Impact of Hydrogen in Aviation

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Introduction

Aviation accounts for about 4% of the total anthropogenic effective radiative forcing (ERF), resulting from aircraft operations since the 1940s. Thereby more than half of the aviation induced ERF is very likely caused by non-CO_2 effects, such as contrails and NO_x emissions. One measure to potentially reduce both CO_2 and non-CO_2 effects from aviation is the use of green hydrogen. Different applications of hydrogen such as direct burn or the use of hydrogen in fuel cells for electric propulsion are developed by the aviation industry, with the promise to decarbonize aviation. Still, the impact of the non-CO_2 effects on climate from these propulsion systems is unquantified as direct measurements were missing until recently and model capabilities need to be enhanced. DLR in collaboration with industry and academic partners investigates the effects of hydrogen on the formation of contrails and NO_x emissions and their effect on climate in internally and industry funded projects as well as using funding by German and European funding sources. These research activities are flanked by emission and contrail measurements from new lean burn technologies which provide a reference of current technologies for the low-soot regime. As the industry is transitioning to the use of hydrogen, projects on the impact of hydrogen leakages and their effect on climate forcing agents have also been launched.

Past Achievements

The goals of the Paris Agreement are not achievable without major changes in the Aviation system, such as a shift to hydrogen, extensive use of SAF and a combination of technological and operational measures. Past studies have focused on specific aircraft concepts (e.g. the multifuel blended wingbody) and simplified models to assess the climate impact of contrails and NO_x emissions from the use of hydrogen in aviation. Past work of DLR and partners has shed light on the impacts of SAF on non-CO_2 effects combining measurements, process modelling and global climate models. This unique understanding is the basis on which the capabilities for current assessments of hydrogen combustion and fuel cell technologies on non-CO_2 effects are built upon. A suite of world-wide unique airborne in-situ measurements together with process and climate modelling provide the means to improve our understanding of contrails and contrail cirrus from current and new technologies and enable the evaluation of mitigation options.

Scientific background

The emissions of hydrogen combustion are comprised of NO_x and water vapor and for fuel cells of water vapor and possibly water in liquid form. Water vapor emissions from aircraft mostly contribute through the formation of contrails to the aviation climate impact. Water vapor emissions of high flying super- and hypersonic aircraft however are a large contributor to their respective climate impact. Depending on the flight altitude of hydrogen propelled aircraft, the effect of water emissions on climate could be enhanced.

Due to the fundamentally different formation process of contrails from hydrogen combustion and fuel cells may differ substantially to contrails from conventional fuels. While ice crystals in conventional contrails form on emitted soot or volatile particulates, it is unclear whether hydrogen combustion or fuel cell exhausts contain initially any particles. One possible scenario is that ice crystal formation occurs predominantly on ambient aerosols entrained into the humid plume. These aerosols may be the nuclei for

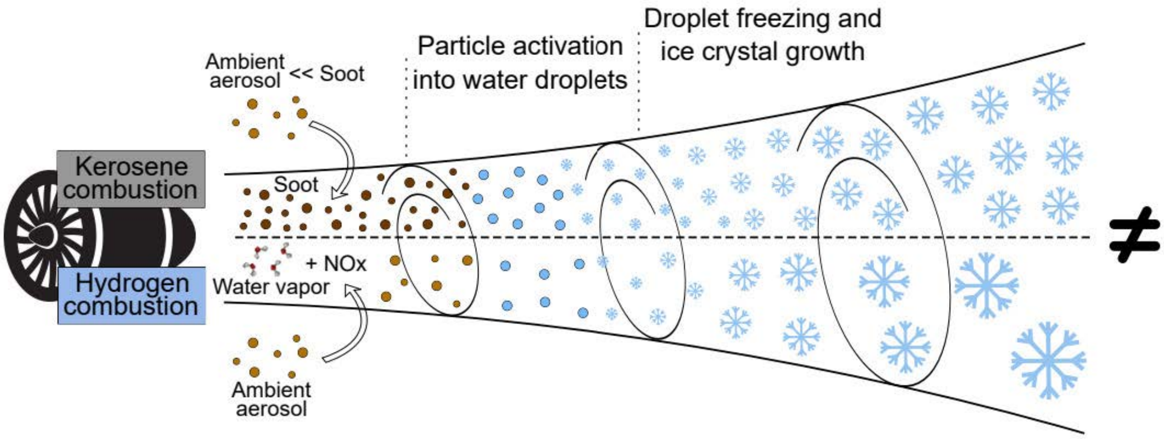

FIGURE 1: Conceptual picture of the formation pathway of contrails from hydrogen combustion in contrast to conventional kerosene-based contrails. Contrails from hydrogen combustion offer the possibility to have larger and less particles which reduce the lifetime of the contrail (Diss De la Torre Castro).

contrail ice particles. The resulting reduction in initial ice crystal number decreases the lifetime of contrail-cirrus and on global scale their radiative forcing. Furthermore, the higher emission index of water vapor shifts the contrail formation altitude to higher temperatures. Projects at DLR aim at measuring and modelling the formation pathways of contrails from hydrogen combustion and fuel cells as well as lean burn and supersonic aircraft (Figure 1).

Benefits of the project

DLR has substantially enhanced the modelling and measurement capabilities of contrails from hydrogen propulsion.

