DOI: 10.13009/EUCASS2022-7260
9TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

Emission and Climate Impact of Alternative Fuels. The ECLIF1 and ECLIF2 Campaigns

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Abstract
Some practical aspects of the two flight and ground measurement campaigns, which took place in the framework of the project Emission and Climate Impact of Alternative Fuels (ECLIF) are presented. After describing the impact of aviation on climate through both its CO_2 emissions and its non-CO_2 effects and after introducing the proper metric for comparing both effects, the benefits of using sustainable aviation fuels (SAF) are described. In addition to reducing the carbon footprint, SAFs, which are characterized by a high hydrogen content than conventional crude-oil based Jet A-1, also reduce the radiative forcing due contrail cirrus.

1. Introduction

Aviation is not directly included in the 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC). However, aviation stakeholders had made statements before this agreement (see ATAG, IATA 2009) in terms of CO_2 emissions reduction targets. Moreover, in July 2021, the European Commission presented the 'fit for 55' package, whereby net greenhouse gas emissions should be reduced by at least 55 % by 2030, compared with 1990 levels. The package includes the ReFuelEU Aviation initiative, which drafts obligations on fuel suppliers to distribute sustainable aviation fuels (SAF) to increase the uptake of SAF by airlines and thereby reduce emissions from aviation.

To realize the necessity and the benefits of mass producing, deploying, and flying worldwide with sustainable aviation fuels (SAF), it is crucial to understand the nature and the scale of aviation's impact on present-day climate forcing.

Long-term effect (accumulation & time-scales) of CO_2 emissions. Short-term effect of other emitted trace species
Aviation has a long-term impact on climate primarily from accumulation of its net carbon dioxide (CO_2) emissions, which acts as a greenhouse gas. The latest available data (2018) evaluates that aviation is responsible for 2.4% of total anthropogenic emissions of CO_2 (including land use change) on an annual basis [1]. The majority of CO_2 emissions come from the combustion of fossil fuels and are balanced out by the various carbon reservoirs of the atmosphere, the ocean, and the terrestrial biosphere on timescales of a few centuries. However, a portion of CO_2 (20-35%), released in the atmosphere today from any source, will still have a warming effect in many thousands of years [2]. Aviation is also responsible for shorter-term impact stemming from non-CO_2 emissions, which cause an additional net warming effect [3]. These emissions include the other main product of the combustion process: water vapor (H_2O) plus the following trace species: nitrogen oxides (NO_x= NO + NO_2), sulphate volatile aerosols arising from sulphur in the fuel (e.g. H_2SO_4), carbon monoxide (CO), unburnt hydrocarbons (UHC), and non-volatile particulate matter (nvPM or also referred to as soot). The different emitted compounds are transported by turbulent mixing, convection, and advection in the atmosphere and alter a wide range of atmospheric processes including the formation of contrail-cirrus and ozone and the depletion of methane.

Common metric to assess all aviation related climate forcing effects: radiative forcing (RF)
In 1999, the Intergovernmental Panel on Climate Change (IPCC) published a report [4] where the global annual average of radiative imbalance (measured in watt per square meters: W/m^2) to the atmosphere-land-ocean system caused by anthropogenic perturbations was presented. This variation in the Earth surface-atmosphere system's energy budget

DOI: 10.13009/EUCASS2022-7260

was defined as the radiative forcing (RF) and where the RF of the pre-industrial atmosphere (1750) is taken to be zero. In spite of many assumptions [4], the radiative forcing of an aviation induced atmospheric perturbation is a useful indicator that allows, to first approximation, the different atmospheric perturbations aforementioned (e.g., aerosols, cloud changes, ozone, stratospheric water, methane) to be summed and compared in terms of global climate impact. Since then, it has been used for the comprehensive assessment of aviation's impacts on climate and the RF enables to predict changes to the global mean surface temperature. The IPCC report [4] concluded that aviation is responsible for a small but increasing forcing of climate with potentially a large contribution of its non-CO_2 effects, which still have high uncertainties in their overall magnitude evaluation. The IPCC estimated that aviation represented 3.5% of the total anthropogenic RF in 1992 (excluding contrail cirrus), which was projected to increase to 5% for a mid-range emission scenario by 2050. Using RF as the common metric to rank the impact of individual forcers Lee *et al*'s review (2021) [1], which compiles many different studies, reveals that in 2018 contrail cirrus is the largest contributor to annual mean RF due to aviation, at 111 ([33, 189] mW/m^2 [95% confidence interval]), followed by aviation's cumulative CO_2 (34 [31, 38] mW/m^2) and annual NO_x emissions (8.2 [-4.8, 16] mW/m^2).

