Emission characteristics of alternative drive technologies regarding type and number of condensation nuclei for contrail formation

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Abstract Aviation remains one of the most challenging sectors to decarbonize, not only because of its reliance on liquid hydrocarbon fuels but also due to its substantial non-CO_2 effects, especially contrails. Understanding how contrails form under alternative propulsion and fuel technologies is therefore of major scientific and policy interest.

This study systematically compares contrail formation from hydrogen combustion, sustainable Aviation Fuel (SAF), and conventional kerosene, drawing on experimental campaigns and advanced modeling. Contrail ice crystal number emissions are evaluated across pathways, providing quantitative ranges and highlighting the large uncertainties involved. Results show that hydrogen combustion generally produces fewer ice crystals than kerosene or SAF, but nucleation regimes strongly influence the outcomes. SAFs do not consistently reduce soot emissions or contrail ice crystal numbers across blends, though synthetic fuels with optimized composition and lean-burn combustors hold potential for improvement. Fuel cells, on the other hand, avoid particle emissions altogether.

The findings underline that contrail impacts depend not only on fuel type, but also on combustion processes, atmospheric conditions, and nucleation pathways. For policy and technology roadmaps, this means neither SAF nor hydrogen can yet be assumed to mitigate contrail forcing without targeted optimization and further field data.

1 Introduction

Contrails form in cold, humid upper-troposphere layers (8–13 km) and contribute significantly to aviation's non-CO_2 climate effects. Fuel choice strongly affects particle emissions and contrail microphysics. Hydrogen propulsion, via combustion or fuel cells, eliminates CO_2, but its impact on contrails remains uncertain. SAFs generally emit fewer soot particles than kerosene, yet variability in measurements leaves their effect on ice crystal numbers unclear.

The present study investigates how hydrogen and SAF combustion influence contrail formation, testing whether hydrogen produces effective condensation nuclei, SAFs reduce soot emissions, and hydrogen contrails contain fewer ice crystals. Combining theory, emission data, and modeling, the work assesses alternative aviation technologies for contrail climate mitigation.

2 Alternative Propulsion and Fuel Pathways

SAFs, defined by International Civil Aviation Organization (ICAO) as aviation fuels from renewable resources or waste, must meet sustainability criteria under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and, in the EU, under the Renewable Energy – Recast to 2030 (RED II) [1]. Drop-in SAFs meet kerosene quality standards without infrastructure or engine modifications. The American Society for Testing and Materials (ASTM) D1655 specifies Jet A-1, while D4054 evaluates SAF equivalence. Approved fuels are added to D7566 [2].

Eight SAF pathways are certified under D7566. Feedstocks include vegetable oils, animal fats, waste, and lignocellulosic biomass, converted via certified pathways. Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) (up to 50 % blend) uses biomass gasification and Fischer-Tropsch synthesis [1]. Hydroprocessed Esters and Fatty Acids-Synthetic Paraffinic Kerosene (HEFA-SPK) derives from lipid-rich biomass via hydrotreating [1]. Other certified routes include HFS-SIP (fermented sugars, max. 10%), FT-SPK/A (with aromatics), Alcohol-To-Jet (ATJ-SPK), Catalytic Hydrothermolysis (CHJ), HC-HEFA-SPK (microalgae-based), and ATJ-SPK/A [5]. Some processes still use fossil feedstocks, affecting soot emissions. Synthetic Power-to-Liquid (PtL) fuels produce kerosene from renewable electricity, water, and CO_2 via Fischer-Tropsch. Hydrogen is supplied by electrolysis and CO_2 from point sources or Direct Air Capture (DAC) [5].

Hydrogen propulsion includes direct combustion in turbines or fuel cells. Combustion is fast and clean, but requires modified combustors and cryogenic storage due to lower energy density (0.25 % of kerosene) [6]. Fuel cells generate electricity from hydrogen and oxygen, producing only water, but face production and infrastructure challenges [6].

The Commercial Aviation Alternative Fuels Initiative (CAAFI) introduced the Fuel Readyness Level (FRL) to complement TRL, capturing certification and market readiness [3]. Among SAFs, FT-SPK and HEFA-SPK are most mature (TRL/FRL 9), while HC-HEFA, SIP, ATJ-SPK, CHJ, and PtL (DAC-based) are at TRL/FRL 5-7 [4]. Hydrogen direct combustion is TRL 3-4, and fuel cells TRL 6-7, with prototype flights demonstrating feasibility [7].

3 Condensation Nuclei for Contrail Formation

3.1 Requirements for Contrail Formation

Contrail formation occurs when hot exhaust gases mix with cold ambient air, cool rapidly, and exceed water saturation. Water vapor condenses on aerosol particles, droplets freeze, and contrails form if the Schmidt-Appleman Criterion (SAC) is met [6]. In ice-supersaturated air, they may persist and evolve into cirrus.

