# Impact of Sustainable Aviation Fuels on Performance Parameters of Small Turbojet Engine

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**Master's thesis / Diplomski rad**

**2024**

UNIVERSITY OF ZAGREB

FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

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# IMPACT OF SUSTAINABLE AVIATION FUELS ON PERFORMANCE PARAMETERS OF SMALL TURBOJET ENGINE

MASTER THESIS

Zagreb, 2024.

**UNIVERSITY OF ZAGREB**
**FACULTY OF TRANSPORT AND TRAFFIC SCIENCES**
MASTER THESIS COMMITTEE

Zagreb, 23 September 2024

# MASTER THESIS ASSIGNMENT No. 7734

Student: **Ivan Martinović (0135251357)**
Study: Aeronautics

Title: **Impact of Sustainable Aviation Fuels on Performance Parameters of Small Turbojet Engine**

Description:

In the thesis, it is necessary to present research on the influence of sustainable aviation fuels on the performance of small turbojet engines, with the application of tests on the JJ1400 engine. It is necessary to carry out experimental tests to compare the performance of the turbojet engine, especially the thrust and temperature of the exhaust gases when using Jet A fuel and mixtures of biofuel and JET A in different ratios. In case of impossibility of conducting experimental measurements, it is necessary to obtain the results with a mathematical model. In the conclusion, it is necessary to present concluding considerations on the results obtained by measurements and/or mathematical model.

Mentor:

Associate Professor Anita Domitrović, PhD

Committee Chair:

**SVEUČILIŠTE U ZAGREBU**
**FAKULTET PROMETNIH ZNANOSTI**
POVJERENSTVO ZA DIPLOMSKI ISPIT

Zagreb, 23. rujna 2024.

Zavod: **Zavod za aeronautiku**
Predmet: **Zrakoplovne emisije**

# DIPLOMSKI ZADATAK br. 7734

Pristupnik: **Ivan Martinović (0135251357)**
Studij: Aeronautika

Zadatak: **Utjecaj održivih zrakoplovnih goriva na parametre performansi malog turbomlaznog motora**

Opis zadatka:

U radu je potrebno prikazati istraživanje utjecaj održivih zrakoplovnih goriva na performanse malih turbomlaznih motora, s primjenom ispitivanja na motoru JJ1400. Potrebno je provesti eksperimentalne testove kako bi se usporedile performanse turbomlaznog motora, posebno potisak i temperatura ispušnih plinova kod upotrebe goriva Jet A te mješavina biogoriva i JET A u različitim omjerima. U slučaju nemogućnosti provođenja eksperimentalnih mjerenja, potrebno je rezultate dobiti matematičkim modelom. U zaključnu je potrebno prikazati zaključna razmatranja o rezultatima dobivenim mjerenjima i/ili matematičkim modelom.

Mentor:

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**SVEUČILIŠTE U ZAGREBU**

**FAKULTET PROMETNIH ZNANOSTI**

**DIPLOMSKI RAD**

# UTJECAJ ODRŽIVIH ZRAKOPLOVNIH GORIVA NA PARAMETRE PERFORMANSI MALOG TURBOMLAZNOG MOTORA

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Zagreb, 2024.

## SUMMARY:

This thesis investigates the impact of Sustainable Aviation Fuels (SAF) on the performance of small turbojet engines, with a focus on the JJ1400 engine model. As the aviation industry seeks to reduce its carbon footprint, SAF presents a promising alternative to conventional Jet A fuel due to its potential to lower greenhouse gas emissions and contribute to the long-term sustainability of aviation. The study assesses how SAF blends, specifically mixtures involving Jet A and biodiesel components like FAME, affect critical engine performance parameters, including thrust, fuel consumption, exhaust gas temperature (EGT), and rotational speed (RPM). Experimental tests were conducted to compare the performance of the turbojet engine running on Jet A and various SAF blends. The results highlight the differences in efficiency, emissions, and thermal behavior under different fuel compositions. This research contributes to the broader discussion on decarbonizing aviation and explores the practical challenges and opportunities in the use of SAF in real-world aviation applications.

KEY WORDS: aviation, sustainability, fuels, SAF, FAME, blends, turbojet engine, thrust, EGT, RPM

## SAŽETAK

Ovaj rad istražuje utjecaj održivih zrakoplovnih goriva (SAF) na performanse malih turbomlaznih motora, s posebnim naglaskom na model motora JJ1400. Kako zrakoplovna industrija nastoji smanjiti svoj ugljični otisak, SAF predstavlja obećavajuću alternativu konvencionalnom gorivu Jet A zbog svog potencijala za smanjenje emisije stakleničkih plinova i doprinos dugoročnoj održivosti zrakoplovstva. Studija procjenjuje kako mješavine SAF-a, posebno kombinacije Jet A i komponenti biodizela poput FAME-a, utječu na ključne parametre performansi motora, uključujući potisak, potrošnju goriva, temperaturu ispušnih plinova (EGT) i brzinu rotacije (RPM). Provedeni su eksperimentalni testovi kako bi se usporedile performanse turbomlaznog motora koji koristi Jet A i različite mješavine SAF-a. Rezultati ističu razlike u učinkovitosti, emisijama i toplinskom ponašanju pod različitim sastavima goriva. Ova istraživanja pridonose širem dijalogu o dekarbonizaciji zrakoplovstva i istražuju praktične izazove i mogućnosti upotrebe SAF-a u stvarnim zrakoplovnim aplikacijama.

KLJUČNE RIJEČI: zrakoplovstvo, održivost, goriva, SAF, FAME, mješavine, turbomlazni motor, potisak, EGT, RPM

# Content

# 1. INTRODUCTION

The aviation industry stands at a critical juncture, facing mounting pressure to reduce its environmental impact while catering to the growing global demand for air travel. As of today, the sector is responsible for about 2-3% of global greenhouse gas emissions, a figure that is projected to rise with increasing flight frequencies and expanding airline networks. The urgency to transition to more sustainable fuels is highlighted by the international community's commitment to global agreements aimed at halting the increase in global warming. Consequently, the decarbonization of air transport has become one of the key priorities for governments and organizations worldwide.

In response, the aviation sector has explored various alternative fuels over the years. Historical initiatives by international bodies such as the International Civil Aviation Organization (ICAO) and the International Air Transport Association (IATA) have been pivotal. IATA first introduced the term Sustainable Aviation Fuel (SAF) in the late 2000s, defining it as fuel that is sustainable, not derived from fossil carbon stock, and capable of reducing an aircraft's carbon emissions. This introduction marked a significant commitment to identifying and implementing cleaner energy sources within the industry.

The search for alternative fuels includes ideas like hydrogen-powered and electric planes. However, these new technologies face big challenges. For example, hydrogen needs complicated systems for storage and refueling at airports, while electric planes, although great for short flights, still don’t have the range or power needed for larger, commercial flights. Additionally, both options have a long way to go in terms of technology development and getting approval from regulators.

Against this backdrop, SAF emerges as a compelling transitional solution. One of the key advantages of SAF is its compatibility with existing aircraft engines and fuel distribution infrastructures. Unlike other alternatives, SAF can be blended with conventional jet fuel, as it is chemically very similar to standard kerosene, and used in current engines without modifications. This "drop-in" feature makes SAF an immediately viable option, significantly lowering barriers to adoption compared to other, more radical technological shifts.

The motivation for this thesis stems from the critical need to assess and validate the effectiveness of SAF. With the aviation industry poised to continue its growth, the potential for SAF to substantially reduce aviation's carbon footprint needs to be empirically examined and scientifically documented. This research focuses on the performance parameters of a small turbojet engine, the JJ1400. By conducting this study, the aim is to provide robust data that can aid policymakers, industry stakeholders, and the scientific community in understanding the practical implications of transitioning to SAF.

The content of this research is divided into 6 main sections:

1) Introduction
2) SAF Production and Characteristics
3) Potential of SAF in Aviation
4) Fundamentals of Turbojet Engine Operation
5) Experimental Methodology
6) Data Comparison
7) Conclusion

In the introductory section, there will be a discussion about the current state of aviation and the need to transition to alternative fuels. The second section will explain what SAF is and the role it can play in the transition. The methods of SAF production and the differences between them will be described. The third section will discuss the benefits to the environment and economy, but also the challenges for its adoption. It will address regulatory frameworks around the world and how they affect the adoption of SAF.

The fourth section of the paper discusses the principles of operation of turbojet aircraft engines. In this section, the JJ1400 engine used in the experiment will also be described. The fifth section will explain the experimental methodology. After that, a theoretical mathematical model for SAF and FAME biofuel will be developed to predict the experimental results. The sixth part is the core of this study and provides an analysis of the experiment in which we operated a small turbojet engine on FAME biofuel, through which the functionality of the theoretical mathematical model for SAF and FAME biofuel was tested. In this section, the results of the theoretical model and the experiment are analyzed, and observations are presented. The last part of this study presents a summary of key findings and recommendations for future research.

# 2. SAF PRODUCTION AND CHARACTERISTICS

## 2.1 INTRODUCTION IN SUSTAINABLE AVIATION FUELS (SAF)

Sustainable Aviation Fuels (SAF) represent a transformative solution aimed at reducing the environmental impact of the aviation industry. SAF encompasses a broad range of fuels derived from renewable and sustainable resources, distinctly different from traditional fossil fuels. These fuels can be produced from various feedstocks, including: waste oils, agricultural residues, municipal solid waste, and algae, offering a cleaner and more sustainable alternative to conventional jet fuel. The primary objective of SAF is to mitigate the carbon footprint and other environmental impacts associated with air travel.

There are several types of SAF, categorized based on their production processes and feedstocks. Bio-based SAF is produced from biological resources such as vegetable oils, animal fats, and agricultural residues. Processes like hydroprocessed esters and fatty acids (HEFA) convert these materials into jet fuel. Synthetic SAF is produced using chemical processes, such as Fischer-Tropsch synthesis, which converts biomass or municipal waste into synthetic hydrocarbons. The Alcohol-to-Jet (AtJ) process converts alcohols (ethanol or butanol) derived from biomass into jet fuel. Additionally, Power-to-Liquid (PtL) technology utilizes renewable electricity to produce hydrogen, which is then combined with captured carbon dioxide to create synthetic hydrocarbons. [1] These SAF production processes will be explained in more detail in section 2.2.

The potential of SAF lies in its ability to significantly reduce greenhouse gas (GHG) emissions compared to traditional jet fuel. Life-cycle analyses of SAF have demonstrated that it can reduce GHG emissions by up to 80% depending on the feedstock and production process used. This substantial reduction is crucial in the aviation industry's efforts to meet international climate goals and reduce its overall environmental impact. This reduction is achieved by using renewable resources that absorb $CO_2$ during their growth phase, thus offsetting the emissions produced during fuel combustion. For better understanding, Figure 1 schematically illustrates the key steps in considering the life cycle of SAF, from the collection of feedstocks to its use in flights. [2]

**Figure 1 Life cycle of SAF**

*Source: [3]*

SAF also has the potential to reduce other harmful emissions, such as particulate matter (PM) and sulfur oxides (SOx). This improvement in air quality is particularly significant around airports, where local communities are often affected by aircraft emissions. Moreover, SAF promotes the diversification of energy sources, reducing the aviation industry's reliance on finite fossil fuels. By utilizing a wide range of feedstocks, including waste and residues, SAF contributes to a more resilient and sustainable energy supply chain. The development and deployment of SAF can stimulate economic growth and job creation in various sectors, including agriculture, waste management, and advanced biofuel production. This economic boost can be particularly impactful in rural and underdeveloped regions. [4]

Despite its numerous advantages, the widespread adoption of SAF faces several challenges. Currently, SAF is more expensive to produce than conventional jet fuel. This cost disparity is primarily due to the nascent stage of SAF technologies and the limited scale of production. However, as production processes become more efficient and economies of scale are realized, it is expected that SAF costs will decrease. The availability of sustainable feedstocks is another challenge. To ensure that SAF production does not compete with food production or lead to deforestation, careful consideration must be given to feedstock sourcing. Existing aviation fuel infrastructure is predominantly designed for conventional jet fuel. Adapting this infrastructure to accommodate SAF, along with establishing robust supply chains, is essential for widespread SAF adoption. Additionally, SAF must meet stringent safety and performance standards before it can be used in commercial aviation. The certification process for new fuels is rigorous and time-consuming, posing a barrier to the rapid deployment of SAF. More on the challenges and regulatory frameworks will be discussed in chapter 3, where the potential of SAF in aviation will be addressed.

## 2.2 TYPES OF SAF

Sustainable Aviation Fuels (SAF) are derived from various sustainable sources and can be categorized based on their production methods and raw materials. All types of Sustainable Aviation Fuels presented in table 1 have been certified by ASTM[1] based on their production methods.

This table presents the successfully completed qualification conversion project processes for the production of sustainable aviation fuels according to ASTM D7566[2] (effective as of August 1, 2023). It includes abbreviations for each process, a description of the conversion process, preferred feedstocks, and the maximum blending ratio with conventional jet fuel. The new standards emphasize the importance of ensuring that the fuel parameters of the blend adhere to both the fossil jet fuel specification ASTM D1655[3] and the synthetic aviation turbine fuel standard ASTM D7566. Once certified, this blend is stored as standard JET A in an airport fuel depot, where it is subsequently blended with other JET A-1 quantities.

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[1] ASTM International (*formerly known as the American Society for Testing and Materials*) plays a crucial role in the certification and approval process of aviation fuels, including SAF. They develop and publishe standards that define the specifications and testing methods for aviation fuels. These standards ensure that fuels meet the necessary safety, performance and environmental criteria required for use in aircraft.

[2] ASTM D7566 – this standard specification covers aviation turbine fuel containing synthesized hydrocarbons, specifically addressing SAFs. It allows for the blending of synthesized hydrocarbons with conventional jet fuel and specifies the properties that these blends must meet to be certified for use.