With cirrus contrails potentially being the strongest aviation-related climate forcer in terms of RF, it is important to briefly explain the physics behind that. Long-lasting (>10 minutes) contrails and the induced high-altitude contrails (cirrus contrails) reflect short-wave radiation from the sun and absorb outgoing long-wave radiation from the Earth's surface and the atmosphere. The imbalance yields a radiative forcing (RF) of climate, which results on average in a warming at the top of the atmosphere [5].

Relationship between radiative forcing (RF) and Earth's mean surface temperature T_s.
Many studies and experiments on climate have found a quasi-linear relationship between a change in global mean radiative forcing (RF in w/m^2) and a change in global mean surface temperature (ΔTs in °C), when the system has reached a new equilibrium, with some proportionality constant: $\Delta T_s \approx \lambda$ RF.

Aviation is characterized by both CO_2 emissions and non-CO_2 effects and we use RF to estimate quantitatively the relative impact of each component. The total climate forcing through all CO_2 and non-CO_2 effects is approximately their sum, assuming that the individual effects are independent of each other, which is also implied by the T=f(RF) relationship aforementioned. Importantly, we can now evaluate aviation's impact with respect to the Paris Agreement temperature goal. Actually, accounting for both CO_2 and non-CO_2 effects the total aviation-induced warming, up to year 2019 is about 0.04 ± 0.02 °C [6]. which corresponds to about 4% of the 1.2 °C that the planet has warmed so far. This figure is consistent with percent estimates of aviation impact on global warming using the RF metric.

Data from measurement campaigns such as ACCESS2 [7], or ECLIF1 & ECLIF2 combined with global models indicate that contrail-cirrus contribute the largest to aviation's climate impact. Several mitigation options to reduce aviation's climate impact have been put forward. They include re-routing to avoid contrail prone regions, flying lower altitudes, or using SAF, which are all less radical in their implementation than a complete change in the existing aircraft & propulsion system and the infrastructure (e.g. H_2 aircraft). We focus here on the use of SAF.

Sustainable aviation fuel (SAF) definition
Alternative aviation fuels are non-conventional or advanced fuels as their feedstock is not crude oil (fossil). However, while being an alternative to conventional crude oil-based Jet A-1/Jet A, the feedstock of certain types of alternative aviation fuels can still be a fossil-source such as coal or natural gas. Following a gasification step and the Fischer-Tropsch process these feedstocks yield coal-to-liquid (CTL) or gas-to-liquid (GTL) fuels or blend stocks. With view to the climate change mitigation target, CTL and GTL, have no potential for reducing greenhouse gas emissions and generally even increase these emissions (in particular CTL) with respect to conventional jet fuel.

Feedstocks for producing sustainable aviation fuels are renewable resources and varied; ranging from cooking oil, plant oils, municipal waste, waste gases, and agricultural residues, or even CO_2, water and renewable energy e.g. renewable electricity from photovoltaic or wind plants, or renewable heat from concentrated solar plants. These last two routes yield fuels which are called power-to-liquid (PTL) or sun-to-liquid (STL), respectively. Renewable fuels result in a reduction in carbon dioxide (CO_2) emissions (one of the main greenhouse gas emission) across their life cycle. The sustainability of the fuel is considered in terms of life-cycle emission reductions including the effect of land use change, indirect land use change (ILUC) and socio-economic impacts. A sustainable feedstock is continually and repeatably resourced in a manner consistent with strong environmental, social, and economic (circular) criteria, specifically something that conserves an ecological balance by avoiding depletion of natural resources and does not contribute to climate change. In the particular case of the aviation industry, the focus is on sourcing sustainable aviation fuels that can be mass produced at low cost with minimal environmental and climate impact. All SAF users including

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commercial airlines request a certificate of sustainability (CoS) in addition to the technical document (certificate of analysis CoA) when purchasing SAF from a supplier to ensure that fuels are sustainably produced.

Internationally recognized sustainability standards for bio-based feedstocks and advanced fuels are being developed by the Roundtable on Sustainable Biomaterials (RSB). The sustainability criteria in the EU are defined by the RED II framework. There are a number of public and private bodies that issue certificates of sustainability (CoS), including the International Sustainability and Carbon Certification (ISCC), which also covers SAF.

