Session 2: Aircraft emissions (Part 2), Talk

Impact of Seasonal Variations on Jet Engine Emissions from a Business Jet Running on Fossil and Sustainable Aviation Fuels

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Characterizing aircraft engine particle emissions is critical for assessing aviation's climate impact. While significant progress has been made in certifying large-thrust engines (>26.7 kN thrust), substantial data gaps remain for non-regulated, smaller engines. Furthermore, while the influences of fuel composition and ambient conditions are known to affect emissions, these factors are rarely quantified for smaller turbofans under varying seasonal conditions.

This study presents emission measurements from a Pilatus PC-24 aircraft equipped with Williams FJ44-4A turbofan engines. Using the Swiss Mobile Aircraft Emission Measurement System (SMARTEMIS), we measured the mass, number, and size distribution of non-volatile particles, as well as organic emissions, both at the engine exit and in the near-field (Figure 1). To isolate the effects of environmental variables and fuel properties, two campaigns were conducted: a "summer campaign" (August 2025) at elevated ambient temperatures and a "winter campaign" (January 2026) at low temperatures. Testing compared standard fossil kerosene against a 30% Hydroprocessed Esters and Fatty Acids (HEFA) blend.

Results indicate that a reduction in fuel aromatic content from 17.5 v% to 11.3 v% (corresponding to a +1 m% increase in hydrogen content), despite a small increase in naphthalene content from 0.57 v% to 1.09 v%, yielded a soot number reduction of up to 60 %. Notably, this reduction efficiency diminished as engine thrust increased. Beyond establishing the emission profile, this study demonstrates the particle reduction potential of small turbofan engines and provides unique empirical data on ambient temperature sensitivity, filling a critical knowledge gap that remains unresolved for larger engine classes.

Figure 1: Setup of the jet engine measurement during the summer campaign.

Session 2: Aircraft emissions (Part 2), Talk

Experimental study on the impact of HVO addition to Jet A-1 on non-volatile particulate matter emissions

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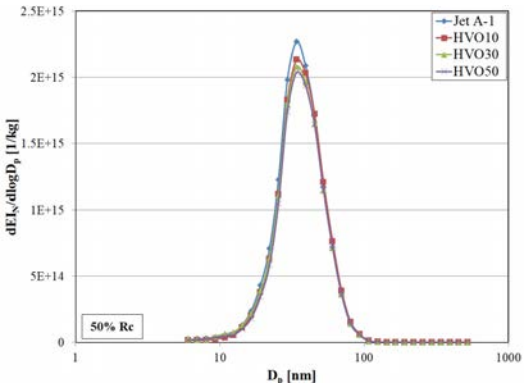
While Sustainable Aviation Fuels (SAFs) have been widely studied regarding their ability to lower particle emissions compared to conventional jet fuels, there is still a need to explore additional options for replacing traditional aviation fuels in the near future.One of the certified SAFs is HEFA-SPK (Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene), derived mostly from used cooking oil, waste and residues [1]. However, the production process is complex and requires advanced technologies, making large-scale implementation in aviation challenging in the short term. Currently, there is also well implanted Hydrotreated Vegetable Oil (HVO) which is dedicated to diesel engines, however the production process and physicochemical parameters are similar to HEFA-SPK. According to other researches, the HVO and HEFA-SPK are often used interchangeably in analyses [2].

This research focuses on analyzing the effect of adding HVO to Jet A-1 fuel and evaluating their impact on PM emissions from a laboratory-scale jet engine. HVO fuel was blended with Jet A-1 at a volumetric ratio of 10% (HVO10), 30% (HVO30) and 50% (HVO50) with the remainder consisting of Jet A-1. Also test were carried out with neat Jet A-1 fuel as a reference fuel. The experiments were conducted using a GTM 400 jet engine under four operational conditions: 10%, 30%, 50%, and 80% of maximum engine power.



For each tested engine operation point, emission indices such as nvPM Number Emission Index [1/kg] and nvPM Mass Emission Index [mg/kg], as well as Particle Size Distribution (PSD) of EI_N [1/kg] and EI_M [mg/kg] were presented. One of the results is that the addition of HVO to Jet A-1 led to a decrease in EI_N at 50% and 80% of the maximum thrust, with the highest value observed for neat Jet A-1 and the lowest for HVO50.

