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Benefits of changes in fuel composition on aviation non-CO₂ emissions

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Benefits of changes in fuel composition on non-CO₂ emissions from aviation

In addition to carbon dioxide (CO₂), aircraft engines emit so-called “non-CO₂” emissions. Non-CO₂ emissions include pollutants that affect human health, so are relevant to air quality research and policymaking. Non-CO₂ emissions also contribute towards aviation’s overall impact on climate change. The latest scientific evaluations support the view that reducing non-CO₂ emissions from aviation would lead to a reduction in its overall environmental impact, including its climate impact [1] [2]. One proposed way to achieve this reduction is by changing the composition of aviation fuel. Other options include improvements in engine and aircraft design and flight routing.

Fuel composition affects the quantity and nature of non-CO₂ emissions, and so emission reductions can be achieved by changing the fuel composition. In the case of non-volatile particles (soot), changes in engine technology can also deliver large reductions. Scientific evidence is most extensive for those limited number of Sustainable Aviation Fuel (SAF) types that have been used most frequently in ground-based and flight tests to date¹.

Recent research [3] [4] on the climate effect of aviation fuel specifications highlights that modifying the composition of a fuel can lead to a reduction in its non-CO₂ emissions. Increasing the hydrogen-to-carbon ratio of the hydrocarbon molecules in jet fuels, which is often done by saturating aromatic molecules, decreases total aromatic and naphthalene content as well as the sulphur content. While various levels of hydro-treatment are options to achieve this, SAF typically already have those properties. Other fuel sources (fossil, bio-coprocessing, etc.) may also produce fuels having higher hydrogen-to-carbon ratios and lower sulphur, aromatic and naphthalene content, but that may require substantial additional treatment². Note that SAF is currently used as a drop-in fuel, blended up to a maximum of 5 to 50% (depending on the type of SAF) with fossil-based Jet A-1.

Different categories of non-CO₂ emissions respond differently to changes in fuel composition, so are discussed here in turn:

- *Nitrogen Oxides (NO_x) and Carbon Monoxide (CO)*: Fuel composition has minimal impact on ground-based and cruise NO_x [5] and CO [6] emission indices, which primarily depend on engine and combustor design, and operating conditions.
- *Water Vapour (H₂O)*: The use of fuels with high hydrogen content increases water vapour emissions. Flight tests powered by 100% HEFA-SPK SAF measured an increase in water vapour emission index by about 10% [7].

¹ Mostly HEFA-SPK (Hydroprocessed Esters and Fatty Acids straight paraffinic jet fuel), but trials have also involved coal-based synthetic jet fuel (Schripp et al. 2018, <https://doi.org/10.1021/acs.est.7b06244>). ARA Readijet and Alcohol to Jet (AtJ) fuels were also used in ground tests (Schripp et al., 2019 <https://doi.org/10.1016/j.fuel.2019.115903>).

² Achieving greater aromatic saturation may require severe hydroprocessing in conventional refineries. Typical kerosene hydroprocessing units are designed for sulphur removal, and tend to be effective at reducing naphthalene concentration, a chemical species often cited as problematic in emission studies. However, typical hydroprocessing units achieve little aromatics saturation, so most refineries would require capital investment for significant aromatic reduction. Greater aromatic saturation of conventional or co-processed fuels would also require additional hydrogen production, resulting in greater energy demand, with higher greenhouse gas emissions and costs. On a positive note, typical hydroprocessing units tend to be effective at reducing naphthalene concentration, a chemical species often cited as problematic in emissions studies.

- *Non-volatile Particulate Matter (nvPM, also called soot)*: As a general principle, paraffinic molecules will combust more readily than aromatic molecules, thereby reducing the chance of nvPM formation caused by incomplete combustion. So the hydrogen content of the fuel is a directional predictor of nvPM emissions (Figure 1). However, individual fuel properties such as sulphur, aromatics and naphthalene content, carbon number distribution and the distillation curve will also each affect nvPM emissions to varying degrees. As such, predictors linked to the specific chemical nature of the molecules in the jet fuel may improve the accuracy compared to using the hydrogen content alone, but this needs to be implemented and tested.

