

# ***Analysis on the Impact of Different Fuels on Aircraft Contrails and the Environment***

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**Abstract:** Aircraft contrails significantly impact the environment, primarily because they emit gases such as carbon dioxide and nitrogen oxides. These contrails are a type of 'cirrus cloud,' composed of young linear condensation trails and older, irregularly shaped trails that they produce. As contrails form, the byproducts of fuel combustion, such as carbon dioxide, linger in the air for a long time, altering the concentration of carbon dioxide in the atmosphere and causing the atmospheric temperature to rise. Different fuels produce different gases when burned, some of which may be harmful to the environment. In this article, this paper will summarize articles on how different fuels affect contrails and the environment. The results show that different fuels produce different gases when burned, some of which are harmful to the environment, while others are not. Traditional fuels like jet fuel generate carbon dioxide and water vapor, whereas new energy sources like hydrogen do not produce carbon dioxide. Different fuel types primarily influence aircraft contrails through their combustion products and efficiency. Aviation kerosene, as the mainstream fuel, produces water vapor that easily forms contrails under high-altitude, low-temperature conditions. In contrast, biofuels or alternative fuels, due to differences in their chemical composition, may produce less water vapor or other gases that affect contrail formation during combustion.

**Keywords:** contrail, jet fuel, new energy fuel, condensation, environment.

## **1. Introduction**

With the advancement of transportation networks, the consequent environmental footprint expands. Emissions from vehicles—airplanes, trains, and cars—release gases like carbon dioxide (CO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>) into the atmosphere. The number of airports has surged in urban landscapes, making airplanes more common in daily life. Offering greater convenience at the cost of increased environmental strain. The contrails left by aircraft are rich in CO<sub>2</sub> and water vapor, with CO<sub>2</sub> being a significant greenhouse gas that warms the atmosphere. To achieve the Net Zero target, there has been a shift towards cleaner energy sources, including biofuels and hydrogen. This article includes the effects of these alternative fuels on both the formation of aircraft contrails and their subsequent environmental implications.

In this article, this study will discuss the following three issues. The first one is the relationship between contrails and environmental impact, research methods, etc. Second, the impact of traditional aviation fuel on aircraft contrails and the environment. Lastly, the impact of new energy fuels on aircraft contrails and the environment in the field of aviation. By reading and summarizing a large

number of different pieces of literature, it can be more clearly studied whether the combustion of different types of fuels has adverse effects on contrails and the environment. As the earth warms and extreme climates intensify, humans are increasingly concerned about the impact of human activities on the environment. As one of the main sources of greenhouse gas emissions, the aviation industry has always attracted the attention of many scholars. This review aims to explore the potential impact of different fuel types on the formation of aircraft contrails and the atmospheric environment, analyze the environmental benefits of existing and emerging fuel technologies, and assess their role in achieving the global net-zero emission target. Through an interdisciplinary research perspective, this paper provides a scientific basis for the sustainable development of the aviation industry. In addition, this review also looks forward to future research directions, aiming to promote technological innovation and jointly address the environmental challenges faced by the aviation industry.

## 2. Analysis of the Impacts

The impact of contrails on the environment can be primarily divided into two categories: global warming and cirrus cloud formation. Firstly, the pollutants in contrails, such as carbon dioxide (CO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>), contribute to climate change. These pollutants absorb more energy than they radiate back into space, leading to the warming of the Earth's atmosphere. Secondly, contrails are line-shaped clouds formed by the exhaust of aircraft engines, which can last from a few seconds to several hours depending on temperature and humidity variations.

