DOI: 10.54254/2755-2721/11/20230223

Diverse sustainable methods for future jet engine

Shuo Zhang

Department of Physics, University of Toronto at Scarborough, Toronto, M1C 1A4, Canada

zsjohn.zhang@mail.utoronto.ca

Abstract. With global concerns over CO_2 emissions and climate change, the aviation industry is investing in renewable fuels and sustainable engines. Bio-Synthetic Paraffinic Kerosene (Bio-SPK) and hydrogen are two significant biofuels that can replace fossil fuels in jet engines. Biofuel is considered a sustainable fuel; it is possible to replace fossil fuel in jet engines. Bio-SPK is an aviation fuel made from plant-derived lipids and processed to have similar properties to traditional jet fuel. It offers significant emissions savings compared to Jet-A1 but is not widely available due to high production costs and limited feedstock availability. While it can improve fuel efficiency and reduce emissions, it has lower energy density than conventional aviation fuels, potentially reducing aircraft range or payload capacity. Hydrogen produces only water but requires careful extraction or manufacturing. Green hydrogen is carbon-neutral, grey hydrogen generates carbon, and blue hydrogen captures and stores carbon. However, most hydrogen is currently generated as grey hydrogen, which offers less environmental benefit than directly burning fossil fuels. This work provides an overview of current and future sustainable jet engine technologies.

Keywords: Bio-SPK, hydrogen, biofuel, jet engine, sustainability.

1. Introduction

Flight has been a topic of fascination for humans since ancient times, predating the Wright brothers by a significant amount [1]. With the development and progress of society, people's demand for fast travel between two places has gradually increased [2]. This demand has also stimulated various aerospace companies to add more routes and planes. Although travel has become more convenient, the pollution and environmental damage caused by airplane exhaust emissions have become increasingly serious [3]. The consumer marketplace is becoming more environmentally conscious, and there is a significant focus on how consumers perceive environmental degradation and how this impacts their purchasing behaviors [4]. Marketing efforts are increasingly targeting environmentally conscious consumers. Adopting green energy to address this trend and the increasing demand for environmentally friendly products [5].

Although the application of green energy has already begun, the effect is not as ideal as expected. Commercial air carriers consumed 363 billion liters of aviation fuel in 2019. However, Sustainable Aviation Fuels (SAF) made up only a tiny fraction of this amount, with just 40 million liters, substantially less than 1%. SAF has been approved by the American Society for Testing and Materials (ASTM) D7566 criterion, and currently, there are 7 authorized transformation methods. These trials

DOI: 10.54254/2755-2721/11/20230223

include Fischer-Tropsch Synthesized Paraffinic Kerosene (FT-SPK), Hydroprocessed Esters and Fatty Acids (HEFA), Renewable Synthesized Iso-Paraffinic (SIP) Kerosene, Synthetic Paraffinic Kerosene with Aromatics via Fischer–Tropsch (FT-SPK/A), Alcohol-To-Jet Synthetic Paraffinic Kerosene (ATJ-SPK), Catalytic Hydrothermolysis Jet fuel (CHJ), and Hydroprocessed Hydrocarbons - Synthesized Isoparaffinic Kerosene (HH-SPK or HC-HEFA) [6].

Four categories of jet engines, including turbojet, turbofan, turbo-shaft, and turboprop engines, run on jet fuels with rigorous quality criteria. Alternative jet fuels can be acquired from coal and natural gas and sustainable sources from plants, animals, or other hydrocarbon materials. Several methods exist to produce these alternative fuels, such as Fischer-Tropsch (F-T) synthesis, biomass gasification, and plant oils and fats hydroprocessing. Franz Fischer and Hans Tropsch create the F-T synthesis process in 1925, which contains a series of chemical reactions to convert synthesis gas into hydrocarbons in liquid form. Sasol and Shell are two companies that offer commercially available F-T fuels globally, with Shell using the gas-to-liquid (GtL) process and Sasol producing F-T fuel using the coal-to-liquid (CtL) process. The utilization of alternative fuels for aviation is anticipated to have a substantial impact on addressing the energy crisis in the coming years. Several other renewable jet fuels, including nuclear, solar power, and hydrogen, are under investigation. However, they are unable to be used on commercial flights right now.