SAF encompasses all three aspects:

1. An alternative to the single-source fossil Jet A-1. The diversity in the type and the geographical source of feedstocks, which can be used for producing SAF is a key advantage identified by commercial aviation stakeholders. Also, it is an alternative with further economic and social benefits. Actually, SAF could reduce the price fluctuations related to fuel cost volatility and it could provide economic benefits to developing nations with land that is unviable for food crops, but that is suitable for SAF feedstock growth.
2. A renewable commodity with its environmental benefits. SAF result in up to an 80% reduction in CO_2 emissions across their lifecycle and can potentially reach 100% in the case of the PTL or the STL routes with CO_2 stemming from direct air carbon capture.
3. Meeting stringent and progressive sustainability criteria comprising environmental, social, and economic aspects.

Technical feasibility

To ensure safe flight operations around the globe with modern, as well as legacy aircraft and engines, aviation turbine fuel has to meet the regulatory specification requirements defined in international standards or in similar national adoptions of these specifications at every airport. In the aviation industry, the two major jet fuel (Jet A-1/Jet A) specifications are the Defense Standard 91-91 and the ASTM D1655. The fuel standard specifications do not explicitly determine the fuel formulation. Instead, they define minimum requirements in terms of safety, performance, material compatibility, and handling.

In 2009, based on the pioneering certification process that the Sasol Semi-Synthetic Jet Fuel had been through, the standard was modified to include approval procedures of new aviation turbine fuels: ASTM D4054 "Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives". During this qualification process, more than 70 different properties were tested to assess the basic fuel chemical/physical properties and the fuel performance in the aircraft engine, fuels system, and ground handling of the fuels. By this rigorous testing, the drop-in quality (i.e., the quality of the new synthetic fuels to be used as equal or improved replacement of conventional crude oil-based jet fuel) is ensured. If a fuel is successfully approved, it will be annexed to ASTM D7566, the standard specification for aviation turbine fuels containing synthesized hydrocarbons.

In recent years, seven pathways for the production of alternative aviation fuels have been approved by ASTM International and further adopted by the Defense Standard and other national regulatory bodies. These alternative aviation fuels have to be blended with conventional aviation fuel from crude oil to fulfil the property constraints that ensure their drop-in capability as defined in ASTM D7566. The maximum blending ratio is up to 50% alternative fuel for Fischer–Tropsch synthesized paraffinic kerosene (FT-SPK), which was approved in 2009; synthesized paraffinic kerosene from hydroprocessed esters and fatty acids (HEFA-SPK), which was approved in 2011; Fischer–Tropsch SPK with aromatics (SPK/A), which was approved in 2015; alcohol-to-jet synthetic paraffinic kerosene (AtJ-SPK), which was approved in 2016; catalytic hydrothermolysis synthesized kerosene (CH-SK, or CHJ); which was approved in 2020, and 10% max for synthesized iso-paraffins (SIP) from fermented sugars, which was approved in 2014 and hydroprocessed hydrocarbons, esters and fatty acids synthetic paraffinic kerosene (HHC-SPK or HC-HEFA-SPK); which was also approved in 2020. The approval process tests fuel physical and chemical properties, as well as complex sub-processes occurring in the aircraft and engine fuel and combustion systems.

Besides crude Jet A-1, which was used as refence fuel for the two measurement campaigns, FT-SPK and HEFA-SPK were the two alternative fuels selected. These are presented in more details in the following section.

DOI: 10.13009/EUCASS2022-7260

2. Fuels for the ECLIF1 & ECLIF2 campaigns

In the project ECLIF, soot is the common denominator. It is the link between the fuel, which affects certain fuel-dependent physical and chemical sub-processes occurring in the combustion system and producing soot, and the water vapor and trace gases nucleation process, which is activated by the soot particles downstream the engine exhaust and generates the contrails. As such, a major task is to select the proper fuels. The measurement campaigns were performed using fossil-based alternative aviation fuels as well as sustainable aviation fuels. A crucial aspect for the quality of the scientific results when comparing the impact of alternative fuels on emissions and climate with respect to conventional jet fuel is the selection and procurement of a reference fuel for the entire campaign.

2.1. Fuel strategy and fuel selection

In the civil or military aviation operational practice, information concerning the kerosene properties is listed in the certificate of analysis (CoA). Often, the fuel's aromatics content is the first indicator of its sooting propensity, even more so than the smoke point, which we consider less reliable as it is more prone to operator's error. In ECLIF1 (ECLIF's first measurement campaign) the aromatics content was thus the main criteria for defining a practical[1] fuel strategy, which can be described as follows:

- Investigate the effect of aromatics volume percent (vol%) on soot emissions: Blend conventional (fossil oil-based) Jet A-1 with SPK (synthetic paraffinic kerosene) to achieve a systematic aromatics content variation yet keeping the aromatic structure identical.
- Investigate the effect of aromatics molecular structure on soot emissions: Keep the vol% of aromatics content quasi constant but vary the origin, which will most likely lead to a different molecular structure of the aromatic molecules. Thus, the 2 reference Jet A-1stemming from two different batches of raw oil. One conventional and one for bitumen run.

