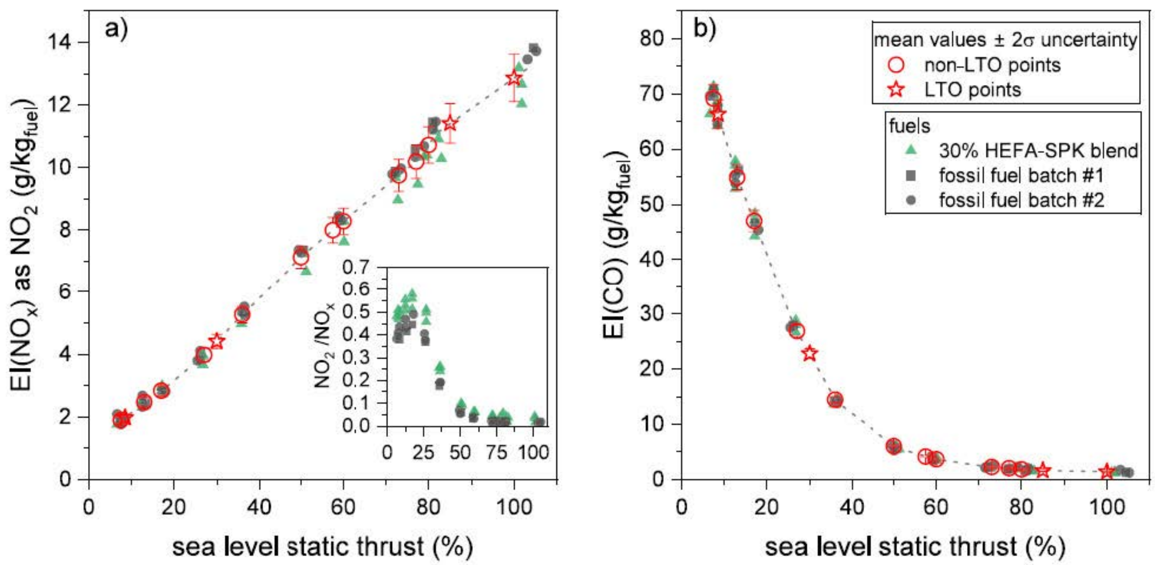

FIGURE 3: Emission Indices for NO_X and CO versus thrust for the PW545A engine, measured with pure fossil fuel batches and the 30% HEFA-SPK SAF blend. No significant differences can be observed, extract from Durdina et al.

which includes PAH. Again, HEFA-SPK SAF blend was used for comparison to the fossil base fuels. As expected, sulfur oxide emissions decreased proportionally to the fuel sulfur content, which was lower in the SAF blend.

The measurements provided SAF blend to fossil fuel signal intensity ratios for VOCs. These ratios provided a relative measure of VOC emission changes and confirmed the findings from Heeb et al.: The burning of the HEFA-SPK blend reduced formation or persistence of complex unsaturated hydrocarbons, such as aromatics and PAHs. It also confirmed no measureable significant change in emission indices for NO_X and CO.

Summary

In summary, the SAF blended fuels tested to date show a win-win-win situation for the environment. They fulfill the primary purpose of reduced life-cycle CO_2-emissions, and additionally, they reduce nvPM, reduce VOC, especially genotoxic PAH, and in general vPM particle precursor emissions like sulfur oxides. On the other hand, they do not reduce NO_X or CO, where combustion technology and fuel efficiency improvement remain as the technical measures. With cleaner combusting modern engines, contributions from lubrication oil are becoming an increasingly major contribution to the total PM emissions from aircraft. From the present state of knowledge, fuels with close to zero sulfur and high hydrogen content, such as observed with very pure SPK SAF, together with technical means to avoid lubrication oil emissions, the particle emissions and also potentially toxic gaseous emissions around airports could be strongly reduced.