2. The primary issues of conventional jet engine

Over the past decade, the increased concerns and awareness in public and politics over the environmental impact of civil aviation. Aircraft designs are based on aerodynamics to lift them off the ground. Compared to the first model of aircraft, it has significantly improved. Each component has been studied. Engines are more efficient. Developed fuels have improved energy-to-weight ratios. With improved designs and lighter structures, aircraft are more efficient in their interior designs and have stronger bodies to build up their safety [1].

As traveling becomes more popular and more aircraft are being used, the pollution released in the atmosphere has also increased. In 1960, there were 100 million passengers who traveled by air. By 2019, 4.56 billion passengers were recorded as the total annual worldwide. Air pollution is the biggest concern. Many researchers use different tools to focus their studies on engine carbon and nitrogen oxide emissions. In 2018, aviation was reported to produce 2.4 percent of total CO_2 emissions. Although the percentage may seem small, aviation ranked number six globally. In January 2021, the journal Atmospheric Environment reported: "In 2011, aviation's contribution to human-caused warming was estimated to be 3.5%, and this percentage was probably unchanged in 2018" [7]. In 2018, 81 percent of global commercial aviation emissions were produced by passenger transport, while the rest 19 percent were from air freight. Based on the constant growth and trend of passenger air travel and freight, it was predicted that by 2050, commercial aircraft emissions would triple.

2.1. Passenger travel's growth

Analyzing past and current commercial aviation trends will provide better growth projections. Figure 1 shows the number of passengers who traveled by air from 1945 to 2021. The rate of passenger traffic was pretty steady from 1945 up to the pandemic. There were short-term declines due to the oil crises, Iran-Iraq War, the 9/11 attacks, etc. However, none can match the sharp decline when Covid-19 hit the world. Over the last 15 years, the rate has increased twofold, with an average yearly growth rate of around five percent. [7]

Between 1945 and 2008, passenger traffic was steady. After the global financial crisis in 2008, the passenger flight rate increased. In 2017, 10.7 percent of airplane passengers contributed to the Asia-Pacific region. According to ATAG, the global aviation industry made roughly $18 billion worth of merchandise transported on 128,000 scheduled flights per day in 2019, with about 12.5 million travelers. The outlook was bright for the aviation industry until Covid-19 hit the world. When the coronavirus spread worldwide, commercial aviation took an extreme drop, which they had never experienced before. Due to the uncertainty, consumer behavior began to change (shifting to alternatives for connecting distant others like video chat). The Federal Aviation Administration's Aerospace Forecast Fiscal Year 2021-2041 report predicts a rapid rise in passenger numbers, and by 2025 air travel will fully recover.