[3] ASTM D1655 – this is the standard specification for conventional petroleum-derived jet fuel (Jet-A and Jet-A1). It defines the requirements for kerosene-type aviation turbine fuels.

## Table 1: ASTM D7566 Approved Conversion Processes for Sustainable Aviation Fuels

| Annex | Abbreviation | Conversion Process | Preferred Feedstocks | Maximum Blending Ratio |
|---|---|---|---|---|
| **1** | FT-SPK | Fischer–Tropsch hydroprocessed synthesised paraffinic kerosene | Coal, natural gas, biomass | 50% |
| **2** | HEFA | Synthesised paraffinic kerosene from hydroprocessed esters and fatty acids | Bio-oils, animal fats, recycled oils | 50% |
| **3** | SIP | Synthesised iso-paraffins from hydroprocessed fermented sugar | Biomass used for sugar production | 10% |
| **4** | FT-SKA | Synthesised kerosene with aromatics derived by alkylation of lights aromatics | Coal, natural gas, biomass | 50% |
| **5** | ATJ-SPK | Alcohol-to-Jet synthetic paraffinic kerosene | Biomass from ethanol, isobutanol or isobutene | 50% |
| **6** | CHJ | Catalytic hydrothermolysis jet fuel | Triglycerides such as oils from soybean, jatropha, camelina, carinata, and tung | 50% |
| **7** | HC-HEFA-SPK | Synthesised paraffinic kerosene from hydrocarbon hydroprocessed esters and fatty acids | Algae | 10% |

*Source:* [4]

The maximum blending ratio for Sustainable Aviation Fuel (SAF) depends on the specific type of SAF and its production pathway, as defined by the ASTM D7566 standard. It must ensure that the blended fuel meets all safety and performance requirements for use in existing aircraft engines without modifications. This ratio is determined by the chemical and physical properties of the SAF, such as energy content and freezing point, and its compatibility with conventional jet fuel. Regulatory standards and rigorous testing are used to set these limits, typically allowing blends of up to 50%. The goal is to balance environmental benefits with the operational reliability of the fuel. A limiting factor in the maximum blending ratio is also a density, as SAF typically has a slightly lower density than 0.80 [kg/L], which is the minimum allowed by ASTM. How this affects some of the engine performance parameters will be explained in Chapters 5 and 6.

Figure 1 shows the timeline of ASTM SAF certification. Completing a qualification project successfully does not necessarily reflect the maturity of the technology. Instead, it confirms that the SAF grade, when produced according to the specification annex criteria, fulfills the requirements for safe flight operations and is, therefore, approved for use. Certifying an individual SAF fuel requires millions in investments with an uncertain outcome. This will be discussed further in Chapter 3.3.

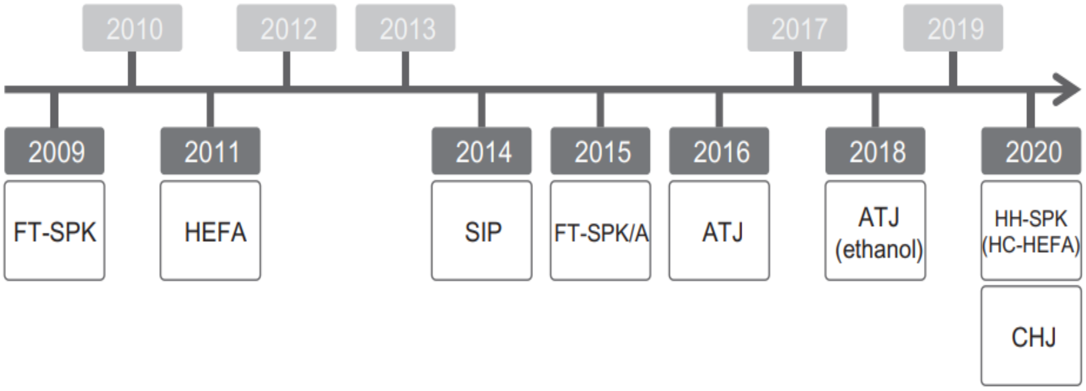

**Figure 2 Timeline of ASTM SAF certification**
*Source: [4]*

From Figure 2, it can be concluded that the past decade has been a trigger for SAF, as there has been a shift towards considering greener alternatives in the aviation industry. It is expected that in the coming years, the use of SAF will increase, and the methods of SAF production will become even more sophisticated.

# 3. POTENTIAL OF SAF IN AVIATION

The potential of Sustainable Aviation Fuel (SAF) in the aviation industry is vast, offering a viable pathway to achieving significant reductions in greenhouse gas (GHG) emissions while supporting the sector's growth. As the aviation industry faces increasing pressure to reduce its environmental footprint, SAF has emerged as a critical component of the industry's sustainability strategy. One of the key advantages of SAF is its favorable life cycle assessment (LCA), which demonstrates substantial benefits in decarbonizing air transport by significantly lowering total carbon emissions compared to conventional jet fuels. This chapter explores the potential of SAF by examining its various types and comparing them with conventional Jet A fuel, understanding the regulatory and industry perspectives that shape its adoption, analyzing the considerations airlines must address when integrating SAF into their operations, and assessing current market implementations and future opportunities for scaling up SAF production and use.

## 3.1 COMPARISON OF SAF TYPES WITH JET A

In considerations about SAF, it is very important to understand the chemical background and properties of different types of SAF. Fuel properties affect aircraft performance. The chemical properties should not significantly deviate from those of JET A fuel because they will be used in prescribed blends in existing aircraft engines without additional modifications.

Table 2 shows the key properties of sustainable aviation fuels in ranges and compares them with JET A. It can be concluded that the properties are very similar; however, some parameters, such as density, suggest caution when considering this fuel for pure use. Perhaps, through the development of existing SAF production technologies or a new production method, the average density of SAF could be raised to a satisfactory 0.80 kg/L.

## Table 2: Comparison of SAF Properties with Jet A

| **Property** | **SAF** | **Jet A** |
|---|---|---|
| **Molecular Mass [g/mol]** | 140 - 170 | 150 - 180 |
| **Energy Density [MJ/kg]** | 42 - 43 | 42 - 44 |
| **Density [kg/L at 15°C]** | 0.75 - 0.84 | 0.80 - 0.84 |
| **Specific Heat Capacity [J/g·K]** | 2.1 - 2.3 | 2.1 - 2.3 |
| **Boiling Point at 1 bar [°C]** | 150 - 300 | 150 - 300 |
| **Freezing Point [°C]** | Below -40 | -40 to -47 |
| **Heat of Vaporization at 1 bar [J/g]** | 200 - 300 | 200 - 300 |
| **Minimum Ignition Energy [mJ]** | 0.2 - 0.3 | 0.2 - 0.3 |
| **Flash Point [°C]** | 38 - 50 | 38 - 50 |

Source: [5]

It is very important to note that these figures for SAF can vary depending on the choice of feedstock and the production method, but all values should fall within the given ranges. The same applies to Jet A fuel.

## 3.2 SAF REGULATORY

The regulation of Sustainable Aviation Fuels (SAF) has evolved within the broader framework of economic, political, and environmental considerations that have shaped the aviation industry over the past century. The contrasting economic theories of John Maynard Keynes and Milton Friedman had a significant impact on the regulation of various industries, including aviation. Keynes advocated for government intervention to stabilize economies, while Friedman promoted free-market principles with minimal government interference. In aviation, these economic theories led to key regulatory shifts, particularly the deregulation era of the 1980s, which saw governments in the United States and Europe adopt policies that opened up air routes and allowed competition to flourish, culminating in the rise of low-cost airlines.

However, the environmental consequences of deregulation, including the aviation sector's contribution to carbon emissions, were initially overlooked. It was not until the rise of green political parties in Europe, entering parliaments and influencing environmental legislation, that attention turned to the aviation sector's impact on climate change. These parties pushed for regulatory frameworks that would address emissions through market-based measures, aligning with Keynesian principles of state intervention in environmental matters.

The creation of mechanisms like the European Union Emissions Trading System (EU-ETS) was a direct response to this political and environmental pressure, allowing airlines to offset emissions while continuing to operate. On a global scale, the Kyoto Protocol and subsequent agreements like CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) were established to manage aviation emissions, while still allowing market forces to play a role in reducing environmental impact. This combination of regulatory intervention and market mechanisms reflects a compromise between Keynesian and Friedman-like philosophies, shaped by the growing global awareness of the need to address climate change.

As the demand for SAF grows, so too does the need for a robust regulatory framework that supports its development and implementation. Green political parties continue to push for stricter regulations, while the aviation industry seeks to balance environmental responsibility with economic viability. This complex interplay of economic, political, and environmental factors continues to drive the evolution of SAF regulation today. As the aviation industry strives for a sustainable future, the convergence of global policies, market dynamics, and environmental activism will continue to shape the regulatory landscape for SAF, ensuring a balanced approach between economic growth and ecological responsibility.

### 3.2.1 EU-ETS

One of the key mechanisms in the EU's regulatory framework is the EU Emissions Trading System (EU-ETS), which plays a crucial role in incentivizing the reduction of carbon emissions in the aviation sector.

The EU Emissions Trading System is a cornerstone of the EU’s policy to combat climate change and is the world’s first major carbon market.

It operates on the principle of „*cap and trade*“, meaning that a limit, or cap, is set on the total amount of greenhouse gases that can be emitted by installations covered by the system. This cap is reduced over time so that total emissions fall. Within this system, companies receive or purchase emission allowances (also known as allocations), which they can trade with each other as needed. Each allowance gives the holder the right to emit one tonne of carbon dioxide ($CO_2$), or the equivalent amount of other powerful greenhouse gases, such as nitrous oxide ($N_2O$) and perfluorocarbons (PFCs).

Each year, airlines operating in the EU are given a certain number of emission allowances, also known as allocations. These allocations are determined based on several factors, including the airline's historical emissions and its planned flight routes. Allocations are typically granted for free to a certain extent, but airlines are also required to purchase additional allowances if their emissions exceed the allocated amount. In recent years, the number of free allowances has decreased, with a growing portion of allowances being auctioned to encourage airlines to adopt more sustainable practices, including the use of SAF.

Once airlines receive their emission allocations, they can either use them to cover their own emissions or trade them on the carbon market. If an airline emits fewer emissions than the amount of allowances it holds, it can sell its surplus allowances to other companies. Conversely, if an airline's emissions exceed its allocated allowances, it must purchase additional allowances from other companies or through carbon auctions. This market-based approach creates a financial incentive for airlines to reduce their emissions, as those who successfully lower their carbon output can profit by selling excess allowances. The trading process is facilitated by the

EU, which maintains a centralized registry for tracking the ownership and transfer of allowances between companies.

The EU-ETS plays a significant role in promoting the use of SAF by making carbon-intensive fuels more expensive. Airlines that incorporate SAF into their operations can reduce their overall emissions, thus requiring fewer emission allowances and lowering their costs within the EU-ETS. This financial benefit, along with EU subsidies and incentives, has encouraged the gradual adoption of SAF in the European aviation market. By continuing to tighten the cap on emissions and reducing the number of free allowances available, the EU aims to further incentivize the use of SAF and other sustainable technologies in aviation.

EU-ETS has been instrumental in driving the reduction of carbon emissions in aviation and encouraging the use of SAF. By setting a clear cap on emissions, allocating allowances based on historical emissions, and facilitating the trading of allowances, the EU has created a market-driven approach to emissions reduction. As the aviation industry seeks to achieve its sustainability goals, the EU-ETS will continue to play a critical role in shaping the future of fuel use and emissions management. [6]

### 3.2.2 Refuel EU

RefuelEU Aviation is a key initiative under the EU's broader "Fit for 55" package, aimed at reducing carbon emissions by 55% by 2030. This initiative specifically focuses on increasing the uptake of SAF across Europe's aviation industry. The primary goal of RefuelEU Aviation is to establish a long-term trajectory for SAF usage, creating a predictable demand for SAF while fostering investments in production capacity. The regulation includes a mandatory SAF blending obligation for airlines, which will start with a low percentage of SAF incorporation and gradually increase by 2050. RefuelEU also emphasizes the need for infrastructure development to support SAF at airports, ensuring that airlines operating in and out of the EU have access to SAF. This regulation aims to strike a balance between ensuring competitiveness and promoting environmental sustainability. By implementing a mandatory SAF blending percentage, the EU is positioning SAF as a key driver for achieving carbon neutrality in aviation by mid-century. [7]

### 3.2.3 EU-RED

The EU Renewable Energy Directive (EU-RED) is a foundational policy instrument that plays a crucial role in promoting the production and consumption of renewable energy, including SAF. Originally adopted in 2009 and subsequently updated, the directive sets binding targets for the share of renewable energy in the EU's energy mix. Under the directive, SAF qualifies as a renewable energy source when produced from sustainable feedstocks, such as waste oils, biomass, or agricultural residues.

EU-RED II, which came into force in 2021, introduced stricter sustainability criteria for renewable fuels, ensuring that the production of SAF does not negatively impact biodiversity or lead to deforestation. One of the significant advancements in EU-RED II is the increased focus on advanced biofuels, which are produced from non-food-based feedstocks. This aligns with the EU's goal of reducing reliance on fossil fuels in aviation and transitioning toward cleaner energy sources.

Airlines that incorporate SAF produced under EU-RED guidelines benefit from favorable treatment under the EU Emissions Trading System (EU-ETS) and other policy mechanisms. [8]

### 3.2.4 NATIONAL REGULATIONS IN NORWAY AND SWEDEN

In 2016, Norway became the first country in Europe to initiate the commercial use of SAF through a pilot program at Oslo Airport. This initiative was part of the EU-funded ITAKA project, which demonstrated the feasibility of using SAF in commercial aviation. The Norwegian government, with support from airlines like SAS, Lufthansa, and KLM, introduced a mandatory SAF blending quota of 0.5% in 2019. This marked a significant milestone, making Norway the first European country to legally mandate SAF use. Norway is now considering increasing its SAF blending quota to 2% to align with the EU-RED III Directive. Despite being outside the EU, Norway closely follows EU regulations and continues to play a leading role in SAF adoption. The Norwegian government's ongoing commitment to SAF development includes addressing challenges such as the transfer of $CO_2$ reduction certificates and international SAF accounting.