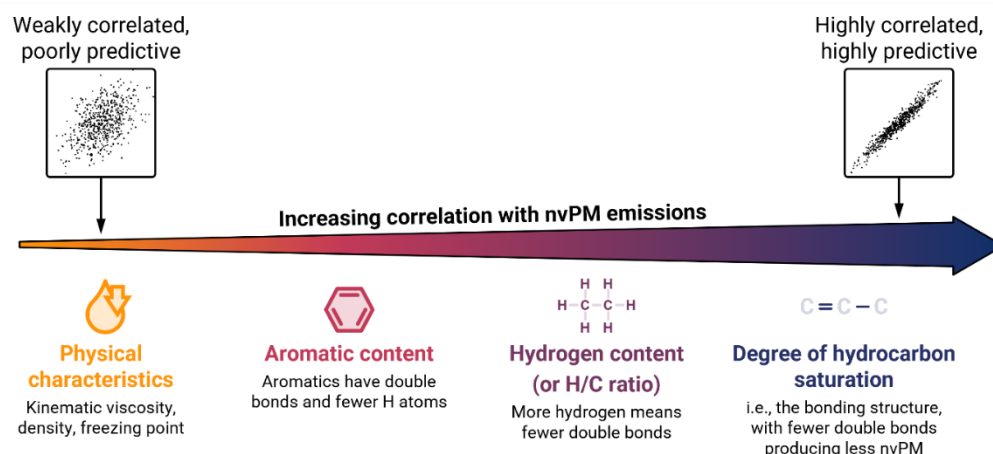
Fossil-based jet fuels have a hydrogen content ranging from 13.5% to 15%, with a global average closer to 13.8% by mass³. Hydrogen content depends on the crude oil origin and the degree of hydroprocessing. The use of fuels with higher hydrogen content of around 15% by mass, including SAF, has been found to lead to reductions in the mass of nvPM emissions. That reduction is expected because a higher hydrogen content is associated with the saturation of aromatic molecules and desulphurisation of fuel, which in turn reduces nvPM formation in the primary zone of the combustor (where fuel-to-air ratio is high to ensure a stable combustion). Reduced nvPM emissions from combustion of 100% SAF (HEFA-SPK), and different blends of fossil-based Jet A-1 and HEFA-SPK or FT-SPK⁴, have been confirmed by ground and airborne measurements, with a reduction in nvPM particle number of 20% to 80%, depending on the fuel tested, engine type and combustor design, and engine power settings [8] [9] [10] [11] [12] [13].

Lean-burn combustion technology has the potential to reduce nvPM emissions significantly when engines operate at medium to high thrust. Recent in-flight nvPM measurements have indicated very low levels of nvPM emissions when burning Jet A-1 [14], while a combination of high hydrogen content fuels with lean-burn combustion technology will minimise nvPM particle number emissions across the thrust range. This result is a logical consequence of the combined effects of fuel and engine technology. High hydrogen content fuel shows significant reductions in nvPM particle number emissions at engine idle [8] [9] [10] [11] [12] [13], where lean burn systems are running rich and producing nvPM like other combustion systems. Therefore, high fuel hydrogen content is important to reduce nvPM emissions at low thrust range, although that range is seldom used in flight so does not affect the climate impacts of non-CO₂ emissions. At medium to high thrust, lean burn systems combust lean, with extremely low nvPM particle emissions even with low hydrogen content jet fuels.

³ Hydrogen content is not currently measured or reported in commercial aviation fuel specifications, nor are there limits on hydrogen content. This is because aromatics, naphthalenes and sulphur are individually measured, and each have their associated limits.

⁴ Fischer-Tropsch straight paraffinic jet fuel

Figure 1 – Cause-effect relationships between fuel properties and nvPM emissions



- Volatile Particulate Matter (vPM):** The impact of fuel composition on the number of emitted vPM particles is more complex. vPM form from precursor gaseous combustion emissions from the aircraft engines, in quantities that also depend on external factors such as weather conditions, or from lubrication oil emissions. The overall ice nucleation ability of combustion emissions depends on the relative quantities of both nvPM and vPM. When nvPM numbers remain relatively large, in the so-called “soot-rich regime” associated with RQL⁵ combustion, sulphur has a limited impact on vPM number but might play a role in activating the hydrophobic nvPM particles to allow water to condense on them [15]. This then leads to the formation of ice crystals, contrails, and cirrus clouds. It is unclear if nvPM particles would form ice nuclei if there was no sulphur present in the fuel. In the so-called “soot-poor regime”, achieved by some advanced RQL and lean-burn combustors, theoretical calculations predict that the lack of nvPM limits the scavenging of vPM precursors (sulphur and organics, including oil vapours) [16], allows higher supersaturation, and opens previously suppressed pathways of volatile particle formation [17] [18] [16] [19]. Flight tests in the soot-rich regime using fuels with different sulphur contents found the expected reduction in vPM with decreasing fuel sulphur content [20].