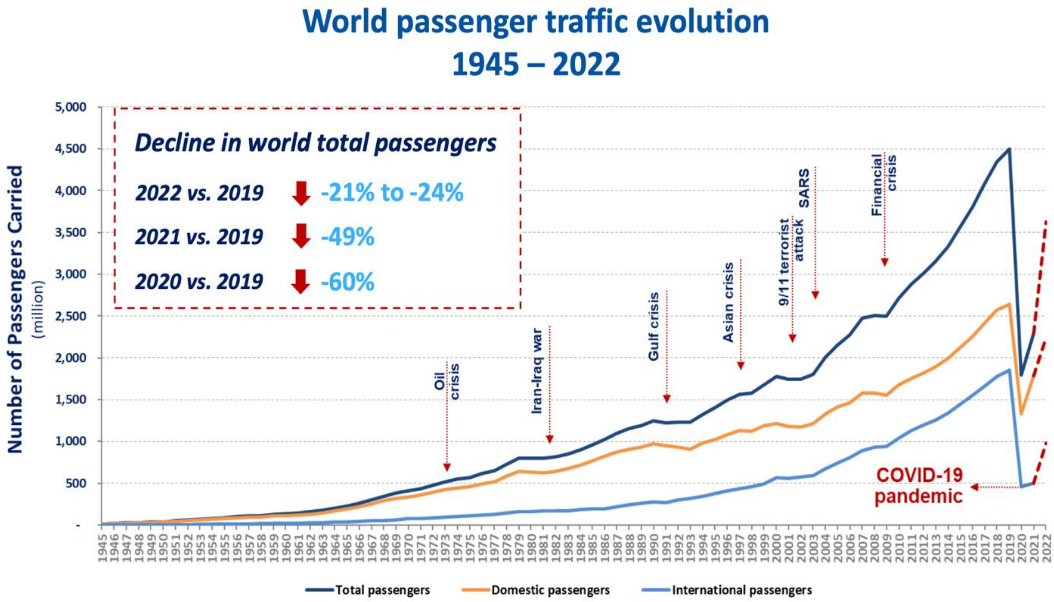

Figure 1. Passenger counted from 1945 to 2021 presented by International Civil Aviation Organization (ICAO) [7].

2.2. Per capita jet fuel use

A direct indicator of CO_2 emissions in aviation is fuel consumption. The October 2021 International Air Transport Association (IATA) report states that 359 billion liters of fuel were used in the airline industry. While in the pandemic, it dropped by 39.5 percent compared to 2019 fuel usage.

There is a direct relationship between carbon emissions and passenger traffic growth. For its central scenario, the International Council on Clean Transportation (ICCT) predicts a 3 percent annual growth in the number of passengers by 2050. As for its high and low growth scenarios, they are 3.7 percent and 2.4 percent. The ICCT examined that if " There are no significant alterations to aircraft design or fuel that would impact emission factors," a variance of 700 million tons of CO_2 could be observed by 2050 between a low-growth and high-growth scenario. On the other hand, the contrast between the central scenario and the high-growth scenario would amount to 400 million tons [2].

3. Biofuel

The aviation industry uses various sources of energy for various power operations. Although conventional fuels derived from petroleum have historically powered airplanes, researchers have been striving to create sustainable alternatives. According to the Air Transport Action Group, sustainable fuels are fossil fuels mixed with renewable hydrocarbons, and many airlines have transitioned to using such fuels to reduce their carbon footprint. The manufacturing has already taken steps to reduce its ecological footprints on land, such as creating regional and secondary airports and integrating sustainable techniques like solar energy and hydrogen. These technologies diminish the dependence on conventional energy sources derived from petroleum. [8].

Bio-jet fuels possess several advantages, such as low sulfur content, minimal tailpipe emissions, excellent cold flow properties, and high thermal stability. Moreover, bio-jet fuels surpass alternatives like ethanol in terms of compatibility with traditional engines and fuel systems since they do not require any modifications and pose no fuel quality concerns.

DOI: 10.54254/2755-2721/11/20230223

3.1. Analysis of Bio-SPK

Bio-SPK is a fuel made from plant-derived lipids. It undergoes a process called "Hydroprocessing" to make its arrangement alike regular aviation fuel, making it compatible with current engine designs. It is considered a "drop-in" fuel because it can deliver similar or better performance than traditional fuels. Advanced biofuels have a wider range of processing options due to their unique morphological characteristics and the locations where they are cultivated, which impacts the carbon intensity of the feedstock [9].