Condensation requires nucleation, either homogeneous (spontaneous freezing at $T < -38°\text{C}$, typically from soluble aerosols) or heterogeneous on Ice Nucleating Particles (INP). INPs are aerosol particles that lower the energy barrier for freezing and originate from natural and anthropogenic sources (e.g., sea salt, dust, sulfates, soot) [6]. Soot, emitted from incomplete combustion, is the dominant INP, with activity influenced by morphology, surface defects, and coatings (e.g., SO_2, NH_3) [6]. At cruise altitudes, where natural INPs are scarce, contrail formation depends largely on emitted soot, whose efficiency varies [11]. Emission and Climate Impact of Alternative Fuels (ECLIF) measurements confirm that soot is re-emitted after ice sublimation, supporting its role as the primary INP in contrail formation [11].

3.2 Ice Nucleation Particles from SAF Combustion

If SAF is derived from fossil carbon, its exhaust contains non-volatile Particulate Matter (nvPM) that serve as condensation nuclei. Combustion of SAF generally produces fewer soot particles (N_{soot}) than Jet A-1, reflecting its higher H/C ratio [12]. Aircraft-based measurements typically report lower N_{soot} than ground tests, likely because ground facilities cannot fully replicate cruise conditions (pressure, temperature, air–fuel ratio). Even flight tests remain uncertain, as higher thrust and fuel flow during operation may enhance soot production.

Results from ECLIF III show that N_{soot} decreases with increasing combustor inlet temperature (T_3) and fuel flow for both Jet A-1 and HEFA-SPK, though less pronounced for the latter [12], in agreement with ECLIF2/ND-MAX. In contrast, Civil Aviation Alternate Fuel Contrail and Emissions Research (CAAFCER) reported higher N_{soot} for certain SAF blends, attributed to differences in engine type, condition, or age [14]. A summary of these results is provided in Figure 1 (left).

The wide variability in soot properties (e.g. density, particle size) complicates quantification of emitted particle numbers. For contrail formation and radiative impact, however, the number of ice crystals (N_{ice}) is decisive under given meteorological conditions [15]. Since soot particles and water vapour may act jointly or independently as INPs, alongside background aerosols, recent measurements of particle emissions from alternative fuels provide valuable constraints on expected N_{ice}.

Ground tests by Lobo et al. with a CFM56-7B engine showed total Particulate Matter (PM) reductions of $34 \pm 7\,\%$ for $50\,\%$ and $52 \pm 7\,\%$ for $100\,\%$ Fischer–Tropsch blends, strongest at idle and weakest at full thrust [16]. ECLIF I flight tests (A320, V2527-A5 engines) reported 50–60 % reductions at low thrust and about 30 % at take-off for 14–45 % Fischer–Tropsch blends relative to Jet A-1 [17].

Across studies, SAF combustion generally yields fewer nvPM than Jet A-1, though results

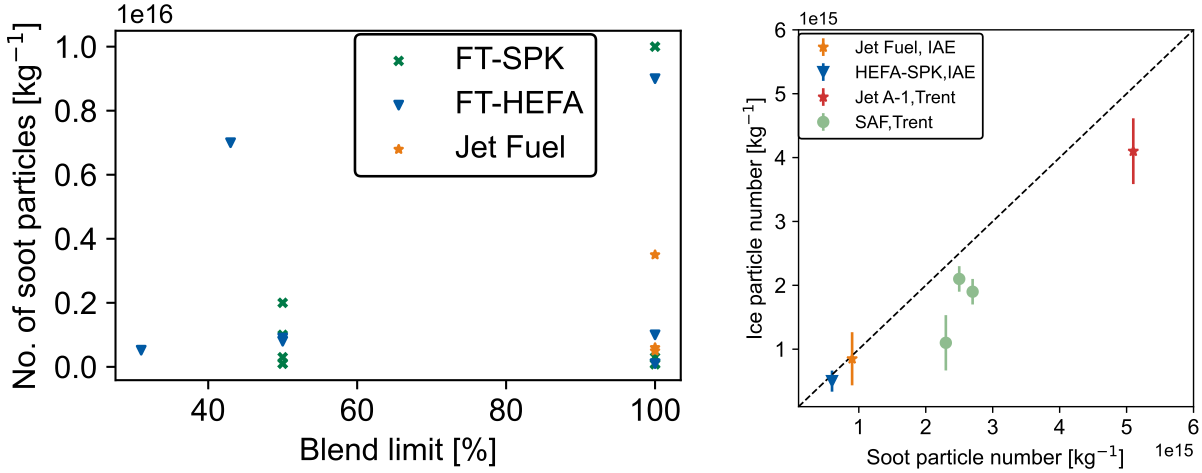

Figure 1: *Left: Measurements of* N_{soot} *(on the ground and during the flight) from various measurement campaigns [12, 14, 18, 22] as a function of the SAF blending. Right: Correlation between* N_{soot} *and* N_{ice}*. Comparison of Jet A-1 and HEFA-SPK from the ECLIF III-1 project using a Rolls-Royce Trent XWB-84 engine, with fuels investigated during ECLIF I and ECLIF II/ND-MAX employing an IAE V2527 engine. Values adapted from [22].*

differ between ground and in-flight measurements. Aircraft-mounted data usually show lower N_{soot} since ground facilities cannot fully replicate cruise conditions (pressure, temperature, air–fuel ratio, thrust) [18]. Even flight tests remain uncertain due to varying payload and operating regimes.