The chemistry equation is:  $Fuel + Air \rightarrow nH_2O + nCO_2$  (1)

The vapour density in the jet exhaust:  $\rho_0 = n_{H_2O} \cdot \frac{M_{H_2O}}{M_{fuel}} \cdot \frac{F_T}{\lambda E_C} \cdot \frac{1}{\pi R^2 v}$  (2)

The saturation curve is described by:  $\rho_s = \frac{e_0 M_{H_2O}}{R_{ideal} T} \exp\left(\frac{L}{R_v} \left(\frac{1}{273.15K} - \frac{1}{T}\right)\right)$  (3)

$R_v=461 JK^{-1}kg^{-1}$ , is the water-vapor gas constant,  $e_0=611 JK^{-1}kg^{-1}$ ,  $R_{ideal}=8.3 J/Kmol$

Conservation of vapour mass:  $\bar{\rho} = \left(\frac{R_0}{R}\right)^2 \rho_0 + \left(1 - \left(\frac{R_0}{R}\right)^2\right) \rho_a$  (4)

Conservation of thermal energy (through enthalpy):  $\bar{T} = \left(\frac{R_0}{R}\right)^2 T_0 + \left(1 - \left(\frac{R_0}{R}\right)^2\right) T_a$  (5)

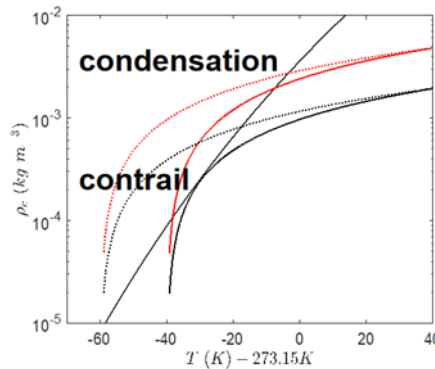


Figure 1: The Impact of Temperature and density of moisture on Condensation Processes and the Temperature Range for Contrail Formation

As is shown in Figure 1 that condensation forms above the line, while below it is just water vapor. When the initial density of moisture is the same, taking the two red lines as an example, within the atmospheric temperature range of  $-40$  to  $-60$  degrees, the lower the temperature, the more likely condensation is to occur. Under the same temperature, taking the two solid lines as an example, the higher the density of moisture, the more likely condensation is to form.

Contrails increase both cloud cover and carbon dioxide emissions. Solar radiation from the sun enters the atmosphere, and infrared radiation exits as heat. If the Earth receives more radiation than leaves, the atmosphere will warm, which is what is happening today. Radiative forcing, which is caused by a perturbation in the concentration of a gas, is defined by the net radiative flux change induced at the tropopause. This forcing is typically interpreted as a gain (positive) or a loss (negative) for the surface-troposphere system as a whole. Due to radiative forcing, the temperature of the Earth's atmosphere will rise [1].

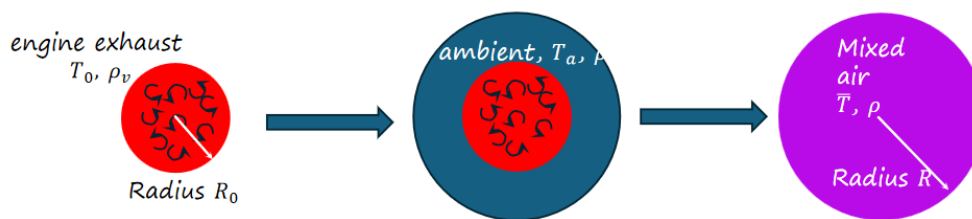


Figure 2: The process of hot air being emitted from the engine.

Figure 2 presents the hot air inside the engine expands, increasing its radius and coming into contact with the cooler surrounding air. The mixing of these air masses leads to condensation, which in turn forms contrails.