In 2021, Sweden introduced a national SAF blending quota of 1%, with an ambitious plan to increase this to 30% by 2030. Sweden has positioned itself as a leader in SAF research and production, with several key projects underway. Swedish Biofuels, for example, is developing three SAF production plants utilizing Alcohol-to-Jet (ATJ) technology. Once operational, these plants are expected to produce up to 400000 tons of SAF annually. Additionally, Sweden has launched innovative partnerships, such as the collaboration between SAS, Swedish energy company Vattenfall, Shell Aviation, and LanzaTech to produce Power-to-Liquid (PtL) jet fuel. These initiatives align with Sweden's broader commitment to achieving carbon neutrality by 2045. The Swedish government's support for SAF is reflected in its policies, which create a favorable environment for SAF development and long-term investment.

### 3.2.6 CORSIA

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a global market-based mechanism developed by the International Civil Aviation Organization (ICAO) to address carbon emissions from international aviation. Implemented in phases, CORSIA aims to stabilize $CO_2$ emissions from international flights by requiring airlines to offset their growth in emissions through the purchase of carbon credits or the use of sustainable aviation fuels (SAF). The following sections outline the history, implementation, and functioning of CORSIA, as well as its future prospects. In the context of CORSIA , one carbon credit typically represents the reduction or removal of one metric ton of $CO_2$ or its equivalent in other greenhouse gases. Therefore, airlines participating in CORSIA purchase carbon credits to offset one metric ton of $CO_2$ emissions produced by their international flights.

CORSIA was adopted during the 39th ICAO Assembly in October 2016, following the European Union's announcement to extend the EU Emissions Trading Scheme (EU-ETS) to international flights, which prompted international protests. CORSIA was introduced as a compromise to create a global solution for carbon emissions from international aviation, applicable to all ICAO member states. It was agreed that only international flights would be subject to the CORSIA system, while domestic flights would remain exempt. In addition, countries with less than 0.5% of global air traffic and flights conducted by small aircraft or for specific purposes (e.g., rescue missions) are also exempt from the scheme.

CORSIA is implemented in three main phases:

1. Monitoring Phase (2019): From 2019, airlines were required to monitor and report their CO2 emissions to ICAO.

2. Voluntary Phases (2021–2026): From 2021, 88 states representing approximately 77% of international aviation traffic participated in the voluntary pilot phase. The first official phase of CORSIA, starting in 2024, also remains voluntary.

3. Mandatory Phase (from 2027): Starting in 2027, participation in CORSIA will become mandatory for states representing more than 0.5% of international aviation, ensuring that at least 90% of global international air traffic is covered.

CORSIA primarily relies on market-based measures, meaning airlines are required to offset their emissions by purchasing carbon credits from emission reduction projects in other sectors. The purchase of these credits helps finance projects that reduce emissions in various industries, balancing out the emissions produced by international flights. Airlines can choose how they want to compensate their emissions by either buying carbon credits or using CORSIA-eligible sustainable aviation fuels (SAF). The SAF used for CORSIA compliance must meet specific certification criteria, ensuring that it contributes to real and measurable reductions in carbon emissions. The International Sustainability and Carbon Certification (ISCC) system provides certification for CORSIA-compliant SAF, ensuring transparency and accountability.

While CORSIA represents a major step towards global emissions reduction in aviation, several challenges remain. One issue is the limitation of CORSIA to international flights, meaning that domestic flights, which account for a significant portion of global aviation emissions are not covered by the scheme. Furthermore, concerns have been raised about the availability of high-quality carbon offset projects and the potential for 'greenwashing' without proper oversight. CORSIA is subject to periodic reviews, with the first major assessment scheduled for 2032 to determine whether the scheme should continue beyond 2035. ICAO’s approach, combining carbon offsetting and SAF, offers a flexible path toward achieving carbon-neutral growth in aviation, but much will depend on the successful scaling of SAF production and the effectiveness of offset mechanisms. [9] [10]

### 3.2.7 ASTM D7566

ASTM D7566 is a critical international standard governing the production, certification, and use of Sustainable Aviation Fuels (SAF) in commercial aviation. Developed by ASTM International, the standard ensures that SAF, when blended with conventional jet fuels like Jet-A or Jet A-1, meets the required safety and performance standards to operate seamlessly within the current aviation infrastructure. This specification is essential for integrating SAF into the global aviation market without the need for engine modifications. One of the core aspects of ASTM D7566 is that it outlines the types of SAF that are approved for use. SAF can be derived from various feedstocks, including waste oils, biomass, or algae, and must be synthesized through specific processes such as Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK) or Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK). The standard ensures that only SAF types that meet rigorous quality criteria are approved for blending with conventional jet fuels.

A key regulation under ASTM D7566 is the limit on the amount of SAF that can be blended with conventional jet fuel. Currently, SAF is permitted to be blended at up to 50% by volume with fossil-based Jet A or Jet A-1. The certification process outlined in the standard ensures that SAF-blended fuels meet essential performance characteristics, such as energy density, freezing point, flash point, and combustion quality. Only once the fuel passes these tests can it be certified as meeting the global aviation fuel specification ASTM D1655.

SAF produced under ASTM D7566 offers significant environmental benefits, with reductions of up to 80% in life-cycle greenhouse gas emissions compared to conventional jet fuel. This makes SAF a critical tool for reducing the aviation industry's carbon footprint. Furthermore, the standard ensures that SAF can be used interchangeably with traditional jet fuels, maintaining operational safety and efficiency in commercial flight operations. ASTM D7566 is designed to evolve with advancements in fuel technology. As new SAF production pathways and innovations emerge, the standard is continuously updated to accommodate new methods and ensure that they meet the required quality and safety standards. This adaptability is essential for the ongoing development of SAF as a viable alternative to conventional jet fuel. [4] [11]

## 3.3 INDUSTRY PERSPECTIVES

Sustainable Aviation Fuel is becoming a key part of the aviation industry's push to reduce its impact on the environment. With the world more focused than ever on cutting carbon emissions, airlines are under pressure to find cleaner alternatives to traditional jet fuel.

In Figure 3, the share of fuel costs in the total expenses of an airline is shown. From the figure, we can see that this value is around 30%. This implies that airlines will be very cautious when it comes to increasing the use of SAF, as it could disrupt their budget balance, given that SAF is currently more expensive than Jet A fuel. The goal of every airline is to cover the operational costs of flights through ticket sales, and this will be a challenge in the coming years unless there are significant incentives and subsidies.

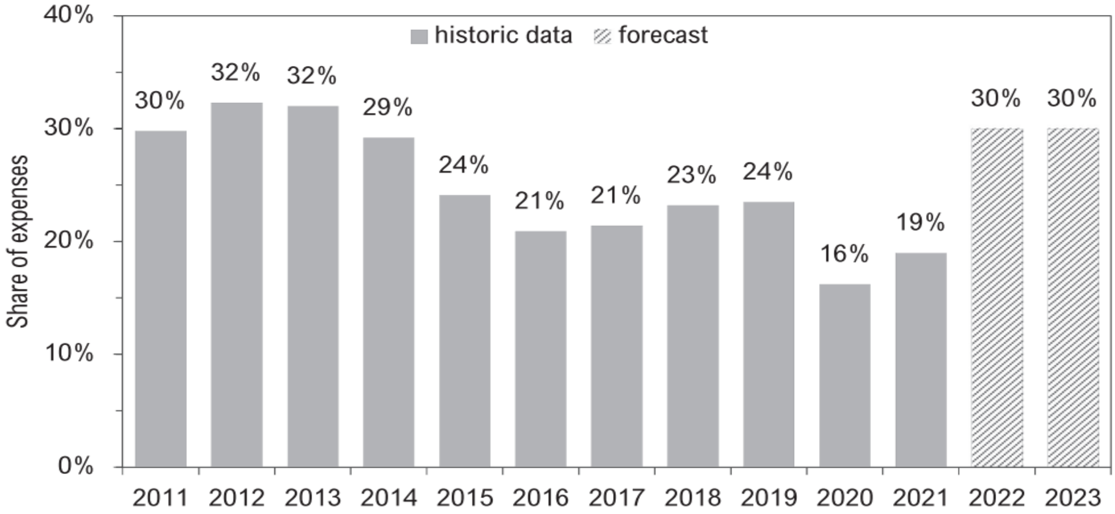

**Figure 3 Fuel cost share of aircraft operating cost**
*Source: [4]*

It is also very important to mention that fluctuations in crude oil prices must be taken into account. There is a high probability that oil prices will rise in the near future because current oil fields are located in the cheapest exploitation areas. Additionally, the existing oil platforms and refineries are aging, which presents a new challenge. The construction of new facilities will only occur if the return on investment justifies the cost. Since new oil fields are expected to be more challenging, new platforms and refineries will also require higher investment capital.

We are witnessing a world striving for decarbonization. Various subsidies and incentives are being introduced, along with additional regulations, rules, and restrictions, all aimed at reducing greenhouse gases. In this context, SAF emerges as a promising solution to current challenges. When looking at the broader global economic picture regarding increased use of

SAF, it becomes clear that SAF presents an opportunity for economically underdeveloped regions that lag behind the developed West. The benefits associated with SAF include the potential for fuel production in these areas, which would directly drive economic growth, development, and increased employment. Due to all the regulations and policies mentioned in this section, the market for SAF production will be secured. This points to the diversification of global supply chains for aviation fuels. By encouraging underdeveloped regions and countries to participate in SAF production, the aviation industry will be able to reach its set goals for reducing its harmful impact on the environment more quickly.

Figure 4 shows the expected SAF required to achieve Net Zero in the aviation industry, measured in billion liters.

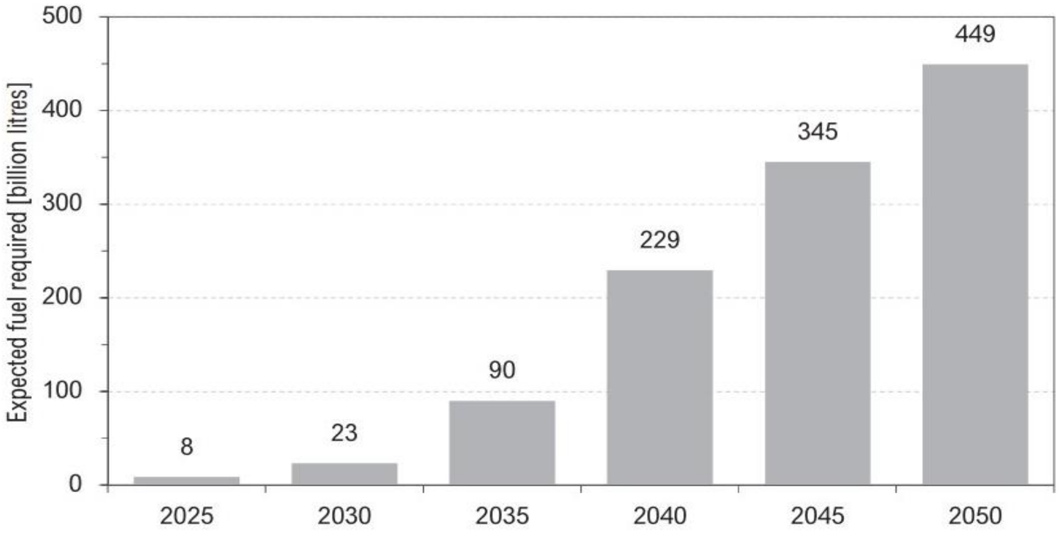

**Figure 4 Expected SAF required to achieve Net zero in the aviation industry**

*Source: [4]*

The projected demand for Sustainable Aviation Fuel is set to increase dramatically in the coming decades as the aviation industry strives to achieve Net Zero emissions by 2050. In 2025, the expected demand is relatively modest at 8 billion liters, but this figure is forecasted to grow substantially over time. By 2030, it is estimated to reach 23 billion liters, and by 2035, it will rise significantly to 90 billion liters. The demand continues to increase sharply, reaching 229 billion liters by 2040, 345 billion liters by 2045, and a staggering 449 billion liters by 2050. This rapid growth in SAF demand underscores the urgent need for scaling up production capabilities to meet the future requirements of the aviation industry, which will be crucial for the industry's sustainability and decarbonization efforts. SAF regulations and subsidies will support the production and use of SAF in the foreseeable future, until the prices of JET A fuel and SAF reach equilibrium.

As I mentioned, the goal of Net Zero is for aviation to be carbon neutral by 2050. An optimistic target has been set, aiming for at least 63% of aviation emissions to be offset by SAF. The remaining 37% is expected to be compensated through the purchase of allowances and carbon credits within various regulatory frameworks, or by investing in green technologies.

When comparing the potential of SAF with electric propulsion using batteries and hydrogen, we can conclude that the energy density of both of these technologies must be significantly improved to compete with SAF. The reason is the sensitivity of aircraft to additional weight and the space taken up by larger hydrogen tanks or batteries, which would reduce passenger seating capacity. There are also safety concerns that currently limit electric propulsion and hydrogen technology, making SAF the most promising and available solution for decarbonization in the near term.