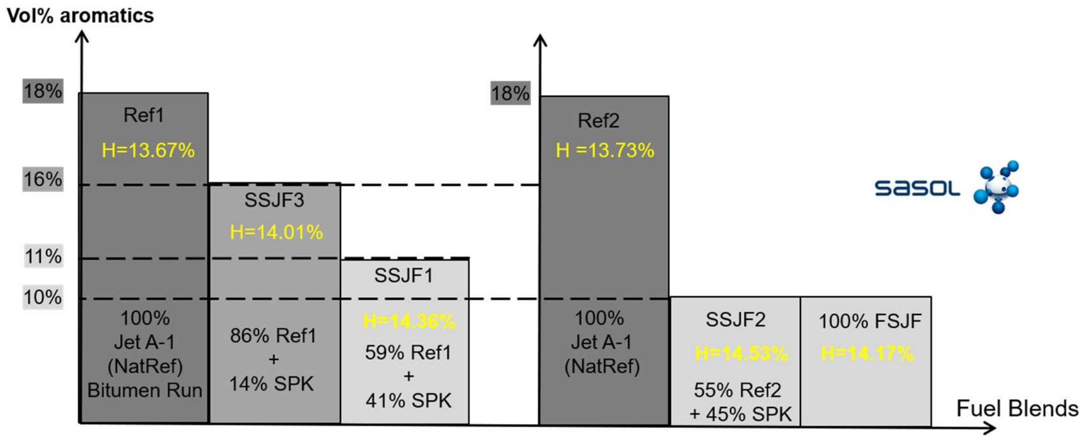

Figure 1. ECLIF1 fuel selection. Ref: Reference Fuel (conventional Jet A-1); SSJF: Semi-Synthetic Jet Fuel; FSJF: Fully Synthetic Jet Fuel. Fuels grouped in aromatics content (not exact value) with shades of grey for clarity. Yellow: hydrogen content of each fuel.

The ECLIF1 measurement campaign took place in Sept-Oct. 2015. Not only the procurement of SAF would have been very long and expensive at that time but most importantly there was no SAF production facility at commercial scale with a continuous production process back in 2015. One of the other main reasons why the FT-SPK (Fischer-Tropsch – Synthetic paraffinic kerosene) of the South African company Sasol was selected as blend stock are i) a given and very useful flexibility in the composition of the final SSJF (semi-synthetic jet fuel: FT-SPK + crude Jet A-1) composition, which enables to explore more systematically the fuel effect on sooting than when relying on random crude Jet A-1 refineries and ii) the possibility to use a fully synthetic fuel in a measurement campaign.

The fuel selection is illustrated in Figure 1. The reference fuels, Ref1 and Ref2 are conventional Jet A-1s from the National Refinery (NatRef) in South Africa. They have aromatics content very close in volume percent but different in nature as they stem from different petroleum products and both were refined according to a different refinery process.

[1] large quantities of certified jet fuel coming from refineries in service

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Ref1 is then the base blend stock for SSJF3 and SSJF1. Ref2 is the one used to blend SSJF2. Within each of the two aforementioned groups, there is a variation in aromatics volume percent (see Figure 1). Moreover, by using two different conventional Jet A-1s for blending, we introduce a variation in the molecular structure. Finally, Sasol had a large enough quantity of FSJF left from the approval campaign (2008), which was recertified for the purpose of being used for the first time in such a measurement campaign. As aforementioned (see footnote 1), in practice when sourcing large quantities of jet fuel, such as those needed for a flight campaign, one needs to introduce a certain tolerance in the targeted properties. For instance, it would have been ideal to have Ref1 and Ref2 or SSJF1, SSJF2, and FSJF with the exact same aromatics volume percent. However, at the commercial scale of a refinery this is not realistic.