The impact of jet fuel on contrails and the environment is primarily manifested in the emissions of carbon dioxide and nitrogen oxides, as well as the formation of soot particles and ice crystals. The traditional Jet A-1 fuel used by aircraft produces pollutants such as carbon dioxide ( $\text{CO}_2$ ) and nitrogen oxides ( $\text{NO}_x$ ) during combustion. These substances contribute to climate change, as they absorb more heat than they radiate back into space, leading to the warming of the Earth's atmosphere. Michael J. Ring used two independent methods to analyze the temperature measurements: Singular Spectrum Analysis and Climate Model Simulation. The two approaches, which used an additional 13 years of temperature measurements from 1998 to 2010, came to the same conclusion: humans, not nature, are responsible for the rise in Earth's global temperatures since the 19th century [2]. In addition to carbon dioxide emissions, the use of conventional fuels also leads to other non- $\text{CO}_2$  effects, such as the formation of soot particles and ice crystals, which also impact the climate. Other gases cannot be ignored either, and ignoring them would make it more difficult to limit global warming. Their inclusion greatly reduces the cost of meeting an overall target [3]. Furthermore, ice clouds play an important role in the climate system. Ice clouds reflect solar radiation back into space, cooling the Earth. However, due to their coldness, ice clouds emit much less longwave radiation into space than low clouds or the surface, which can also lead to the warming of the Earth. The balance of these two processes determines the net ice cloud radiative forcing, which strikes a delicate balance between warming and cooling, with warming being considered slightly greater [4].

Figure 3 reveals that jet fuel, biofuel, and hydrogen fuel are three types of fuels that form contrails with some differences. Jet fuel, the traditional aviation kerosene, produces pollutants, including carbon dioxide ( $\text{CO}_2$ ) and water vapor ( $\text{H}_2\text{O}$ ), when burned, which contribute to the formation of contrails. Due to the presence of these pollutants, traditional aviation kerosene has a direct impact on climate change. Aircraft emissions vary depending on the type of engine, engine load, and fuel. In jet

aircraft, there are differences between civil and military jet engines and their fuels. The combustion of jet fuel produces CO, H, O, CO, C, NO, particles, and a large number of organic compounds [5].

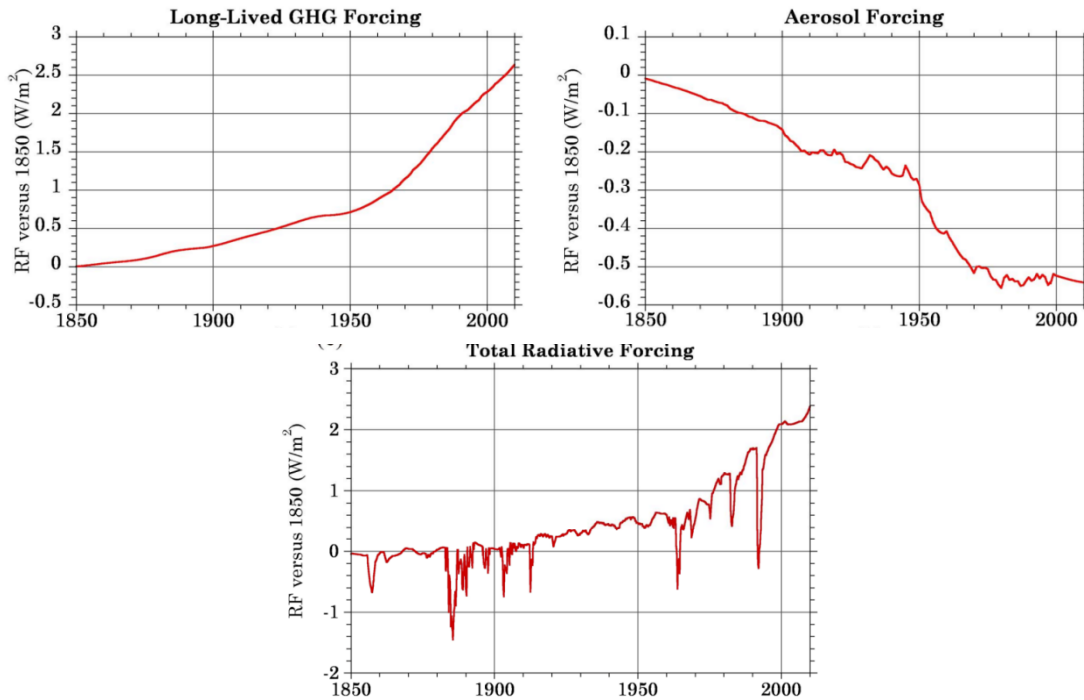


Figure 3: Time Series Analysis and the Impact of Various Factors on the Environment or Climate..[5]