The logistics of Sustainable Aviation Fuel present a complex array of challenges and require careful planning by producers and airlines alike. SAF producers must determine whether they want to engage in Business-to-Business (B2B) transactions, where they sell to oil companies that blend the SAF with JET A-1, or Business-to-Consumer (B2C) models, where they sell directly to airlines. In both cases, logistics play a crucial role, especially in blending, transportation, and storage. Several options exist for SAF blending and distribution, each with its own advantages and disadvantages. Refinery blending offers quality assurance and potentially lower transport costs, but it requires agreements with refinery operators and may incur monopoly pricing. Neutral blending depots allow for more competitive blending prices but introduce additional storage and handling costs. Airport blending minimizes transport costs by blending SAF directly at the airport, although this option requires additional storage capacity. Another logistical challenge is ensuring that SAF complies with ASTM regulations, which require it to be blended with JET A-1 before aircraft refueling. This blending must be closely monitored to ensure quality. Furthermore, producers need distribution licenses and contracts with airport fuel depots to handle SAF storage and throughput, which introduces additional costs related to liability insurance, storage fees, and refueling charges. Figure 5 shows the scheme of LCA of SAF, the journey from feedstock, transport to refineries and from there to fuel depot where it is blended with Jet A, and finally to the end point – the aircraft.

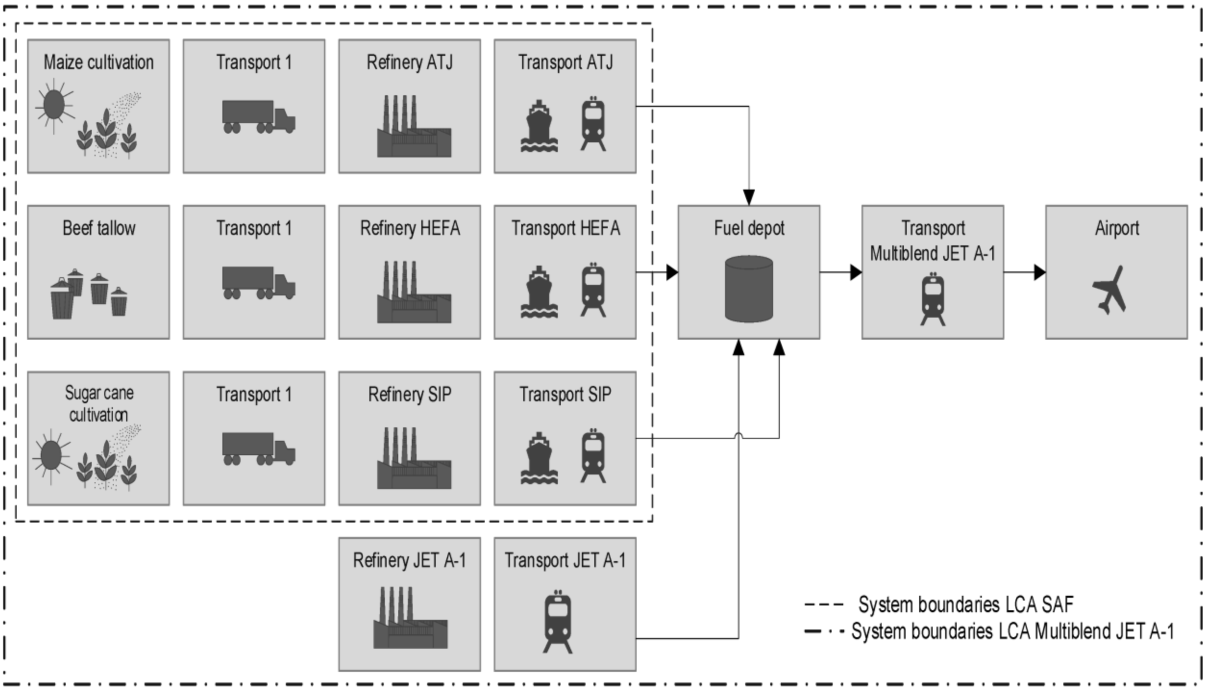

**Figure 5 LCA of SAF, the journey from feedstock to the aircraft**
*Source: [12]*

In the future, as SAF scales up, solving these logistical challenges efficiently will be essential to making SAF a more competitive and viable option for airlines.

There are several strategies for introducing SAF into the market, ranging from supply-side approaches to government regulations. One strategy is blending SAF with JET A-1, which can be done through oil companies or directly by alternative fuel producers. Governments can also step in with subsidies to reduce production costs, making SAF more affordable for airlines. Another approach is introducing blending mandates, requiring oil companies to mix a certain percentage of SAF into their fuel, or setting usage quotas for airlines, which would naturally boost demand. On the consumer side, airlines can offer more sustainable travel options, giving passengers the choice to pay a bit more for environmentally friendly flights. The oil industry still plays a crucial role in SAF adoption. Although their involvement has been minimal so far, oil companies may start producing SAF to meet regulatory demands, especially in regions like Europe, where blending quotas are being introduced. However, this will need to be managed carefully to avoid market disruptions, such as price wars or excess supply. Additionally, SAF producers face high production costs, and without government subsidies or additional revenue from by-products, SAF remains more expensive than traditional JET A-1 fuel. A mix of government support, industry partnerships, and creative pricing will be essential for making

SAF a significant part of the aviation fuel market. A balanced strategy that focuses on both supply and demand will be key to overcoming the hurdles of SAF implementation and ensuring it becomes a viable solution for the aviation industry's future.

An challenging factor for most start-ups looking to produce SAF is the initial capital. It is estimated that, in the initial phase, just for certifying the production process in compliance with all regulations, between €10 and €12 million is required. Investors will need to be convinced to invest capital in the start-up and to be patient with the return on investment. This is best illustrated in Figure 6. In addition to certification, the construction of new refineries will incur significant costs. The size of the refineries will depend on the availability of feedstock and raw materials for SAF production.

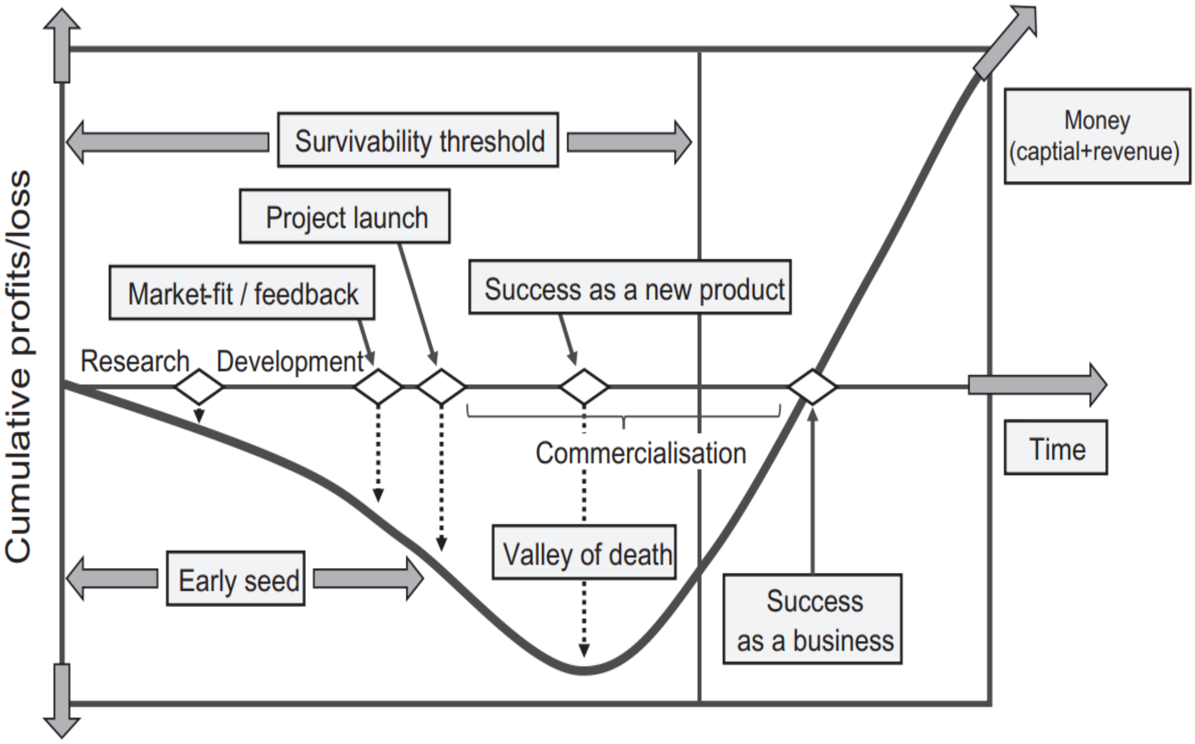

**Figure 6 The Valley of Death for Start-ups**
Source: *[4]*

One of the key challenges for SAF is ensuring a consistent and reliable supply of feedstock and raw materials, as shortages could limit production and delay widespread adoption. To prevent this, the industry needs to find diverse and sustainable sources of feedstock and raw materials. Additionally, ensuring reliable supply chains is essential since any disruption in transportation or processing could limit SAF availability. Significant new investments will be needed across various areas, including raw material sourcing, expanding supply chains, and constructing or upgrading refineries. These steps are crucial for scaling up SAF production to meet demand and keeping supplies stable in the long run.

# 4. FUNDAMENTALS OF TURBOJET ENGINE OPERATION

## 4.1. BASICS OF TURBOJET ENGINE OPERATIONS

The primary task of a turbojet engine is to generate thrust, which propels the aircraft forward. Thrust is achieved by accelerating air through the engine, resulting in a forward force according to Newton’s Third Law. Mathematically, the effective thrust ($T$) of a turbojet engine is expressed as:

$$T = \dot{m}(V_{exit} - V_{intake}) + (p_{exit} - p_{intake})A_{exit} \qquad (1)$$

Where:

- $\dot{m}$ is the mass flow rate of air through the engine,
- $V_{exit}$ is the exhaust gas velocity,
- $V_{intake}$ is the free stream velocity of air ahead of the engine,
- $p_{exit}$ is the pressure at the exhaust,
- $p_{intake}$ is the free stream pressure,
- $A_{exit}$ is the area of the nozzle.

The mass flow rate of air or fuel $\dot{m}$ s expressed as the amount of mass passing through a specific area of a system in a given time interval. The unit for mass flow rate is typically kilograms per second (kg/s). The formula for mass flow rate is:

$$\dot{m} = \rho \cdot A \cdot V \qquad (2)$$

Where:

- $\rho$ is the fluid density
- $A$ is the cross-sectional area through which the fluid passes,
- $V$ is the fluid velocity.

The change in kinetic energy at the intake and exhaust of a turbojet engine is primarily governed by the difference in the velocities of the air entering the engine and the exhaust gases leaving the engine.

Kinetic energy ($K_e$) of a mass ($m$) moving at velocity ($V$) is given by the equation:

$$K_e = \frac{1}{2} m V^2 \tag{3}$$

When dealing with mass flow rate $\dot{m}$, the kinetic energy per unit time (or power associated with kinetic energy) is given by:

$$K_e = \frac{1}{2} \dot{m} V^2 \tag{4}$$

This equation is adding the dimension of time through the mass flow rate - $m$.

The change in kinetic energy from the intake to the exhaust can be expressed as the difference between the kinetic energy of the exhaust gases and the kinetic energy of the incoming air. If $V_{intake}$ is the velocity of air at the intake and $V_{exit}$ is the velocity at the exhaust, the change in kinetic energy rate (power) is:

$$\Delta K_e = \frac{1}{2} \dot{m} \left( {V_{exit}}^2 - {V_{intake}}^2 \right) \tag{5}$$

Where:

- $\dot{m}$ is the mass flow rate of air through the engine,
- ${V_{exit}}^2$ is the velocity of the exhaust gases,
- ${V_{intake}}^2$ is the velocity of the air entering the intake.

At the intake, the air velocity $V_{intake}$ is lower, so the kinetic energy of the incoming air is relatively small.

At the exhaust, the velocity $V_{exit}$ is significantly higher due to the acceleration of gases through the combustion process and nozzle, leading to a much larger kinetic energy at the exhaust.

The difference in kinetic energy represents the energy converted into thrust, as the turbojet engine accelerates the air and exhaust gases to create forward motion. [13]

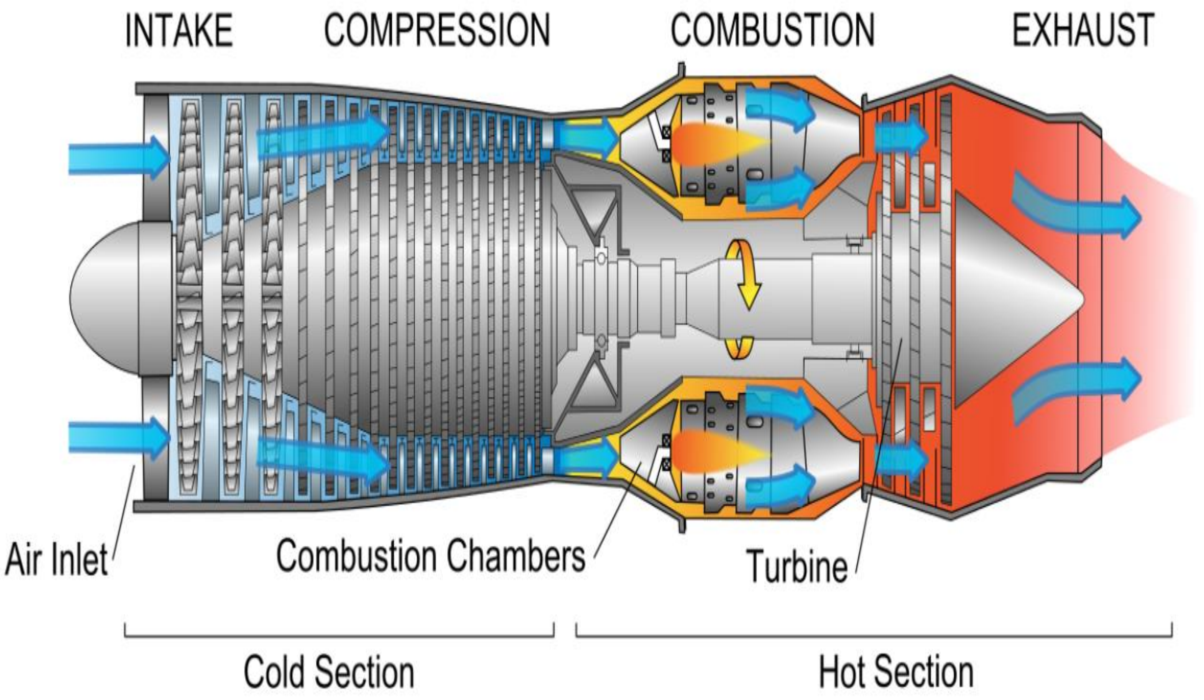

**Figure 7 Turbojet Engine Operating Cycle Diagram**
Source: *[14]*

The aircraft turbojet engine (Figure 7) operates using a mixture of hot gases, which consists of air and gaseous combustion products of the fuel. This mixture of hot gases is produced by the chemical reaction between the oxygen in the air and the propellant fuel from the aircraft's fuel tanks. The process follows a specific sequence: first, air is drawn through the inlet and enters the compressor, where it is compressed, increasing both its pressure and temperature. The high-pressure air is then directed toward the combustion chamber, where it mixes with fuel. This air-fuel mixture is ignited by a spark plug. Ideally, combustion occurs at constant pressure; however, in reality, there is a slight pressure loss during the process. As combustion takes place, chemical energy is converted into kinetic energy. The hot gas mixture, now at high pressure and temperature, leaves the combustion chamber and transfers its kinetic energy to the turbine blades, causing the turbine to rotate. The kinetic energy transferred to the turbine is used to drive the compressor via a shaft. The combustion products, having passed through the turbine, experience a drop in both pressure and temperature as energy is transferred. The exhaust gases, now at high velocity, reach the nozzle. As they pass through the convergent nozzle, their velocity further increases.