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Session 2: Aircraft emissions (Part 2), Talk

Physical and chemical properties of non-volatile and volatile nanoparticles emitted from turbofan jet engines

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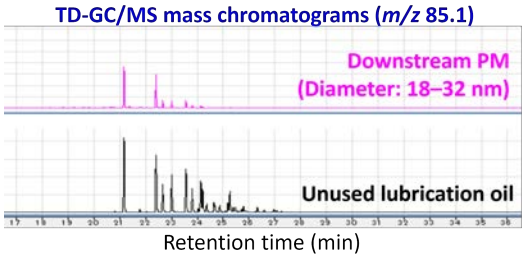
There is worldwide concern about the effects of aircraft exhaust particles on human health and the climate. The particle number concentrations in exhaust plumes of turbofan jet engines, which are commonly used in civil aviation, are generally dominated by volatile particles rather than nonvolatile particles (mostly soot). However, the mechanisms of emission and formation of volatile particles are unclear. We examined the exhaust particles from in-service commercial turbofan engines at the engine exit and 15 m downstream in a test cell at SR Technics, Zurich Airport. The target engines were PW4000 and CFM56. Real-time measurements of particle size distributions and gases (e.g., CO_2) were performed, as well as filter-based sampling, and subsequent high-resolution transmission electron microscopy and chemical analyses (e.g., organic species with thermal desorption gas chromatography/mass spectrometry (TD-GC/MS)). At the engine exit, the turbostratic (soot) particles were dominant, which mostly existed as agglomerates [1]. In downstream samples, the number of soot particles was <1% of the total number of particles analyzed. The remaining fraction predominantly contained trace amorphous, amorphous, and onion-like particles that partially contain graphene-like spherical layers. The microphysical structures of these three types of particles in aircraft exhaust plumes were newly identified. They were mainly single spherical particles with diameters of approximately 10−20 nm, suggesting that they were formed via nucleation and partial pyrolysis and were not significantly affected by coagulation with preexisting soot particles. The organic analysis revealed that the concentrations of lubrication oil markers (i.e., fatty acid esters of pentaerythritol, and tricresyl phosphate) in the bulk particulate samples were much higher downstream than at the engine exit. The results suggest that the hydrocarbons in downstream nanoparticles were mainly composed of lubrication oil (Fig).



This work was supported by the Environment Research and Technology Development Fund (JPMEERF20205004 and JPMEERF20245005) of the Ministry of the Environment, Japan, the Scientific Exchanges Grant of the Swiss National Science Foundation (IZSEZ0_198063), and the Swiss Federal Office of Civil Aviation (FOCA) Projects (AGEAIR SFLV 2017-030 and AGEAIR 2 SFLV 2018-048).

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Session 2: Aircraft emissions (Part 2), Talk

SOURCE FFR: Recent activities within the UFP exposure study in the Frankfurt Rhine-Main region

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Over the past years, the emissions and impacts of ultrafine particles (UFP) have received increased attention, especially in densely populated and urbanized areas close to a widespread highway net and large airports, like the Frankfurt Rhine-Main region. The project SOURCE FFR (*Study On Ultrafine Particles in the Frankfurt Airport Region, https://www.ultrafeinstaub-studie.de/en/*) was commissioned by the Umwelt- und Nachbarschaftshaus (UNH) in order to provide a scientific basis for further discussions. The study is divided into an UFP exposure study presented here and an impact study which started in September 2025.

Since Frankfurt Airport is one prominent source of UFP in the region, two emission measurement campaigns were performed at four different positions on the airport apron. Part of this data was used to obtain real-world emission indices (EI's) by assigning measured exhaust plumes to specific aircraft. These EI's contain emission information of both non-volatile and total particle number concentrations and are used as an input for the dispersion modelling after the clustering of the data according to aircraft engine types.Aside from UFP emissions directly at the airport, a public concern is the potential for the transportation of UFP in the downward direction via the wake vortices generated by aircraft on the glide paths. This question was assessed by performing wake vortex predictions considering wind conditions prevailing in 2019 and the respective traffic mix of Frankfurt Airport. Results indicate only a minor contribution of wake vortices to the ambient particle concentrations close to the airport and no significant influence on the surrounding area.

To characeterize the spatial and temporal distribution of UFP (number size distributions among other parameters) in the study area, immission measurements were carried out at ten locations in both upwind and downwind locations, considering the most prevalent wind directions. While particle sizes in some cases allow for conclusions to be drawn on UFP sources, further information is needed for a clear source apportionment. Taking advantage of the characteristic compounds present in aircraft engine oils, comprehensive chemical analyses facilitated the identification of aircraft-related emissions despite the manifold UFP sources in the area (e.g. ground traffic, industry, domestic fuel etc.). The quantification of these engine oils in particle filter samples provides valueable insight into the distribution and dispersion of the emissions within the studied area.

The dispersion modelling aims for an accurate and detailed description of air qualitiy parameters in both time and space. It relies on both emission measurement results provided by the project consortium and emission data of third-party providers as input parameters. Results of the aforementioned immission measurements serve as a validation target to investigate the quality of the model output. This presentation aims to give an overview on the project by showing selected results (emission measurements, vortex modelling, chemical characterisation).