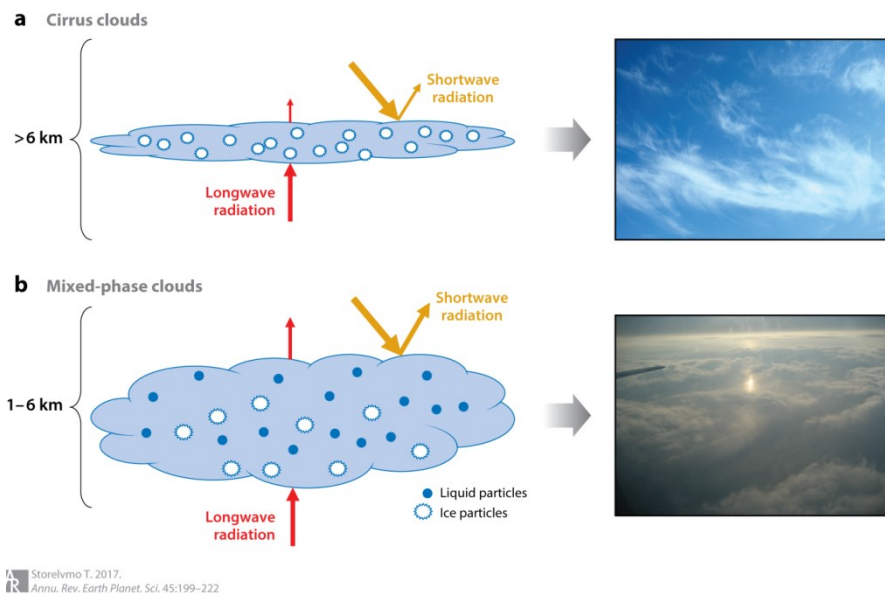


Figure 4: Impact of Cirrus and Mixed-Phase Clouds on Shortwave and Longwave Radiation[6]

As is shown by Figure 4 that mixed-phase clouds can be composed of a combination of liquid and ice, while cirrus clouds are entirely made up of ice crystals, hence, the mechanisms related to their formation may be affected differently by IN perturbations. IN perturbations will primarily affect them by altering the size distribution of their ice crystals. In the absence of IN, cirrus cloud formation occurs once the air is cold enough and supersaturated to the point where the abundant solution droplets

in the upper troposphere spontaneously freeze (homogeneous nucleation), resulting in the production of many small ice crystals. In the presence of IN, ice nuclei can initiate at lower supersaturations, and the subsequent growth of ice crystals can suppress the supersaturation to the extent that homogeneous nucleation never occurs. The latter scenario results in an optically thin cloud composed of fewer and larger ice crystals. Consequently, IN perturbations may significantly alter the optical properties of mixed-phase clouds and cirrus clouds, thereby affecting the Earth's radiative balance and climate [6].