Air enters the engine through the intake and slows down to ensure the compressor can operate efficiently. At this stage, the mass flow rate of air $\dot{m}$ is critical, and it can be calculated using the following equation:

$$\dot{m} = \rho \cdot A_{intake} \cdot V_{intake} \tag{6}$$

Where:

- $\rho$ is the fluid density
- $A_{intake}$ is the cross-sectional area through which the fluid passes,
- $V_{intake}$ is the fluid velocity.

The compressor increases the pressure and temperature of the incoming air. Ideally, the pressure ratio $\pi_c$ in the compressor is defined as the ratio of the outlet to inlet pressure:

$$\pi_c = \frac{p_{exit,compressor}}{p_{intake}} \tag{7}$$

Where:

- $p_{exit,compressor}$ is the air pressure at the compressor exit,
- $p_{intake}$ is the pressure at the compressor inlet.

In the combustion chamber, fuel is mixed with the compressed air and ignited. The combustion process releases a large amount of heat, increasing the temperature and pressure of the gases. The thermal energy $\bar{Q}$ generated in this phase can be calculated as:

$$\bar{Q} = \dot{m}_{fuel} \cdot H_{fuel} \tag{8}$$

Where:

- $\dot{m}_{fuel}$ is the mass flow rate of fuel,
- $H_{fuel}$ is the heating value of the fuel (calorific value).

The turbine extracts energy from the high-temperature, high-pressure exhaust gases to drive the compressor. The energy extracted by the turbine $W_{turbine}$ is dependent on the mass flow rate of gases and the enthalpy drop $\Delta h$ across the turbine:

$$W_{turbine} = \dot{m} \cdot \Delta h_{turbine} \tag{9}$$

Where:

- $\Delta h_{turbine}$ is the enthalpy drop of the gases through the turbine.

Finally, the gases exit the engine through the nozzle, accelerating to produce thrust. The exhaust velocity $V_{exit}$ can be determined using Bernoulli's equation:

$$V_{exit} = \sqrt{2 \cdot (h_{turbine} - h_{exit})} \tag{10}$$

Where:

- $h_{turbine}$ is the enthalpy at the turbine exit,
- $h_{exit}$ is the enthalpy of the gases at the nozzle exit.

These equations describe the core physical processes inside a turbojet engine and their dependence on key parameters such as mass flow rate, pressure, and enthalpy. The thrust generated by the turbojet engine allows the aircraft to move, and the efficiency of each step directly affects the engine's overall performance. [15]

## 4.2. DESCRIPTION OF A SMALL TURBOJET ENGINE JJ - 1400

The JJ-1400 is a single-shaft, single-flow turbojet engine with a single stage centrifugal compressor and an axial turbine (Figure 8). The primary purpose of the engine is to power flying model aircraft, and for the purposes of this study, it was used during testing on a test bench. The engine is designed to use kerosene (JET A) as the primary fuel, while a propane/butane gas mixture is used as the secondary fuel for ignition.

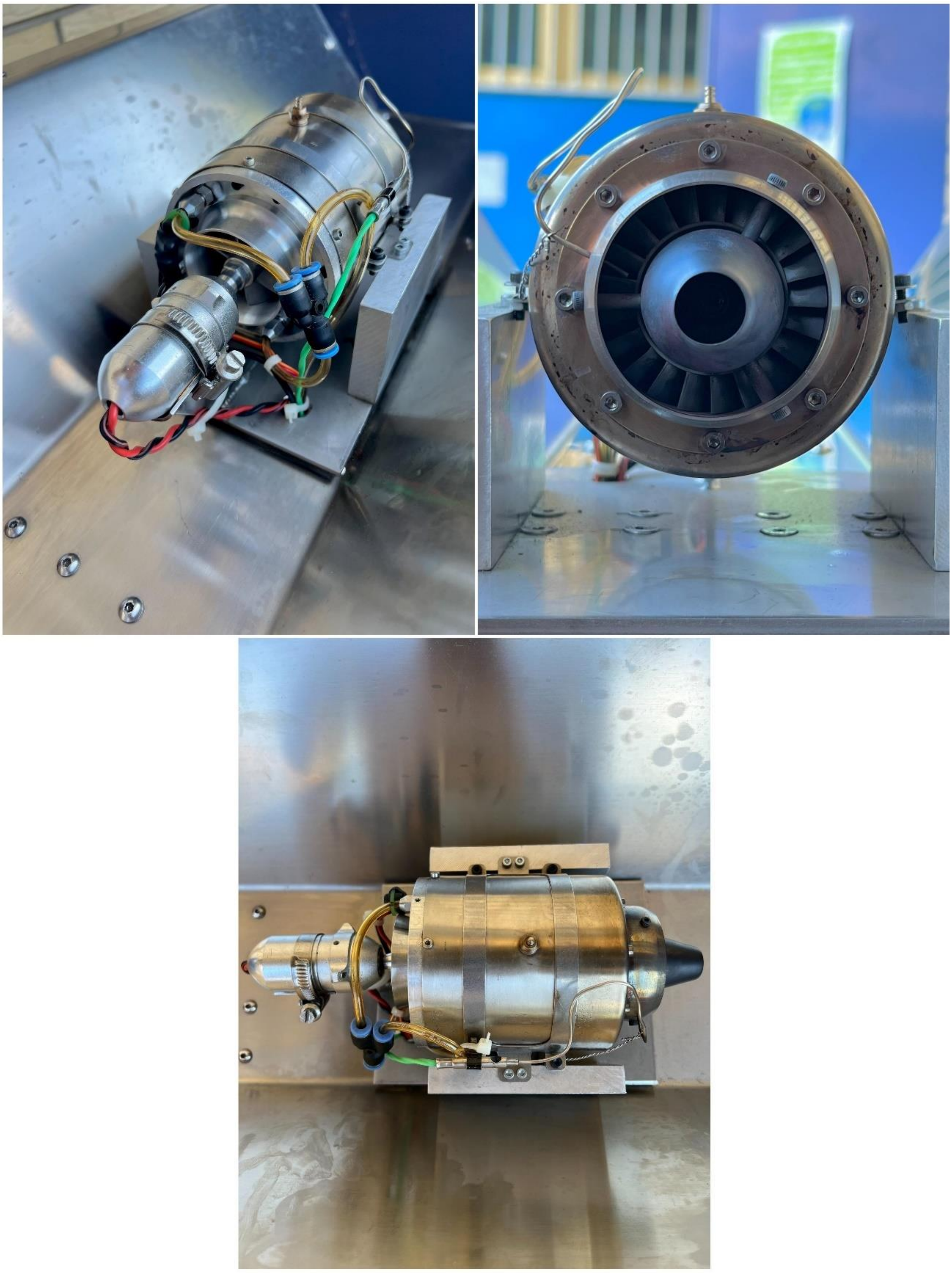

Figure 8 JJ - 1400 Turbojet Engine

The main parts of this engine are:

- Inlet (Figure 9)
- Centrifugal compressor (Figure 10)
- Combustion chamber (Figure 11)
- Turbine (Figure 12)
- Convergent nozzle (Figure 13)

**Figure 9 Inlet**

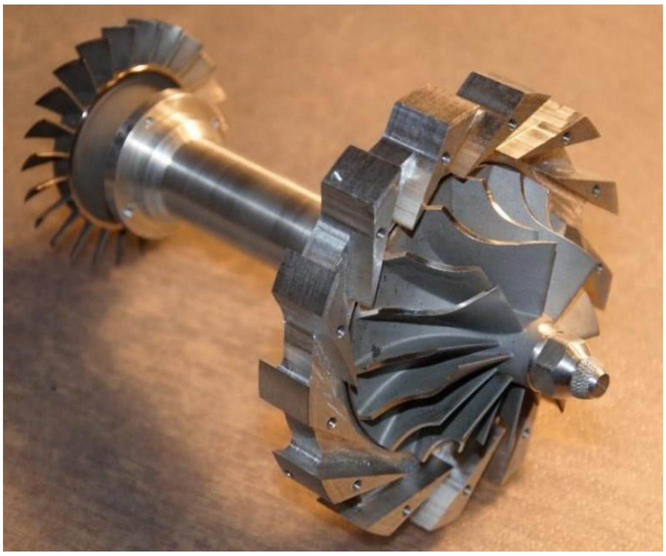

***Figure 10 Compressor-turbine unit***

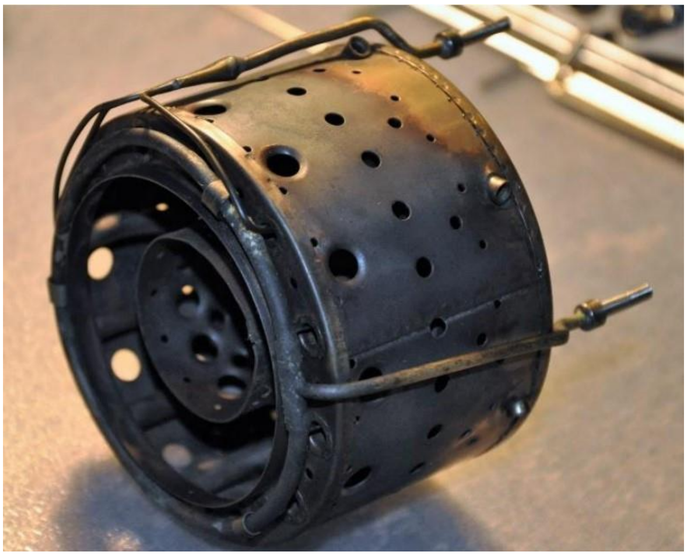

**Figure 11 Combustion chamber**

**Figure 12 Nozzle**

*Source:* [16]

The declared specifications of the JJ 1400 aircraft engine by its manufacturer are shown in the table below:

**Table 3 Specifications of JJ - 1400 Turbojet Engine**

| JJ 1400 | Value |
|---|---|
| **Outer Diameter [mm]** | 90 mm |
| **Length [mm]** | 230 mm |
| **Mass [g]** | 970 g |
| **Approx Thrust** | 6.35 kg at 160,000 RPM |
| **Idle [RPM]** | 42,000 |
| **Exhaust Gas Temperature (EGT) at Max RPM [°C]** | Approx. 680 |
| **Fuel Consumption** | Approx 177-207 mL per minute at max RPM |

Source: *[17]*

The JJ-1400 engine was chosen for this study due to its simple design, which is sufficient to observe and analyze the key performance parameters selected for this research: thrust, EGT, and RPM. The following chapter will describe the experimental methodology and the sensors used in the experiment, which were connected to this engine.

# 5. EXPERIMENTAL METHODOLOGY

The idea of measuring certain performance parameter indicators arose to gain the best possible insight into the impact of sustainable aviation fuels on the performance of aircraft engines. The goal is to consider the broader picture and reach a conclusion on whether modifications to existing engines or aircraft will be necessary if sustainable aviation fuels are more widely implemented in aviation practice.

In this chapter, the chronology of the conducted experiment will be described, covering the setup, the selection of performance parameters, and the installation of sensors. At the end of this chapter, theoretical and practical results will be compared and analyzed.

## 5.1. EXPERIMENTAL SETUP

For the purposes of this experiment, the JJ1400 turbojet engine was used. The engine was mounted securely onto the test table (Figure 13) to minimize any movement during operation and to ensure that accurate data could be collected. The table was also designed to withstand the vibration and forces generated during engine operation.