New and smaller instruments operating autonomously were installed on different airborne platforms for the detection of aerosol particles, trace gases and ice crystals from hydrogen combustion and fuel cells. Particularly, in the Blue Condor project, Airbus and DLR partnered to provide first measurements of contrails from a small hydrogen combustion engine installed on a glider operated at contrail formation altitude. Supporting box models were developed and provided a theoretical framework, showing that the initial ice number could be reduced by 80 to 90% in the absence of contaminations like lubrication oil. Oil entering through leakages into the hot exhaust may form small oil droplets. Box model simulations suggest that oil particles could be the dominant nuclei when soot particle numbers are low (low-soot regime) or zero (e.g., for hydrogen combustion). The design of the fuel cell system allows to modify the heat and water vapor emission. These additional degrees of freedom can affect the initial contrail formation process and ultimately also the contrail climate impact. First experiments of ice crystal measurements from a bulk liquid water release system show a large reduction of the initial ice crystal number compared to conventional contrails. Final conclusions on the contrail composition can only be drawn with measurements of representative exhaust conditions. Large eddy simulations for different atmospheric conditions were performed to understand H_2 contrail formation for a large parameter space. Based on this data set, parametrizations of early contrail properties are developed and integrated into a global climate model that computes the radiative response to the contrail cirrus properties. Based on climate model simulations, surrogate models like AirClim will assess the combined impact of non-CO_2 effects on surface temperature. On a fleet level, these assessments will be compared to corresponding simulations for current and future technologies with conventional and sustainable low-aromatic aviation fuels.

With the combination of measurements and model chains, DLR is targeting a holistic, evidence-based climate impact assessment of hydrogen propulsion aircraft (Figure 2). This work supports legislative aviation authorities and industrial stakeholders for investment decisions into a climate neutral aviation sector.

FIGURE 2: (upper panel) Picture of the Blue Condor glider equipped with a hydrogen engine (front) and a kerosene engine (back) both forming contrails of different optical thickness (Rogero et al., 2024; https://www.dlr.de/en/latest/news/2025/world-first-in-flight-measurements-of-contrails-from-hydrogen-propulsion). (lower panel) Picture taken from the instrumented chase aircraft Egrett during contrail and emission measurement of a turbo prop aircraft equipped with a water release system simulating fuel cell emissions (Neumann et al., 2025).

Future Directions

In the future, DLR will be focusing on three areas to improve our understanding of emissions and contrails:

1. Emissions and formation pathways of contrails and clouds from hydrogen propulsion but also from RQL and lean burn technologies, in particular the impact of lubrication oil and ions on contrail formation.
2. Quantification of emissions and contrail properties through airborne and ground-based measurements.
3. Modelling of local and global contrail radiative effects for different technologies and different fuel types in the low-soot regime.

DLR is actively involved in or leads different projects to address these challenges. Specifically, DLR is coordinator of the Horizon Europe project A4CLIMATE with 18 partners to investigate the effect of contrail formation in the low-soot regime. DLR also leads campaigns investigating aircraft effects on high and low clouds. While not representative for hydrogen propulsion emissions, these investigations will still enhance our understanding on the effects of sulfur and soot emissions from current aircraft on clouds, to reduce their climate impact uncertainty.

DLR is active in a national funded project where contrail formation and properties of hydrogen propulsion systems are emulated in a German high-altitude test facility. This will enable contrail measurements in a controlled environment, with a large flexibility on emission parameters and thermodynamical properties and allows to better validate contrail formation models. Further, DLR and partners investigate the effect of particulate emissions like oil and ions on contrail formation in engine test rig environments. Airborne flight test programs will focus on emission measurements with enhanced capabilities in ion measurements as well as ultra-fine particles. Furthermore, long term goals are the miniaturization of instruments for installation on different chase aircraft to measure emissions and contrails from demonstrators in flight. On the modelling side, the application of machine learning methods will be expanded.

Conclusion

Hydrogen propelled aircraft offer the possibility to decarbonize aviation. First important steps to constrain estimates of the non-CO_2 effects of these technologies, in particular the formation of contrails, have been made. Since the use of hydrogen will require large aircraft modifications, the impact on the environment has to be integrated into the engine and aircraft design to avoid counteracting contrail effects to the gain from mitigated CO_2 emissions. The impacts of hydrogen propulsion on climate are currently explored within DLR in order to advise aircraft and engine manufacturers on mitigation strategies. This advice is given on a science-based framework combining measurements with high-resolution and global modelling. Next to global simulations on the contrail climate impact exploring a wide parameter space of fuel cell and hydrogen combustion exhaust conditions, future work will focus on emission and contrail measurements to assess their actual climate impact.

vSimilarly, current technologies like lean burn engines offer a massive soot reduction but depend on the additional reduction of volatile particle emissions to substantially reduce contrail ice particle number and the respective climate impact (Figure 3). Further strategic and systematic fundamental research in collaboration of academia and industry is required to pave the way for future competitive climate compatible aviation.

FIGURE 3: Foto taken from the cockpit of the DLR research aircraft Falcon chasing an Airbus A320neo in 50 m distance to probe the emissions from its CFM LEAP-1A engines during the NEOFUELS/VOLCAN project coordinated by Airbus and DLR (Voigt et al., 2025 submitted; https://www.dlr.de/de/medien/videos/2023/video-projekt-volcan)

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