Bio-SPK, a type of bio-jet fuel, is considered one of the most encouraging and tactical answers for reducing aviation emissions. In the book Biomass and Bioenergy using the cradle-to-grave greenhouse gas emissions throughout the life cycle model-Assessment of Life Cycle Emissions of Biofuels (ALCEmB), the environmental performance of Bio-SPKs is compared to that of traditional Jet-A fuel. The model accurately estimates the greenhouse gas emissions throughout the life cycle of advanced biofuels, by utilizing a multidisciplinary approach that encompasses aspects ranging from engine/aircraft performance to life cycle analysis, including hydrocarbon chemistry, thermodynamic behavior, and fuel combustion, this study differs from earlier ones. By carefully estimating and incorporating combustion emissions to foresee the cradle-to-grave carbon intensity of Camelina SPK, Microalgae SPK, and Jatropha SPK, these emissions account for approximately 70% of total life cycle emissions (LCE). This study utilizes numerical modeling and nonlinear/dynamic simulation of a twin-spool turbofan, along with a suitable airframe, to examine how alternative fuels impact engine/aircraft performance. ALCEmB reveals that Camelina SPK, Microalgae SPK, and Jatropha SPK offer LCE savings of 70%, 58%, and 64%, respectively, compared to Jet-A1. Net energy ratio analysis demonstrates that existing biofuel processing technologies are both energy-efficient and technically viable. A detailed gas property analysis concludes that bio-synthetic paraffinic kerosene exhibits improved thermodynamic behavior when operating gas turbine engines. The thermodynamic effect benefits aircraft's fuel consumption and emission properties, resulting in fuel savings of approximately 3-3.8% and emission reductions of 5.8-6.3% for CO_2 and 7.1-8.3% for LTO NO_x compared to Jet-A [9]. Table 1 shows the differences in anticipated fuel usage among the various fuel options and the resulting engine emissions.

Table 1. The H/C ratio will be compared with the outcomes of flight missions, including fuel consumption and CO_2 emissions [9].

Fuel type	% Diff in H/C ratio	% Diff in fuel burn	Mission CO_2 (kg)	% Diff relative to Jet-A	Fuel combustion CO_2 emissions (g MJ^{-1})
Jet-A	-	-	53,263	-	73.2
Camelina SPK	+11.3	−3.7	49,960	−6.2	71
Microalgae SPK	+9.6	−3.1	50,173	−5.8	72
Jatropha SPK	+13.0	−3.8	59,907	−6.3	70.6

In terms of emissions, the mid-range trajectory showed an average percentage reduction in CO_2 emissions of 6.2%, 5.8%, and 6.3% for LokAir-C, LokAir-M, and LokAir-J aircraft models, respectively. To ensure consistency in the study, the same engine was used to test the three different Bio-SPKs in various scenarios. Nevertheless, a thorough cost analysis is required to establish these results' significance and provide more detailed insights into fuel and emissions costs [9].

However, Bio-SPK, a bio-based aviation fuel, is not widely available due to its early stages of development and limited production. Its high production cost, technical challenges, and limited feedstock availability contribute to its limited availability. Bio-SPK is more expensive than conventional petroleum-based aviation fuels, which makes it less appealing to airlines and end-users. Furthermore, Bio-SPK has a lower energy density than conventional aviation fuels, which may lead to a reduced range or payload capacity for aircraft.

3.2. Analysis of hydrogen (in biofuel)

Hydrogen is considered a pure fuel, producing only water in the air. However, extract or manufacture should be taken to produce pure-form hydrogen. Several processes exist for creating hydrogen fuel, but not all are pollutant-free, except for green hydrogen, which is zero-carbon throughout its creation and usage. Grey hydrogen generates carbon during extraction/manufacturing, while blue hydrogen captures and stores the carbon produced in the manufacturing process, improving upon grey hydrogen [1]. Table 2 displays the three shades of hydrogen in the spectrum, namely grey, blue, and green, categorized according to the level of carbon they produce.

Table 2. The colors of different types of hydrogen spectra are determined by their carbon emission levels [1].

	Grey Hydrogen	**Blue Hydrogen**	**Green Hydrogen**
Process/ Technology	Steam methane reforming (SMR) Auto-thermal reforming (ATR)	Carbon capture and storage (CCS)	Electrolysis
Source	Natural gas, gasifier coal, or heavy oil	CO_2-rich stream	Water
Carbon Output	8.5–10 kg	0.8–4.4 kg	No carbon emissions

The most common way to produce hydrogen is through SMR technology. As shown in equation one, this method combines two reactions with the chemicals of multiple steps to create green hydrogen using Ni-based catalyst:

$$CH_4 + H_2O = H_2 + CO \quad (1)$$

The primary criticism of hydrogen is not related to safety but rather the cost of the fuel. While it is possible to produce "green" hydrogen using renewable energy and water, the majority of hydrogen generated is known as "grey hydrogen". This type of hydrogen is made by burning fossil fuels and does not offer significant environmental benefits compared to simply burning the fuels themselves [10].