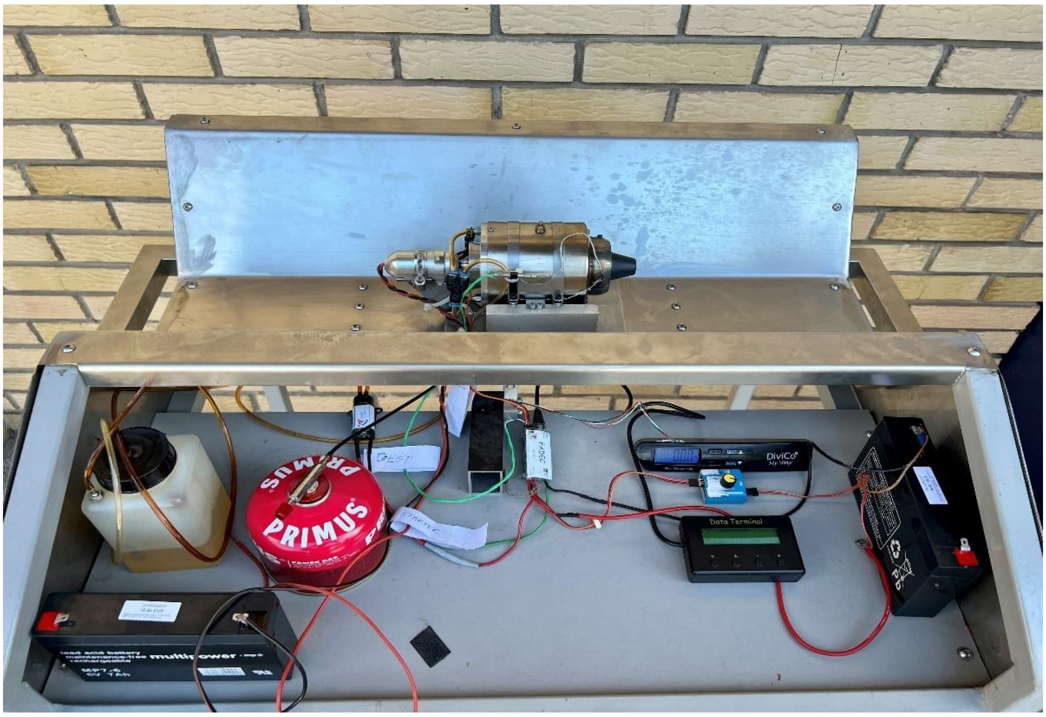

**Figure 13 Test bench with the JJ1400 engine, sensors, and data terminals**

The test bench consists of the JJ1400 turbojet engine, a fuel tank, two batteries, a propane/butane mixture for starting the engine, sensors, and their data terminals.

Before starting the engine, several pre-experimental checks were carried out such as: Fuel System Inspection, Instrumentation Calibration, Safety Precautions. The fuel lines were inspected to ensure no blockages or leaks were present. All measurement devices were calibrated to ensure accurate data collection. Fire extinguishers and emergency shutoff mechanisms were placed near the test table. The surrounding area was cleared of any flammable materials to ensure safe operation.

In the experiment, a piezoelectric system is used to measure the thrust produced by the engine. For exhaust gas temperature (EGT) and engine speed (RPM), sensors connected via a FADEC system are utilized, transmitting the data to a data terminal for monitoring and analysis. Figure 14 shows the data terminal for the mentioned sensors.

Figure 14 Data Terminals of Sensors

In the absence of SAF, the experiment was conducted using biofuel composed of fatty acids, vegetable-oil, and methyl esters (FAME). The theoretical results for JET A, SAF, and biofuel are presented in section 5.2 and compared with the experimental results (Chapter 6) to assess the accuracy of the model and ensure that the analysis is as accurate as possible.

Due to the lubrication method of the bearings in the JJ1400 turbojet engine, AeroShell Turbine Oil, a synthetic lubricating oil for aircraft turbine engines, was added in an amount of approximately 5% to each of the fuel blends used in the experiment.

The experiment is structured to be conducted in multiple stages:

- First, the engine's performance and output parameters are measured while operating on 100% JET A fuel.
- In the second stage, the engine is tested with a fuel blends consisting of 75% JET A and 25% biofuel.
- In the third stage, the engine is run on a 50% JET A and 50% biofuel blend.

For each of these stages, data was recorded and will be presented in following sections.

## 5.2. THEORETICAL MODEL OF PARAMETERS

For the purposes of this study, the selected parameters are thrust, EGT, and RPM. In this section, we will establish a theoretical model of parameter changes in relation to the engine's operation on 100% JET A fuel. The theoretical parameters for biofuel (FAME) and SAF will be compared with the experimental ones.

### 5.2.1 THRUST

The thrust produced by a jet engine can be related to engine speed and fuel properties. According to Mattingly (1996) and Hill & Peterson (1992), thrust is a function of mass flow rate and exhaust velocity. By incorporating the dependence of mass flow rate on RPM and the effect of fuel energy density and density on exhaust velocity, the thrust can be expressed as:

$$T \propto RPM^n \times \sqrt{\frac{E_f \times \eta_c}{\rho_f}} \tag{11}$$

For thrust, an equation was used that proportionally shows how thrust changes depending on the type of fuel used. This relationship highlights how variations in fuel properties influence engine performance. The theoretical model will be derived step by step for better understanding, along with its variables in the equation.

1. Basic Thrust Equation

In jet engines, thrust is generated by accelerating air through the engine. The fundamental thrust equation as I already said is:

$$T = \dot{m}_{air}\ (V_{exit} - V_{intake}) \tag{12}$$

Assumption: At low speeds or static conditions, $V_{intake}$ is much smaller than $V_{exit}$, so we can simplify:

$$\dot{m}_{air}\ \times\ V_{exit} \tag{13}$$

2. Relationship Between Mass Flow Rate and RPM

The mass flow rate of air through the engine is proportional to the engine's rotational speed (RPM):

$$\dot{m}_{air} \propto\ RPM^n \tag{14}$$

- $n$ is an exponent that depends on the engine design. For simplicity of model, assumption of $n = 1$ is made, but in most cases $n = [1,3]$

So:

$$\dot{m}_{air} = k\ \times\ RPM \tag{15}$$

- $k$ is a proportionality constant.

3. Exhaust Gas Velocity and Fuel Properties

The exhaust gas velocity is related to the energy added to the airflow by fuel combustion. The energy per unit mass added to the air is proportional to the specific energy content of the fuel-air mixture.

Assuming ideal behavior:

$$V_{exit} \propto \sqrt{\Delta h} \tag{16}$$

- $\Delta h$ - Specific enthalpy rise due to combustion [J/kg]

The specific enthalpy rise is proportional to the fuel's energy density and the fuel-to-air ratio $(f)$:

$$\Delta h \propto f \times E_f \tag{17}$$

- $f$ - Fuel-to-air mass ratio [kg fuel per kg air]
- $E_f$ - Energy density of the fuel [J/kg]

4. Fuel-to-Air Ratio and Fuel Density

At a constant throttle setting, the volumetric fuel flow rate $(\dot{V}_{fuel})$ is constant.

The mass flow rate of fuel is:

$$\dot{m}_{air} = \dot{V}_{fuel} \times \rho_f \tag{18}$$

The fuel-to-air ratio is:

$$f = \frac{\dot{m}_{fuel}}{\dot{m}_{air}} = \frac{\dot{V}_{fuel} \times \rho_f}{k \times RPM} \tag{19}$$

Since $\dot{V}_{fuel}$ and $k$ are constants:

$$f \propto \frac{\rho_f}{RPM} \tag{20}$$

## 5. Combining Equations to Derive Thrust Model

Substitute $V_{exit}$ and $f$ into the thrust equation:

$$T \propto \dot{m}_{air} \times \sqrt{f \times E_f} = (RPM) \times \sqrt{\left(\frac{\rho_f}{RPM}\right) \times E_f} \tag{21}$$

Simplify:

$$T \propto RPM \times \sqrt{\left(\frac{\rho_f \times E_f}{RPM}\right)} = RPM \times \frac{\sqrt{\rho_f \times E_f}}{\sqrt{RPM}} \tag{22}$$

Simplify the RPM terms:

$$T \propto \frac{RPM}{\sqrt{RPM}} \times \sqrt{\rho_f \times E_f} = RPM^{(1-0.5)} \times \sqrt{\rho_f \times E_f} = RPM^{0.5} \times \sqrt{\rho_f \times E_f} \tag{23}$$

Since $RPM^{0.5} = \sqrt{RPM}$:

$$T \propto \sqrt{RPM} \times \sqrt{\rho_f \times E_f} \tag{24}$$

This derivation suggests that thrust is proportional to the square root of RPM and the square root of the product of fuel density and energy density. To align model, the inverse relationship between fuel density and thrust will be considered.

## 6. Adjusting the Model

Suppose that higher fuel density leads to a lower fuel flow rate (since the engine meters fuel volumetrically). Then, the fuel-to-air ratio $f$ is inversely proportional to fuel density:

$$f \propto \frac{1}{\rho_f} \tag{25}$$

Substitute this into the expression for $V_{exit}$:

$$V_{exit} \propto \sqrt{f \times E_f} \propto \sqrt{\frac{E_f}{\rho_f}} \tag{26}$$

For greater accuracy of the theoretical mathematical model, combustion efficiency $(\eta_c)$ will be included in the calculation to better approximate the experimental results.

Final Simplified Model:

$$T \propto RPM^n \times \sqrt{\frac{E_f \times \eta_c}{\rho_f}} \tag{27}$$

Source: *[13] [15] [18]*

## Calculating Theoretical Thrust for Each Phase

Assumptions:

- RPM is Constant: Since RPM dana is unknown in this phase, it is assumed that the engine operates at the same RPM in all phases.
- Exponent $n = 1$ for simplicity

**Table 4 Comparison of the chemical properties of Jet A, FAME biofuel, and SAF**

| Fuel Type | Energy Density [MJ/kg] | Density [kg/L] | Density [kg/m³] | Combustion Efficiency [$\boldsymbol{\eta_c}$] |
|---|---|---|---|---|
| JET A | 43 | 0.80 | 800 | 0.99 |
| FAME BIOFUEL | 37 | 0.88 | 880 | 0.85 |
| SAF | 42 | 0.775 | 775 | 0.98 |

Source: [5] [19] [20]

Calculating Fuel Blend Properties

Phase 2: 75% Jet A, 25% Biofuel

Volumes in 1000 Liters [1 $m^3$]:

- Jet A Volume: 750 L
- Biofuel Volume: 250 L

Masses:

- JET A mass: $0.75\ L \times 800\ kg/m^3 = 600\ kg$
- Biofuel mass: $0.25\ L \times 880\ kg/m^3 = 220\ kg$
- Total mass: $0.60\ kg + 220\ kg = 820\ kg$

Mass Fractions:

$$w_{JET\ A} = \frac{600}{820} \approx 0.7317$$

$$w_{Phase2} = \frac{220}{820} \approx 0.2683$$

Energy Density of the Blend $E_{blend}$:

$$E_{blend} = w_{JET\ A} \times E_{JET\ A} + w_{biofuel} \times E_{biofuel} \tag{28}$$

$$E_{Phase2} = (0.7317 \times 43) + (0.2683 \times 37)$$

$$E_{Phase2} = 31.462 + 9.931$$

$$E_{Phase2} = 41.393\ \text{MJ/kg}$$

Density of the Blend ($\rho_{blend}$):

$$\rho_{Phase2} = 820\ kg/m^3$$

Combustion Efficiency of the Blend ($\eta_{c,blend}$):

$$\eta_{c,blend} = w_{JET\ A} \times \eta_{c,JET\ A} + w_{biofuel} \times \eta_{c,biofuel} \tag{29}$$

$$\eta_{c,Phase2} = (0.7317 \times 0.99) + (0.2683 \times 0.85) = 0.7244 + 0.2281 = 0.9525$$

Phase 3: 50% Jet A, 50% Biofuel

Volumes in 1000 Liters [1 $m^3$]:

- Jet A Volume: 500 L
- Biofuel Volume: 500 L

Masses:

- JET A mass: $0.50\ L \times 800\ kg/m^3 = 400\ kg$
- Biofuel mass: $0.50\ L \times 880\ kg/m^3 = 440\ kg$
- Total mass: $0.60\ kg + 220\ kg = 840\ kg$

Mass Fractions:

$$w_{JET\ A} = \frac{400}{840} \approx 0.4762$$

$$w_{Phase3} = \frac{440}{840} \approx 0.5238$$

Energy Density of the Blend $E_{blend}$:

$$E_{blend} = w_{JET\ A} \times E_{JET\ A} + w_{biofuel} \times E_{biofuel}$$

$$E_{Phase3} = (0.4762 \times 43) + (0.5238 \times 37)$$

$$E_{Phase3} = 20.4766 + 19.3806$$

$$E_{Phase3} = 39.8575 \text{ MJ/kg}$$

Density of the Blend ($\rho_{blend}$):

$$\rho_{Phase3} = 840\ kg/m^3$$

Combustion Efficiency of the Blend ($\eta_{c,blend}$):

$$\eta_{c,blend} = w_{JET\ A} \times \eta_{c,JET\ A} + w_{biofuel} \times \eta_{c,biofuel}$$

$$\eta_{c,Phase3} = (0.4762 \times 0.99) + (0.5238 \times 0.85) = 0.4714 + 0.4452 = 0.9166$$

Calculating Thrust Proportionality Term:

$$T \propto RPM^n \times \sqrt{\frac{E_f \times \eta_c}{\rho_f}}$$

Phase 1: 100% Jet A Fuel:

$$T_{JET\ A} \propto \sqrt{\frac{E_{JET\ A} \times \eta_{c,JET\ A}}{\rho_{JET\ A}}} = \sqrt{\frac{43 \times 0.99}{800}} = \sqrt{\frac{42.57}{800}} = \sqrt{0.0532125} \approx 0.2306$$

This value will be used as reference.