Session 2: Aircraft emissions (Part 2), Talk

A "2nd" (> 150 nm) Size Mode in Aircraft Gas Turbine Engine Exhaust, New Analysis

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We have been pursuing this project for several years, and last year we reported our progress at the 28th ETH-Nanoparticles Conference. That presentation focused on detailed experimental observations but did not yet offer a theoretical interpretation. In this presentation, we introduce new analyses that provide fresh insight into the mechanisms responsible for the formation of the second mode.

Piston-engine exhaust particle size distributions (PSD) typically exhibit three modes: a 3-30 nm nucleation mode of semi-volatile material, a 30-300 nm soot mode of carbonaceous aggregates, and a coarse mode of larger mechanically generated particles from oil atomization and surface re-entrainment. Measuring PSDs from commercial aircraft gas-turbine engines is much more challenging than with piston engines due to more extreme conditions: exhaust temperatures up to 900 °C, near-Mach-1 velocities. The long sampling lines required suppress nucleation-mode formation. Turbine-engine soot aggregates are smaller (15-50 nm GMD), and coarse particles were not expected given limited exhaust–surface interactions and the absence of piston rings. Nevertheless, under some conditions—particularly at low soot concentrations—we observed a distinct "2nd mode" of particles larger than ~150 nm. Daily zero checks and step-change tests showed no evidence that these particles were due to sampling-system particle shedding.

These results were obtained during the EPA/USAF VARIAnT 1–4 measurement campaigns, designed to refine methods for quantifying non-volatile aircraft-engine particles. The findings reported here draw on VARIAnT 3 and 4, using a GE J-85 turbojet and Libby Welding GT-05 and LGT-60 turbine start carts operated across a range of conditions and fuels. Particle size, concentration, and composition were measured with multiple instruments.

PSD measurements employed SMPS, EEPS, and DMS500 systems, supplemented by Aerodyne CAPS PMSSA extinction/scattering measurements in both campaigns and miniSPLAT single-particle mass spectrometry in VARIAnT 4. The 2nd mode was quantified using volume above 150 nm (V150) and a bimodal lognormal fit of soot mode and 2nd mode. V150 and the fitted volume in the 2nd mode, V_{2nd}, were well correlated. With the J□85, V_{2nd}/V_{total} ratios approached 50% in some tests and generally decreased with increasing engine load and total mass emissions. The mode was far more pronounced for the J-85 than for the start carts.

Its formation also coincided with increased single□scattering albedo and the appearance of particles with distinct compositions and morphologies in the miniSPLAT data.

Session 2: Aircraft emissions (Part 2), Talk

Characterizing Aviation Contributions to Particulate Matter near Zurich Airport using Chemical Composition and Source Apportionment

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Aircraft emissions are a major source of particulate matter (PM) and ultrafine particles (UFP) during takeoff, landing, taxiing, and idling, degrading air quality near airports. With global air traffic projected to grow by ~4.2% annually and potentially doubling by 2040 (IATA, 2023a), aviation-related PM represents an increasing public health concern due to its links to respiratory and cardiovascular effects. Airport emissions contribute to both primary and secondary PM and can influence air quality well beyond airport boundaries, with impacts observed up to 18 km downwind (Hudda et al., 2012). Within the APPROPRIATE project, a month-long field campaign was conducted in fall 2022 at a downwind site ~1 km east of Zürich Airport, using LToF-AMS and EESI-LToF to characterize real-world aircraft emissions. PMF analysis of LToF-AMS data resolved nine PM□.□ factors (Figure 1), including two oxygenated organic aerosol (OOA) factors, primary combustion-related components (HOA and COA), two biomass burning factors, a nitrogen-containing organic aerosol (NOA), an organic nitrogen–rich factor, and an event-related factor. Compared to the seven factors resolved by Lu et al. (2019, ACP), two additional factors were identified: one showing strong correlations with aircraft lubrication oil markers (Yu et al., 2012), indicating a distinct primary aviation-related organic aerosol source, and another dominated by organonitrates. The event-related factor contributed 46.8% during the first campaign week (28 October–3 November) and 14.4% over the full sampling period. Ongoing integration of complementary molecular- and gas-phase measurements will further refine source attribution and improve separation of airport emissions from other anthropogenic and biogenic influences.

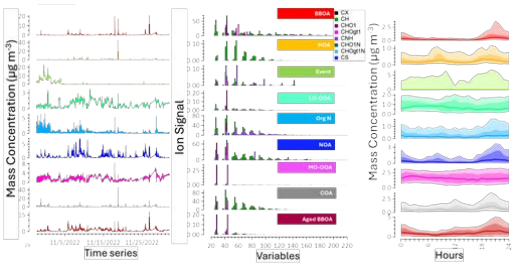

Figure 1. Factor solution for 2022 campaign with factor time series, factor profiles and diurnal variation

This work was supported by the Swiss Federal Office of Civil Aviation (SFLV 2020-080). We acknowledge the support from ZHAW, EMPA, Frithjof Siegerist (SRTechnics), and the City of Kloten.

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