The fuel strategy for the second measurement campaign: ECLIF2, was developed based on the analysis of the measurement results from lab-scale experiments (not presented) and from the first measurement campaign ECLIF1. Additionally, the fuel design methods developed in the framework of the DLR internal strategic project Future Fuels (2014 – 2018) was also applied. In ECLIF2, the aim was first to use a sustainable blend stock mixed with conventional crude Jet A-1. Fifty thousand liters of pure hydrotreated esters and fatty acids - synthetic paraffinic kerosene (HEFA-SPK) were thus sourced through and purchased from airBP Hamburg. Such large quantities cannot be purchased with special compositional requirements so the fuel design had to take a different strategy, namely select conventional Jet A-1s for blending with the HEFA blend stock, which would lead to a final certified jet fuel with the targeted properties.

The practical fuel design consisted in selecting reference crude Jet A-1s with specific hydrocarbon families in small amounts (< 3 mass%) but with strong soot propensity. Hence, the strategy was to achieve very similar aromatics- and hydrogen-contents but have a difference in naphthalenes (di-aromatic type of molecular structure). As can be seen in Figure 2, SAF1 has slightly lower aromatics content than SAF2 (potentially lower sooting tendency). Also, at the time of the fuel selection, the CoA was showing quasi identical hydrogen content for both fuels (according to ASTM D3343 standard method). The more accurate NMR measurement results presented in Figure 2, show higher hydrogen content for SAF2. Noteworthy the fact that with respect to ECLIF1's synthetic fuels, the naphthalene content is here low for both fuels, yet there is one order of magnitude difference between the two (see Figure 2).

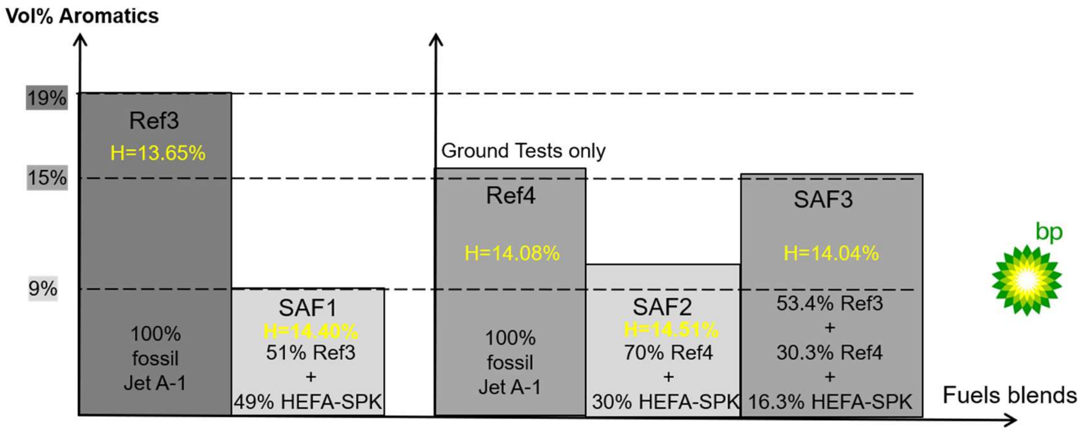

Figure 2. ECLIF2 fuel selection. Ref: Reference Fuel (conventional Jet A-1); SAJF: Sustainable Aviation Jet Fuel. Fuels grouped in aromatics content (not exact value) with shades of grey for clarity. Yellow: hydrogen content of each fuel.

2.2. Fuel logistics

For ECLIF1, a total of 118 tons of fuel was shipped from Sasolburg, South Africa to Manching, Germany. The whole logistics included a stop for customs in Hamburg, a short-term storage in Munich and, delivery plus TÜV certified storage in Manching. As can be seen in Figure 3, iso-containers were stored on the WTD61 apron#2. A total of eight iso-containers for the 6 sorts of fuels were necessary.

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Figure 3: ECLIF1 fuel iso-container delivery and uploading with crane (left). Iso-containers storage in certified dedicated area.

For the ECLIF2 campaign, 163 Tons (5 sorts) of fuels, including HEFA-SPK blend stock from California (Altair) and Jet A-1 from Germany (Gelsenkirchen & Schwedt) were used for the blending. A total of 7 iso-containers (see Figure 4 left) plus 3 US Air Force Tank Trucks (see tanking Figure 4 right) were used for fuel storage in Ramstein

Figure 4: ECLIF2 fuel iso-container storage in Ramstein (left). Tanking of test fuels in Ramstein (right).

2.3. Fuel quality control

The certificates of analysis (CoAs) for all ECLIF fuels were provided by the different producers. All fuels tested in the DLR ATRA during the ECLIF program were conform with Jet A-1 specification requirements as stated in the MoD DEF STAN 91-91 and the ASTM D 1655 (Grade Jet A-1). With its freezing point measured at -46.8 °C, SAF1 was certified as Jet A.