4. Conclusions

From the above analysis, this paper illustrates that both Bio-SPK and hydrogen have advantages and disadvantages. Bio-SPK and hydrogen are different fuels with distinct properties and characteristics. Bio-SPK is derived from plant-derived lipids and undergoes hydroprocessing to create a fuel with similar properties to traditional jet fuel. Hydrogen, on the other hand, is a clean fuel that produces only water when used, but creating pure hydrogen requires careful extraction or manufacturing. One of the main advantages of Bio-SPK is that it is considered a "drop-in" fuel, which means it can be used without modifying existing aircraft engines. It also offers significant life cycle emissions savings compared to Jet-A1 fuel, which can help reduce the environmental impact of aviation. However, Bio-SPK has limited feedstock availability and a higher production cost than traditional fuels. It also has a lower energy density, which can result in reduced range or payload capacity for aircraft using it.

Hydrogen, on the other hand, is a clean fuel that produces only water when used, making it an attractive option for reducing emissions in the transportation sector. However, creating pure hydrogen requires careful extraction or manufacturing; not all methods are pollutant-free. Grey hydrogen, produced by burning fossil fuels, offers less environmental benefit than burning them. Blue hydrogen captures and stores the carbon produced in manufacturing, while green hydrogen is carbon-neutral throughout its creation and usage. The main disadvantage of hydrogen is its cost, as most hydrogen generated currently is grey hydrogen made by burning fossil fuels. In summary, Bio-SPK and hydrogen are both promising options for reducing emissions in the transportation sector. Bio-SPK offers significant life cycle emissions savings compared to traditional fuels but has limited feedstock availability and a higher production cost. Hydrogen is a clean fuel that produces only water when used, but creating pure hydrogen requires careful extraction or manufacturing, and the main disadvantage is its cost. Ultimately, the choice between these fuels will depend on the specific application and availability of feedstocks and infrastructure.

References

[1] Yusaf T, Fernandes L, Abu T, Altarazi Y, Alrefae W, Kadirgama K, Ramasamy D, Jayasuriya A, Brown G, Mamat R, Dhahad H, Benedict F and Laimon M 2022 Sustainable Aviation – Hydrogen is the future, Sustainability 14 548

[2] Boehm R, Scholla L and Heyne J 2021 Sustainable alternative fuel effects on energy consumption of jet engines, Fuel 304 121378

[3] Baharozu E, Soykan G and Ozerdem M 2017 Future aircraft concept in terms of energy efficiency and environmental factors, Energy 140 1368

[4] Han H, Chua B and Hyun S 2020 Consumers' intention to adopt eco-friendly electric airplanes: The moderating role of perceived uncertainty of outcomes and attachment to eco-friendly products, International Journal of Sustainable Transportation 14 671

[5] Han H, Lee M, Chua B and Kim W 2019 Triggers of traveler willingness to use and recommend eco-friendly airplanes, Journal of Hospitality and Tourism Management 38 91

[6] Kroyan Y, Wojcieszyk M, Kaario O and Larmi M 2022 Modeling the impact of sustainable aviation fuel properties on end-use performance and emissions in aircraft jet engines, Energy 124470

[7] Overton J 2022 Issue Brief | The Growth in Greenhouse Gas Emissions from Commercial Aviation (2019, revised 2022) https://www.eesi.org/papers/view/fact-sheet-the-growth-in-greenhouse-gas-emissions-from-commercial-aviation

[8] Chen L, Gao K, Zhang and Lang W 2019 Chapter 2 - Alternative fuels for IC engines and jet engines and comparison of their gaseous and particulate matter emissions Abul Kalam A, Mohammad R Advanced Biofuel Woodhead Publishing Series in Energy 17

[9] Lokesh K, Sethi V, Nikolaidis T, Goodger E and Nalianda D 2015 Life cycle greenhouse gas analysis of biojet fuels with a technical investigation into their impact on jet engine performance, Biomass and Bioenergy 77 26

[10] Gegg P, Budd L and Ison S 2014 The market development of aviation biofuel: Drivers and constraints, Journal of Air Transport Management 39 34