Phase 2: 75% Jet A, 25% Biofuel

$$T_{Phase2} \propto \sqrt{\frac{E_{Phase2} \times \eta_{c,phase2}}{\rho_{phase2}}} = \sqrt{\frac{41.393 \times 0.9525}{820}} = \sqrt{\frac{39.457}{820}} = \sqrt{0.0481182}$$
$$\approx 0.2193$$

Relative Thrust Compared to Phase 1:

$$Relative\ Thrust_2 = \frac{T_{Phase2}}{T_{Phase1}} = \frac{0.2193}{0.2306} \approx 0.951$$

Thrust Reduction: $(1 - 0.951) \times 100\% \approx 4.9\ \%$

Phase 3: 50% Jet A, 50% Biofuel

$$T_{Phase3} \propto \sqrt{\frac{E_{Phase3} \times \eta_{c,phase3}}{\rho_{phase3}}} = \sqrt{\frac{39.8575 \times 0.9166}{840}} = \sqrt{\frac{36.533}{840}} = \sqrt{0.043491}$$
$$\approx 0.2085$$

Relative Thrust Compared to Phase 1:

$$Relative\ Thrust_3 = \frac{T_{Phase3}}{T_{Phase1}} = \frac{0.2085}{0.2306} \approx 0.9046$$

Thrust Reduction: $(1 - 0.9046) \times 100\% \approx 9.54\ \%$

SAF:

$$T_{SAF} \propto \sqrt{\frac{E_{SAF} \times \eta_{c,SAF}}{\rho_{SAF}}} = \sqrt{\frac{42 \times 0.98}{775}} = \sqrt{\frac{41.16}{775}} = \sqrt{0.053106} = 0.2304$$

Relative Thrust Compared to Phase 1:

$$Relative\ Thrust_{SAF} = \frac{T_{SAF}}{T_{Phase1}} = \frac{0.2304}{0.2306} \approx 0.9991$$

Thrust Reduction: $(1 - 0.9991) \times 100\% \approx 0.09\ \%$

**Table 5 Theoretical model expected thrust change for JET A, blends and SAF**

| Phase | Thrust Proportionality | Relative Thrust (%) | Thrust Change (%) |
|---|---|---|---|
| **Phase 1 (Jet A)** | 0.2306 | 100% | — |
| **Phase 2 (blend 2)** | 0.2193 | 95.1% | –4.9% |
| **Phase 3 (blend 3)** | 0.2085 | 90.46% | –9.54% |
| **SAF** | 0.2304 | 99.91% | -0.09% |

Theoretical Model Limitations: The simplified model provides an initial estimation but does not account for changes in combustion efficiency or engine performance due to different fuel properties.

SAF Performance: The theoretical model predicts that SAF would perform similarly to Jet A fuel, with an almost identical thrust. This aligns with expectations, as SAF is designed to be a drop-in replacement.

### 5.2.2 EGT

Based on theoretical knowledge of the combustion process, EGT, and the properties of FAME biofuel and JET A, it is possible to make assumptions about the changes in EGT during the three phases of the experiment.

The possible increase in Exhaust Gas Temperature (EGT) with higher concentrations of biofuel in the mixture can be attributed to several factors, and it likely results from a combination of properties related to biofuel chemistry and combustion characteristics.

Biofuels, specifically Fatty Acid Methyl Esters (FAME), generally have a lower energy density compared to conventional jet fuel like JET A. This means that, for the same mass of fuel, biofuel releases less energy during combustion. To compensate for this, the engine must burn more fuel to maintain the same thrust output, which can lead to higher EGTs because more fuel is being burned.

The autoignition temperature and boiling point of biofuels like FAME can differ significantly from those of JET A. Biofuels tend to have a higher flash point and a higher boiling point, which can affect how they vaporize and combust.

Incomplete combustion: if biofuel vaporizes less efficiently or burns more slowly than JET A, it may lead to delayed combustion, causing higher temperatures in the exhaust as more energy is released at a later stage in the cycle.

Biofuels like FAME contain oxygen within their molecular structure, unlike traditional jet fuels. This intrinsic oxygen content can lead to a more complete combustion process, resulting in higher combustion temperatures and consequently higher EGT. The presence of oxygen in the fuel means that less oxygen is required from the intake air, which can lead to a more intense combustion phase and increased exhaust temperatures.

Biofuels typically have higher viscosity and density than JET A. The engine might also adjust its fuel flow rate to maintain proper combustion, potentially leading to higher fuel consumption and higher EGT.

With a higher percentage of biofuel, the combustion might shift towards a slightly different stoichiometric balance. Since biofuels have different molecular compositions, the air-fuel ratio might change, leading to more complete combustion and higher flame temperatures, which in turn raise the EGT.

Regarding SAF, EGT could be similar or slightly lower than with Jet A fuel, as SAF has better combustion with fewer impurities, which may result in lower heat emissions in the exhaust gases.

### 5.2.3 RPM

In turbojet engines, when operating at a fixed throttle setting (e.g., 75% throttle), the engine control system aims to maintain a constant RPM. This is because the throttle position dictates the fuel and air flow rates, which determine the engine's rotational speed.

Theoretical expectations from the experiment are that the EGT will not change at fixed throttle settings or there will be minor changes throughout the phases of the experiment.

# 6. DATA COMPARISON

Each phase of the experiment was conducted twice, and the values taken were the arithmetic mean of the values at a specific RPM and throttle setting.

## 6.1. THRUST

During the experiment, data were recorded at three constant RPMs: 60000, 80000, and 120000. The goal of all three points was to gather data on the behavior of thrust in relation to the theoretical model. The obtained thrust data are presented in the following table.

**Table 6 Experimental Thrust Data**

| RPM | JET A (reference) [N] | EXPERIMENTAL 75% JET A, 25% FAME [N] | EXPERIMENTAL 50% JET A, 50% FAME [N] |
|---|---|---|---|
| 60 000 | 4.704 | 4.508 | 4.116 |
| 80 000 | 8.428 | 8.036 | 7.448 |
| 120 000 | 29.596 | 27.538 | 25.676 |

The theoretical model indicated that at a given constant RPM, for phase 2 (75% Jet A and 25% FAME), the theoretical thrust will be reduced by 4.9%. Similarly, it showed that for phase 3 (50% Jet A and 50% FAME), the thrust should be reduced by 9.54%. The theoretical thrust for the mixtures is shown in the table below.

**Table 7 Theoretical Thrust Values**

| RPM | JET A (reference) [N] | THEORETICAL 75% JET A, 25% FAME [N] | THEORETICAL 50% JET A, 50% FAME [N] |
|---|---|---|---|
| 60 000 | 4.704 | 4.474 | 4.255 |
| 80 000 | 8.428 | 8.015 | 7.62 |
| 120 000 | 29.596 | 28.146 | 26.772 |

Following the tabular comparison of theoretical and experimental data, a graphical representations are provided below for easier understanding.

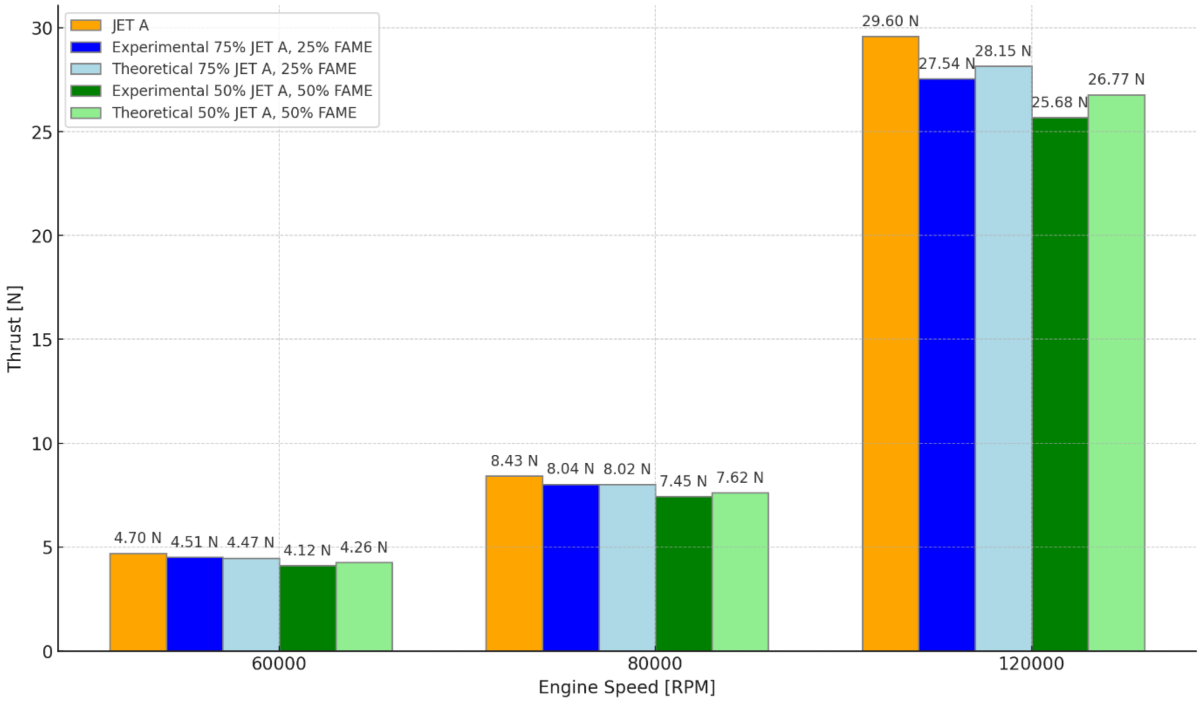

**Figure 15 Experimental vs theoretical thrust for both blends**

100% JET A (Orange bars) represents the reference thrust for each RPM level, used for comparison with the blended fuels. For the 75% Jet A and 25% FAME blend (Blue bars), the experimental percentage reduction in thrust compared to 100% Jet A aligns relatively closely with the theoretical prediction of 4.9%. However, there are minor deviations from the theoretical values. At 60000 RPM, the experimental thrust reduction is 4.16%, slightly less than the expected 4.9%, at 80000 RPM, the reduction is 4.65%, also below the expected 4.9%, and at 120000 RPM, the reduction is 6.94%, exceeding the expected reduction by about 2%. For the 50% Jet A and 50% FAME blend (Dark green bars), the experimental reduction in thrust shows larger deviations from the expected theoretical reduction of 9.54%. At 60000 RPM, the experimental reduction is 12.49%, about 3% greater than the theoretical reduction. At 80000 RPM, the reduction is 11.63%, again higher than the predicted 9.54%. At 120000 RPM, the reduction is 13.25%, exceeding the predicted 9.54% by about 3.7%. The experimental results indicate differences in thrust between Jet A fuel and the blends, which were also predicted by the theoretical model. It can be concluded that the theoretical model does not deviate significantly from the experimental results, considering the model's simplifications.

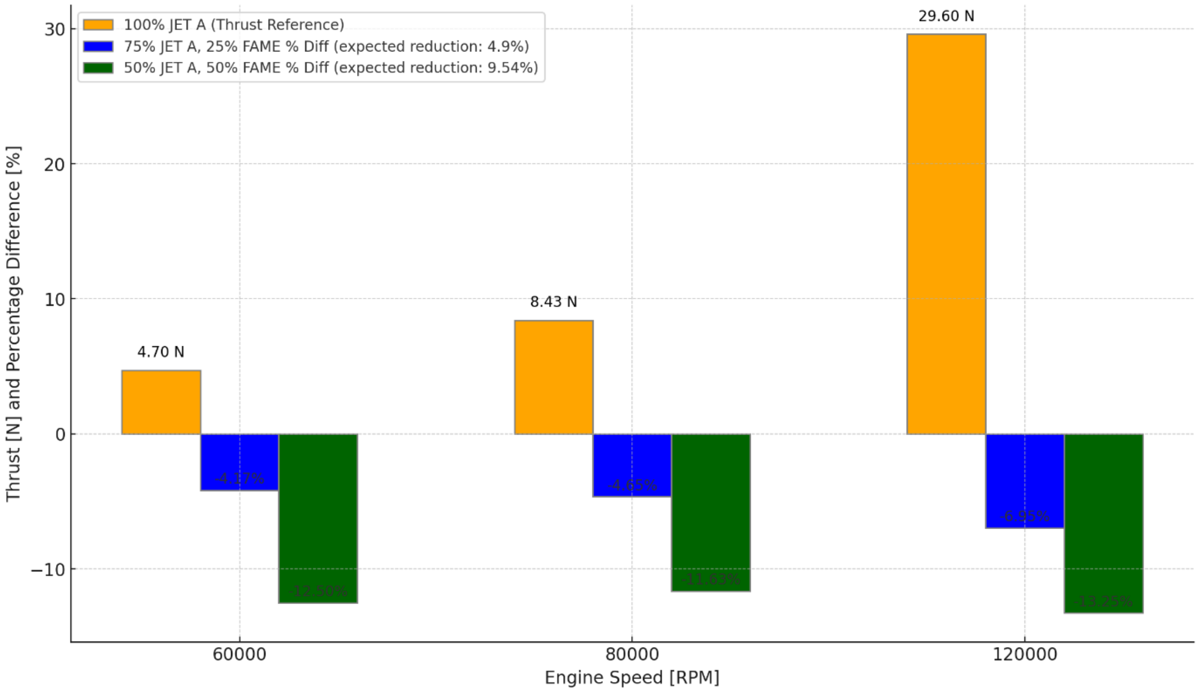

**Figure 16 Experimental thrust and percentage change compared to 100% JET A**

This graph illustrates the drops in thrust relative to the reference values of Jet A fuel In percentage points more clearly, and we can conclude that the theoretical model was accurate with an error margin of approximately 3%.