Due to the scientific nature of the project, it was necessary to ensure that the fuels sourced and delivered at the time of the measurement campaign matched the targeted properties. Moreover, it was necessary to ensure that no contamination from one flight to the next or between the tank trucks had occurred. For that purpose, fuel samples were drawn from one of the ATRA wing tanks after each flight. These samples were then taken to the WIWeB[2] during the first measurement campaign (ECLIF1) and to the external laboratory PetroLab GmbH, Speyer, during the second measurement campaign (ECLIF2). Results always showed that, within the accuracy of the standard method, the actual fuel properties corresponded to the targeted fuel.

2.4. Fuel statistics

In addition to the specific ECLIF fuel strategy developed in Section 2.1 it is important to compare the selected ECLIF fuels with a large variety of conventional Jet A-1s in order to assess how representative these fuels are with respect to what is used worldwide. Actually, the main properties identified for selecting the fuels: the aromatics content, the hydrogen content, and the naphthalene content are compared to data collected and summarized in the Petroleum Quality Information System (PQIS) Annual Reports (2010 and 2013) as well as in the Biofuel Blends in Aviation

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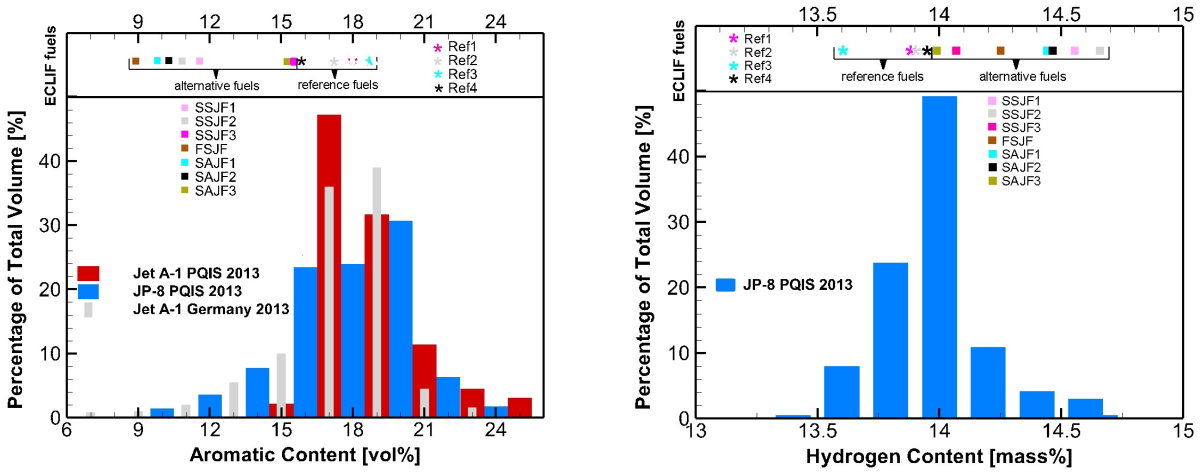
Study [8] for German fuels. JP-8[3], which is the US military designation for Jet A-1, is used in the PQIS database. As can be seen in Figure 5 a) all the reference fuels, which were sourced for ECLIF1 and for ECLIF2 lay in the same narrow region of volume percentage of aromatics (vol% aromatics). The first reason is that these reference fuels serve also as blending material for final blends with up to 50 vol% SPK, which precludes an aromatic content below 16 vol% in the conventional Jet A-1. Then, in practice, a safety margin is added so that the conventional Jet A-1 selected for blending is often closer to 18 vol% aromatics. The second reason relates to getting closer to the upper limit (25 vol% aromatics). It had been a priority in both test campaigns to purchase a reference Jet A-1 with a very high aromatic content. Although, as shown in Figure 5 such Jet A-1 fuels with an aromatic content above 20 vol% are available in Germany, in practice they are very difficult to source. Actually, such fuels could potentially yield very high emissions with respect to other fuels and in turn when reported in scientific reports and journals lead to bad publicity. The fuel strategy was therefore adapted.