ECLIF III confirmed decreasing nvPM with rising combustor inlet temperature (T_3) and fuel flow for both Jet A-1 and HEFA-SPK, with a weaker response for HEFA-SPK [12], consistent with ECLIF2/ND-MAX [12]. Conversely, CAAFCER observed higher nvPM for certain SAF blends, attributed to engine characteristics rather than fuel composition [14].

In summary, SAFs typically reduce soot number emissions, yet values remain within 10^{14}-10^{15} kg^{-1} fuel for both Jet A-1 and SAF, indicating that substantial reductions in soot and contrail ice crystal numbers through SAF use are not yet confirmed.

3.3 Ice Nucleation Particles from Hydrogen Combustion and Fuel Cell Exhaust

Hydrogen combustion primarily emits water vapor, forming a moister exhaust than kerosene but without direct CO_2 or soot emissions [8, 9]. High flame temperatures can generate NO_x, metals, and metal oxides acting as ice-nucleating particles (INPs), while Ultrafine Volatile Particle (UFP)s from nitrogen compounds or oil vapors may also form, though their role in ice nucleation remains uncertain [8, 9].

Hydrogen fuel-cell propulsion emits only water vapor. At strong supersaturation, numerous small droplets may freeze rapidly, producing high ice particle numbers N_{ice} [6]. As hydrogen systems emit neither soot nor metals, ice formation likely occurs via activation of background aerosols or homogeneous nucleation [6, 9, 19, 20].

Background aerosols from dust, soot, and organics vary in abundance and composition [9], their INP activity and effect on contrails remain uncertain. Overall, the assumption that H_2 combustion emits no INPs is only partly valid, since small amounts of NO_x, metals, or UFPs may still form, whereas fuel-cell systems emit solely water vapor.

Formed ice particle numbers depend nonlinearly on ambient aerosol load and temperature, increasing with colder conditions [20]. Regional aerosol sources further modulate INP levels. Mineral dust dominates in arid regions, organic INPs in tropical zones [23]. Model estimates span wide ranges of $N_{\mathrm{INP}} = 10^9$-$10^{14}\,\mathrm{m}^{-1}$, depending on assumptions for $E_{\mathrm{I,H2O}}$ and fuel flow [9, 19, 20, 23].

3.4 Correlation Between Soot Particles and Ice Crystals

The relationship between emitted soot particles and apparent ice crystals determines contrail properties relevant to lifetime and radiative impact. N_{ice} scales linearly with N_{soot} in soot-rich regimes, with ultrafine background particles contributing little. The nucleation efficiency is $\sim 96\,\%$ [21].

Figure 1 (right) shows N_{ice} and N_{soot} per kilogram of fuel from ECLIF I (SSF1: 41 % FT-SPK), ECLIF II (SAF1: 49 % HEFA-SPK; SAF2: 30 % HEFA-SPK), and ECLIF III-1 (100 % HEFA-SPK). "Apparent" denotes ice crystals not directly emitted. Only data with relative humidity over ice $> 100\,\%$ are included. A quasi-linear N_{soot}-N_{ice} relationship is observed, supporting the theory. ECLIF III shows lower soot and N_{ice} than ECLIF I/II due to the XWB-84 engine. Jet A-1 exhibits reduced soot and N_{ice} versus SAF blends, and HEFA-SPK produces the lowest apparent N_{ice} [12, 22].

Fuel composition alone does not control the emissions. Engine type, combustion parameters, and ambient conditions strongly influence N_{ice} [22]. ACCESS II observed 10-100 % of soot acting as INPs, ECLIF III 80-100 %. Reduced sulfur in SAF may suppress activation, lowering N_{ice} more than soot [22]. Ice formation correlates with soot mainly at low temperatures and high supersaturation [19].

4 Summary, Conclusion and Outlook

This study evaluated alternative aviation fuels and propulsion systems regarding emissions and contrail formation based on a review of existing studies. SAFs (bio-based or synthetic) and hydrogen systems (combustion or fuel-cell) were compared by maturity, payload, range, and cruise conditions.

SAF combustion emits similar species to kerosene but with modified emission indices. Soot particles act as primary ice-nucleating particles, producing $N_{\mathrm{ice}} \sim 10^{14}$–$10^{15}\,\mathrm{kg}^{-1}$. Hydrogen combustion mainly emits water vapor, ice formation depends on mechanism. Nucleation on ambient aerosols yields $N_{\mathrm{ice}} \sim 10^9$-$10^{10}\,\mathrm{kg}^{-1}$ with short-lived, large crystals, while homogeneous nucleation can produce $N_{\mathrm{ice}} \sim 10^{14}\,\mathrm{kg}^{-1}$ with lower density. Fuel cells emit only water vapor. Most SAFs are fossil-derived, so soot emissions remain kerosene-like, and ambient aerosols often replace soot as condensation nuclei, limiting contrail-lifetime reductions. Future work should quantify emissions under cruise conditions, characterize INP properties, refine microphysical contrail models, and optimize SAF composition and engine technologies to reduce non-CO_2 climate impacts.

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