New energy is meaningful in achieving low-carbon development. The accelerated development and utilization of new energy have triggered global energy to grow further [7]. The "PRESAV Final Report" considered a variety of fuels and energy sources, including biodiesel, methanol, ethanol, Fischer-Tropsch (FT) synthetic kerosene, nuclear energy, liquid hydrogen, and liquefied biogas. However, it ultimately concluded that methanol, ethanol, and biogas are unsuitable as jet fuel, and nuclear energy was also excluded due to safety concerns. A detailed analysis was conducted on synthetic Fischer-Tropsch kerosene, biodiesel, and hydrogen as potential alternative fuels. These fuels can reduce the aviation industry's reliance on non-renewable energy sources and greenhouse gas emissions. A quantitative analysis of the energy ratio, greenhouse gas emissions, production potential, and costs of the three fuels mentioned above was carried out. Hydrogen (especially hydrogen transported through pipelines or liquefied) has the greatest environmental benefits, followed by Fischer-Tropsch kerosene and biodiesel [8]. While the production costs of these renewable fuels are currently much higher than conventional jet fuel, in the long term, the production costs of hydrogen and Fischer-Tropsch kerosene are likely to fall, making renewable fuels a viable option. One of the new energy sources, biofuels such as Hydroprocessed Esters and Fatty Acids (HEFA) or FT fuels, can significantly reduce soot emissions, which may reduce the number of ice nuclei in contrail formation. However, due to the higher water vapor emission index when biofuels are burned, it may lead to an increased frequency of contrail occurrences. Moreover, contrails formed from biofuels may contain larger ice crystals but in fewer numbers, which could lead to a reduction in contrail optical depth but also a decrease in their albedo, and the impact on radiative forcing depends on various factors, including the shape of the ice crystals. Aviation-grade ethanol (AGE-85) is a high-performance ethanol-blended fuel used in reciprocating engine aircraft, which can improve aircraft performance and reduce maintenance costs [9]. The article mentions the possibility of converting biomass (such as cellulose) into fuel through electrochemical synthesis pathways, for example, by electrocatalytic hydrogenation of furfural to the corresponding furan compounds [10]. The potential of hydrogen fuel as an aviation fuel is being explored because it does not produce CO<sub>2</sub> during combustion. However, the combustion of hydrogen fuel also produces water vapor, which may affect the formation of contrails. Oxidation of hydrogen in combustion or fuel cells can provide higher efficiency, from 40% in combustion to 55% in fuel cells [10].

Currently, research on the specific characteristics and climate impact of contrails produced by hydrogen fuel engines is ongoing. In theory if the number of ice nuclei in engine emissions can be effectively controlled, it may reduce the formation and duration of contrails.

Soot particles play a key role in the formation of contrails by promoting the formation of ice crystals. Reducing emissions of soot particles may reduce the radiative effect and lifespan of contrails, thus having a smaller impact on the climate. Sustainable Aviation Fuels (SAFs) have the potential to reduce the impact on the climate, but whether their production can be carried out in a CO<sub>2</sub>-neutral manner, and whether they can meet other fuel functions (such as lubrication) still requires further research [11].

### 3. Conclusion

In this research, this paper has highlighted the pivotal role that contrails play in the environmental impact of aviation. It has delved into the effects of emissions from various fuels on both contrails and

the wider environment. Firstly, hydrogen-powered aircraft release a double mass of H<sub>2</sub>O into the atmosphere, presenting a higher potential for triggering contrails compared to hydrocarbon fuels. Secondly, flying at an altitude of 8 kilometers provides a background temperature of -40°C, which is sufficient to prevent the appearance of contrails from hydrocarbon fuels. Thirdly, through fluid dynamics calculations, it can be observed that the trajectory of contrails is influenced by the vortex phenomenon occurring near the aircraft's wings. Lastly, by developing a model that accounts for condensation and contrails, it is possible to simulate the patterns of contrail formation associated with different fuel types. In summary, different types of fuels have varying impacts on the formation and characteristics of contrails. Although biofuels and hydrogen fuels have the potential to reduce soot emissions, which may in turn lessen the climatic impact of contrails, the effects they have on the frequency and properties of contrail formation require further investigation. Specifically, biofuels may increase the frequency of contrail occurrence, while the combustion products of hydrogen fuels can also affect the contrail formation process.

However, the limitation of this paper is that there is currently insufficient literature to definitively prove whether the impact of hydrogen fuel on the climate is beneficial or detrimental at this time.

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