When blended with SPKs (FT-SPK in ECLIF1 or HEFA-SPK in ECLIF2) then the spectrum becomes wider, especially towards the lower aromatics content (see Figure 5 a) or the higher hydrogen content (see Figure 5 b).



a) b)

Figure 5. a) Distribution of aromatic content in Jet A-1 and JP-8 fuels according to the PQIS statistics in regions 6, 7, and 8 for Jet A-1 and in the PQIS regions 1 to 8 for JP-8 and of Jet A-1 in Germany [8]. ASTM D1319 is the standard test performed in all certificates of quality (CoQ) used here. b) Distribution of hydrogen content in JP-8 fuel according to the PQIS statistics in regions 1 to 8. Top of graphs, position of ECLIF reference fuels and alternative fuels with respect to this statistical distribution.

Concerning the naphthalene content, Figure 6 shows that the fuels selected and blended in ECLIF cover the largest possible range, going from values close to 0 vol% all the way to the maximum, which is 3 vol%.

[3] JP-8 and Jet A-1 differ only from the nature and the content of their respective additives

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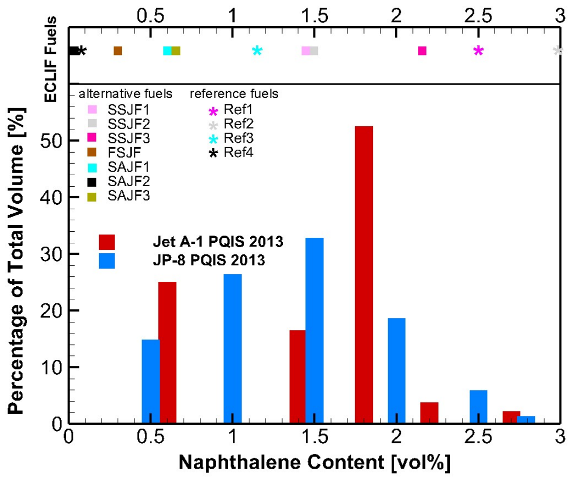

Figure 6. Distribution of naphthalene content in Jet A-1 and JP-8 fuels according to the PQIS statistics in regions 6, 7, and 8 for Jet A-1 and in the PQIS regions 1 to 8 for JP-8. Top of graph, position of ECLIF reference fuels and alternative fuels with respect to this statistical distribution.

3. In-Situ flight and ground measurements

DLR's research aircraft ATRA (Advanced Technology Research Aircraft), Airbus A320-232 equipped with International Aero Engines (IAE) V2527-A5 was used as the source aircraft for both campaigns. It is a modern turbofan engine with a two-spool mixed flow high bypass engine configuration, rated at about 100 to 140 kN take-off thrust. The fan bypass ratio at sea level static take-off conditions is about 4.5 with an overall pressure ratio of about 33.4. The engine consists of a 1.613m single stage fan, a 4-stage low pressure compressor and a 5-stage low pressure turbine on the low-pressure spool. The 10-stage high pressure compressor is driven by a cooled 2-stage high pressure turbine on the high-pressure spool of the core engine.

The ground and flight tests were performed during two campaigns, ECLIF1 at the German Air Base in Manching in Sept.-Oct. 2015 and ECLIF2 at the USA/NATO Air Base in Ramstein in Jan.-Feb. 2018 (see Figure 7). Both field campaigns were conducted in a close collaboration between DLR and NASA. The DLR Falcon 20 served as measurement aircraft and chased the ATRA during ECLIF1 and the NASA DC8 flying lab was the chaser for far-field in-situ plume probing and measuring during ECLIF2.

The ground measurements focused on the determination of emission indices for ICAO LTO (Landing and Take-off) power settings and additional power settings reflecting cruise conditions. Results from the ECLIF1 and ECLIF2 ground tests are presented in [9] and [10], respectively. Additionally, an instrument comparison was performed during ECLIF2 and is presented in [11]. Reductions in soot particle mass emission indices of up to 70% compared to the fossil reference fuel were measured [9], [10]. The fuels showed a monotonic decrease in particle emission with increasing fuel hydrogen content. However, the fuel's emissions do not correlate when using the aromatics content. This was revealed prominently when measuring the fully synthetic jet fuel FSJF.

The flight tests included measurements in the wake of source aircraft in the near-field (~100-200 m) and far-field (~10-20 km) for different fuels, cruise altitudes, power settings and for conditions with and without contrail formation. Combined ground and flight emission data are important to develop and validate engine emission models relating cruise to LTO emissions.

As briefly explained in the introduction, aviation-related soot emissions play a crucial role in the formation of contrails. The number of soot particles emitted per kilogram of fuel burnt determines the initial number of ice crystals in contrails, according to model simulations [12]. Alternative fuels contain near-zero levels of aromatics which are mainly responsible for the formation of soot during combustion. Thus, the experimental investigation of the relation between soot emissions and contrail properties of alternative fuel blends was a major focus of the flight tests.