In both cases, having extremely low sulphur content in the fuel will reduce ice nucleation. The sulphur content threshold is not known but is likely below 10 ppm. Fossil-based Jet A-1 typically contains several hundred parts per million of sulphur by mass⁶. In contrast, the process to produce SAF makes them sulphur-free, although cross-contamination during fuel delivery or on the aircraft means SAF fuels may end up with sulphur. The extent to which oil droplets, nitric acid, or organic compounds would drive volatile particle formation in soot-poor, ultra-low sulphur, conditions remains an open question because of a lack of knowledge of emission rates and characteristics of the formed vPM.

⁵ Rich burn – Quick quench – Lean burn combustion technology

⁶ For the sake of comparison, for road transport, ultra-low sulphur diesel fuel has been required in Europe by the Euro V fuel standard since 2009, to a maximum of 10 ppm of sulphur, and in the United States and Canada since 2006, to a maximum of 15 ppm of sulphur. For shipping, the IMO 2020 (MARPOL Annex VI) regulation mandates a maximum 0.5% (5000 ppm) fuel sulphur content since 1 January 2020, down from 3.5% previously, except in Sulphur Emission Control areas where the limit is even lower, at 0.1% (1000 ppm).

- The impact of fuel composition on the emissions of *Volatile Organic Compounds (VOC)*, including *Unburnt Hydrocarbons (UHC)* has also been measured, with varied findings depending on fuel tested and test conditions [21] [22].

Reduced particulate matter emissions is expected to reduce contrail formation and therefore decrease the climate impact of contrails. However, recent research stresses that the reduction should be in total particle emissions, not just nvPM (soot) emissions, because from a thermodynamics perspective, ice crystals will form on any available hygroscopic particle given favourable environmental conditions.

As already highlighted, fuels with high hydrogen content and low sulphur content, such as but not limited to SAF, reduce the number of particles generated by aircraft engines. This is one of the main factors, along with atmospheric conditions, that determines the initial number of ice crystals in contrails. Contrail ice crystals form when water vapour condenses onto the particles emitted or formed in the aircraft engine exhaust plume, forming liquid water droplets that quickly freeze. It is expected that the emission of fewer particles will lead to the formation of fewer ice crystals [16].



Several in-flight measurements behind aircraft burning fuels with varying hydrogen and sulphur contents confirm the formation of fewer ice crystals from reduced numbers of nvPM (soot) and/or vPM emissions [14]. Most recently, reduced ice crystals numbers have been observed in the case of SAF [20].

Climate modelling suggests that a reduced ice crystal number translates into reduced radiative forcing by contrails and contrail-cirrus due to reduced contrail optical depths and shorter lifetimes [23]⁷. Simulations using the Schmidt-Appleman criterion to determine conditions favourable to contrail formation find that the use of SAF increases slightly the extent of the regions where persistent contrails are formed because of its higher water vapour emission index compared to Jet A-1. However, this effect is small and consequently models still find a net reduction in contrail-cirrus radiative effect, driven by decreases in contrail optical properties and lifetime [24].

A reduction in particulate matter emissions would modify non-CO₂ effects other than contrail cirrus in sometimes unintended directions [25], although the size of potential counter-effects remains a topic of ongoing research. This includes potentially reducing the climate impact from the interactions between aviation particulate matter and radiation and clouds, which is not yet quantified but could be cooling. Sulphur dioxide emissions for example are known to form liquid particles of sulphuric acid and sulfate, which are involved in the formation of liquid clouds, making them brighter and resulting in a cooling effect of uncertain size.

⁷ Note that [26] shows that this reduction in climate impact is due to the reduction in the radiative forcing of long-lived contrails. The reduction in ice crystal numbers is negligible for short-lived contrails.

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European Union Aviation Safety Agency

Konrad-Adenauer-Ufer 3
50668 Cologne
Germany

<https://www.easa.europa.eu/ANCEN>

Mail ANCEN@easa.europa.eu
Web www.easa.europa.eu

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