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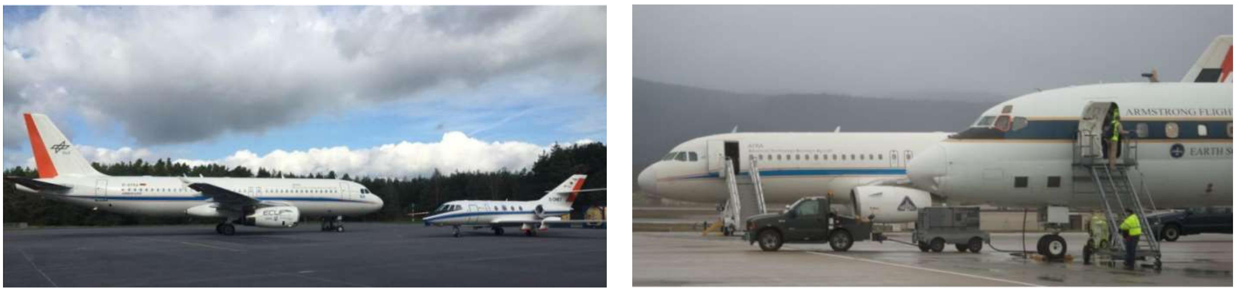

Figure 7: DLR Falcon and ATRA at Manching Airport (left) and NASA DC8 and ATRA at Ramstein Air Base (right).

The joint flights were conducted in restricted air space coordinated with military air traffic control. Typically, both aircraft flew race tracks at varying speeds and altitudes. Viewed real-time data from gas and particle instruments onboard the measurement aircraft were used to detect exhaust plumes and contrail crossings. During the second ECLIF campaign the DC-8 received real-time displays of wind-advected flight tracks of the ATRA, which greatly helped to detect the exhaust trails and contrails (Figure 8).

a) b)

Figure 8: a) Race tracks in restricted air space in northern Germany during ECLIF2 and display of wind-advected ATRA flight track for guiding exhaust plume interceptions. b) View from the DC-8 cockpit of the ATRA contrail. The ice particles in the secondary and primary wake are clearly visible.

Contrail measurements were performed in the secondary and primary wake of the ATRA (Figure 8 b). ECLIF members also participated in the NASA-coordinated ACCESS2 (Alternative Fuel Effects on Contrails and Cruise Emissions Study) campaign at the NASA Armstrong Flight Research Center in Palmdale, California, USA in March 2014 including DLR Falcon measurements in the wake of the NASA DC-8 burning JP-8/HEFA fuel blends [7].

These in-situ measurements in cruise conditions have confirmed model predictions [12] and thereby demonstrated that a lower soot particle number emission index reduces the ice crystal number and optical depth of young contrails [13], [14]. Moreover, it was found that the fraction of aircraft soot particles that activates into contrail ice crystals depends on the ambient temperature [15].

Studies that used a contrail lifecycle simulation have shown that a lower soot number density emission index can reduce contrail lifetime and climate forcing [5].

Conclusion

The fuel hydrogen content has been shown to be a better parameter than the fuel aromatic content for correlating the fuel properties with its sooting behavior. As aforementioned, this information is not always available in CoAs. For the sake of a thorough scientific investigation, the hydrogen-content was measured with a nuclear magnetic resonance system (NMR), which is based on the relaxation method as described in ASTM D7171. This approach improved the correlation analysis between the fuel composition and the detected particle emission indices.

Actually, during ECLIF1 the two conventional fuels Ref1 and Ref2 had very similar aromatics- and hydrogen-content yet they displayed slightly different soot emission indices (ground and in-flight). In particular, according to all the correlations known so far, Ref2 with a slightly lower aromatics content (20.2 mass% with respect to 20.5 mass% for Ref1), a slightly higher hydrogen-content (13.73 with respect to 13.67 for Ref1, see Figure 1) should have led to slightly higher soot particle emissions. This was not the case, for ground tests at fuel flow 0.21 kg/s and 0.90 kg/s and for in-flight measurements at maximum range. Ref2 emits less soot particles than Ref1 for certain engine conditions. The main difference between the two fuels that would explain such a behavior is the amount of naphthalenes. Our fuel design study had shown that the effect of aromatics is not linear. A very small difference in the content of double-ring aromatics (naphthalenes) has substantially more impact on soot emissions than a larger difference in single-ring aromatics. The aforementioned strategy is captured in the two blends SAF1 and SAF2, which were blended for ECLIF2.

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