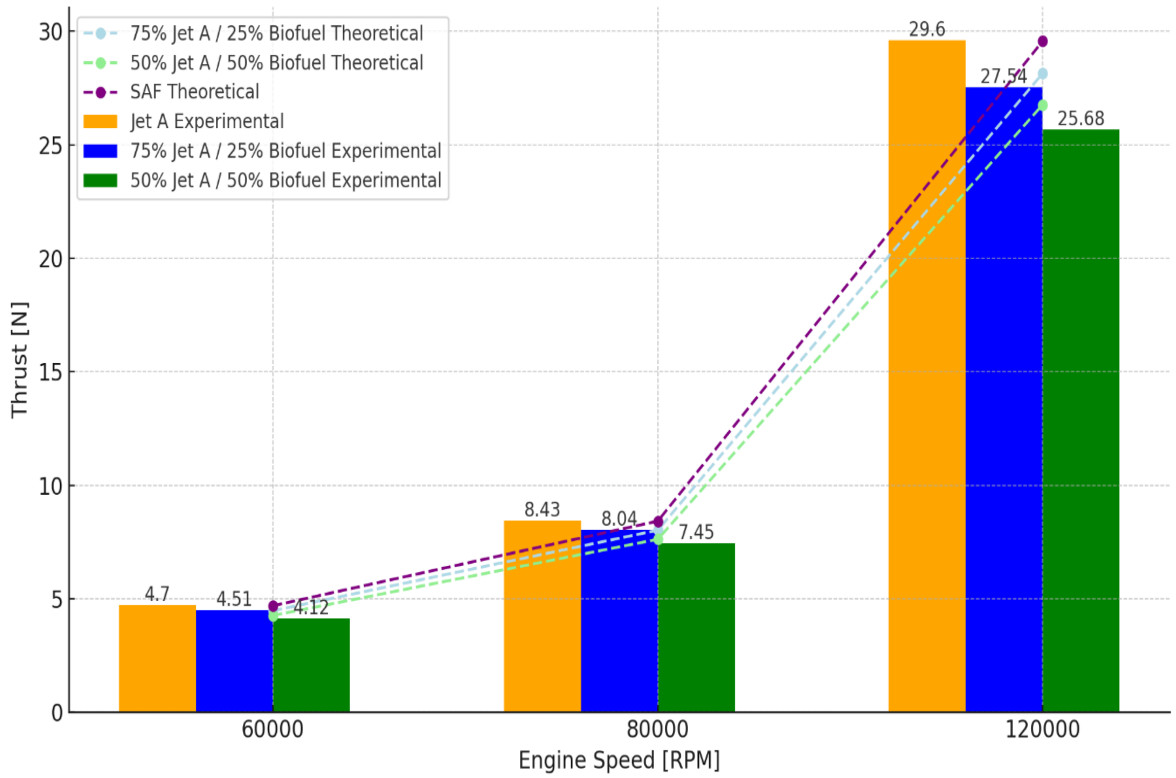

**Figure 17 Experimental and theoretical thrust for different fuels, including SAF**

This figure presents a comparison of experimental and theoretical thrust values for different fuel blends at three RPMs. In this graph, lines representing the theoretical model have been added to provide a clearer comparison of the theoretical and experimental results.

Notably, SAF's theoretical thrust values are consistently high, with 4.69 N at 60000 RPM, 8.42 N at 80000 RPM, and 29.57 N at 120000 RPM. The values for SAF indicate that it theoretically delivers 99.91% of the same performance as Jet A in terms of thrust across all RPMs.

## 6.2. EGT

In this experiment, the change in EGT at different RPM settings was monitored. The results are shown in Figure 18.

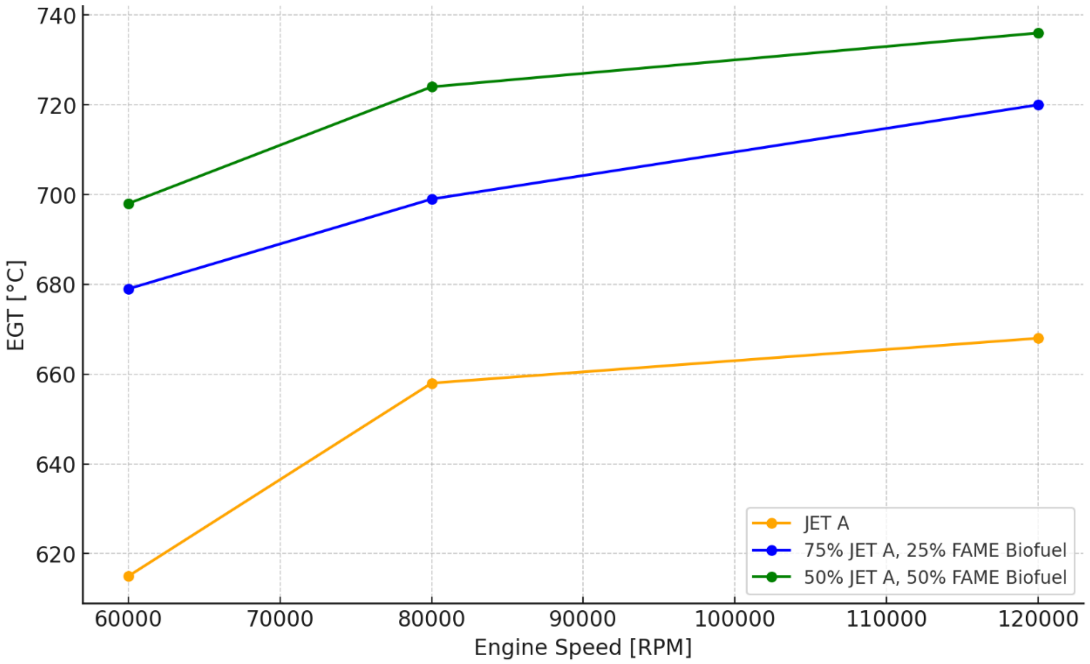

**Figure 18 Exhaust Gas Temperature (EGT) vs RPM for different fuels**

Jet A, being a conventional aviation fuel, provides a relatively moderate increase in EGT with rising RPM. The combustion is efficient and predictable, with only a modest increase in temperature at higher RPMs, reflecting stable combustion properties.

Introducing 25% FAME biofuel into Jet A noticeably increases the EGT across all RPMs. This is likely due to the delayed combustion characteristics of biofuels, as they have a higher flash point and autoignition temperature compared to Jet A. The higher viscosity and boiling range of FAME biofuel contribute to slower, less complete combustion at lower RPMs, causing increased thermal stress and higher EGT values.

With a higher proportion of FAME biofuel (50%), the EGT further increases across all RPMs. This substantial rise is attributed to the greater presence of FAME's chemical properties, which continue to cause delayed combustion. The incomplete combustion at lower RPMs leads to increased temperatures as the engine compensates with higher fuel flow. The increased autoignition temperature and flash point of FAME biofuel (ranging from 256°C to 266°C and 120°C to 180°C, respectively) delay the combustion onset, meaning more fuel burns later in the cycle, raising EGT.

Furthermore, due to the increased oxygen concentration in FAME biofuels, it was expected that there would be a rise in EGT.

## 6.3. RPM

This experiment and theoretical model were designed to measure data at constant RPM. Additionally, from this experiment, it is concluded that for constant throttle settings at three different RPMs, the RPM did not oscillate but remained around fixed values with negligible fluctuations. The graph below shows the relationship between thrust and RPM for the different fuels used in the experiment.

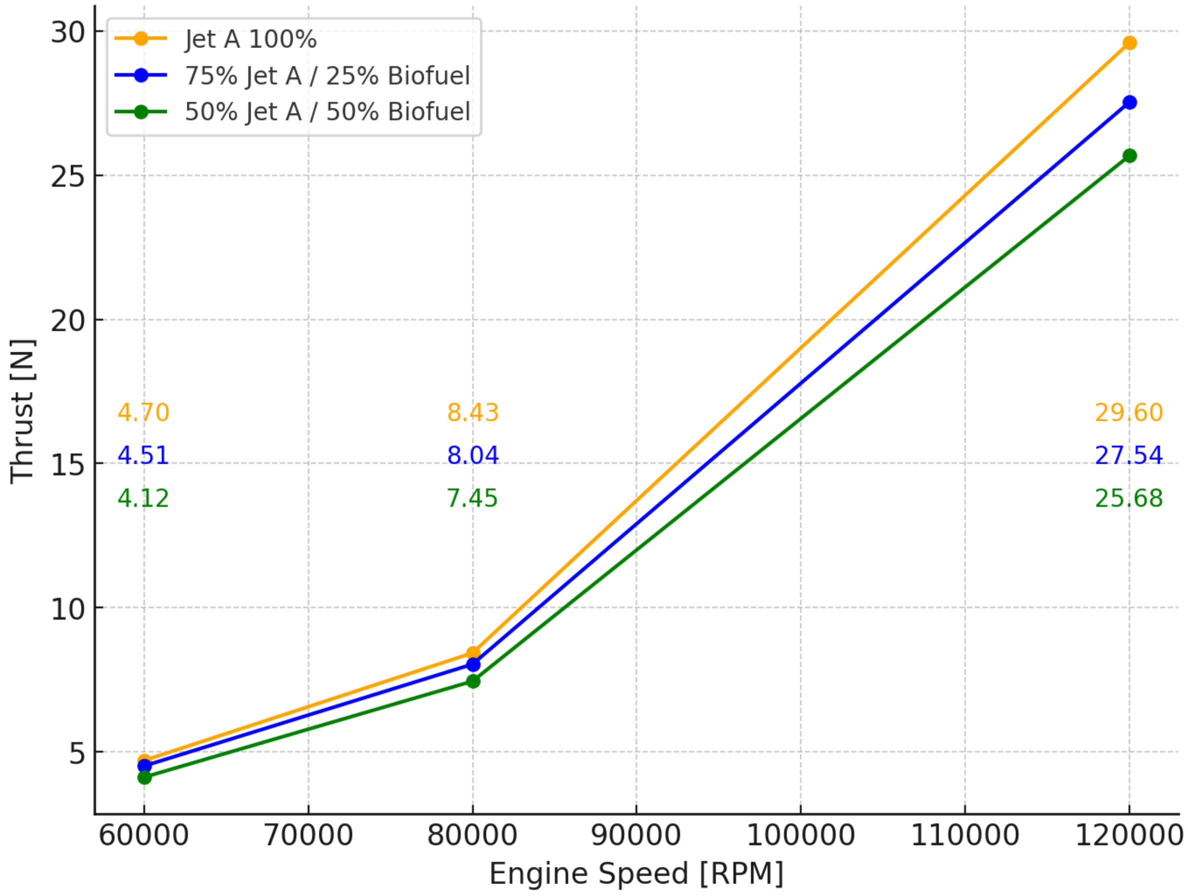

**Figure 19 The relationship between thrust and RPM for different fuels**

## 6.4. OTHER OBSERVATIONS, INCLUDING SAF

Regarding the experiment, although it was not directly measured by a sensor, it can be concluded that the throttle response was best when using 100% Jet A kerosene fuel, which is logical given that the JJ1400 turbojet engine is designed for such use. With each increase in the proportion of FAME biofuel in the fuel mixture, the throttle response weakened, and it took longer to reach certain thrust values.

Additionally, with the increased proportion of FAME biofuel, a lower concentration of $CO_2$ in the exhaust was observed, which is also a logical assumption considering the type of fuel. Similarly, an increase in $NO_x$ concentration in the exhaust is expected due to the increased oxygen concentration in the fuel. As for soot, there should be more of it in Jet A fuel because it contains more carbon.

The small deviation in the results between the experimental and theoretical model indicates that the theoretical model is accurate. Based on this, it is clear that the theoretical assumptions for SAF would also be applicable if we had conducted the experiment, meaning the results would be similar to those of Jet A due to the similar chemical properties between these two fuels. The only issues for greater SAF implementation remain its price and the lack of availability on the market.

During the experiment, it was evident that the highest fuel consumption occurred with fuels containing a higher proportion of FAME biofuel. It is clear that due to the reduced energy content, the pump compensated by increasing the fuel flow to achieve the same RPM.

# 7. CONCLUSION

In recent decades, the impact of climate change, largely due to human activities, has led to devastating natural events. Governments and international organizations are actively seeking solutions, and the aviation industry is no exception. Sustainable aviation fuels (SAF) are seen as a key driver in decarbonizing air traffic, but widespread adoption relies on mass production to reduce costs, along with government support for faster implementation.

If the complete life cycle analysis is considered, there may be even better methods.. One option could be requiring airlines to engage in reforestation efforts with plants that contribute the most to oxygen production and the reduction of carbon oxides. There are surely plants that contribute more to this than the mentioned plant raw materials, allowing continued use of Jet A.

This thesis aimed to evaluate the impact of Sustainable Aviation Fuels and biofuels on the performance of small turbojet engines, with a focus on the JJ1400 model. The theoretical results indicate that SAF should behave comparably to conventional Jet A fuel, although specific blends like the 75% Jet A and 25% FAME showed slight variations in terms of thrust and EGT. The theoretical model showed that the thrust of SAF will have almost identical behavior as in the engine using exclusively Jet A. The limiting factors for SAF remain its cost and production.

Both theoretical and experimental results for FAME biofuel have shown that it is not suitable for use in aviation turbojet engines due to significant deviations in engine performance, exceeding 10%. Due to safety concerns and the overall impact on observed performance parameters, FAME biofuel will not be certified as aviation fuel, although it has potential based on the raw materials used and green production process.

This research adds valuable insights into the potential of SAF in aviation. As the industry moves toward greener technologies, SAF, along with electric and hydrogen propulsion, will be crucial in achieving global decarbonization goals.

# References:

[1] Air bp. *How all sustainable aviation fuel (SAF) feedstocks and production technologies can play a role in decarbonizing aviation*. Downloaded from: https://www.bp.com/en/global/air-bp/news-and-views/views/how_all_sustainable_aviation_fuel_SAF_feedstocks_and_production_technologies_can_play_a_role_in_decarbonising_aviation.html. [Accessed: August 10 2024].

[2] IATA. *Net zero 2050: sustainable aviation fuels*. IATA & FLY NET ZERO. 2024.

[3] Air Bp. *What is sustainable aviation fuel (SAF)?*. Downloaded from: https://www.bp.com/en/global/air-bp/news-and-views/views/what-is-sustainable-aviation-fuel-saf-and-why-is-it-important.html. [Accessed: September 3 2024].

[4] Buse J. *SUSTAINABLE AVIATION FUELS; Transitioning Towards Green Aviation*. Boca Raton: CRC Press. 2024.

[5] ASTM International. *ASTM D7566-20, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons.* ASTM: West Conshohocken, 2020.

[6] European Commission. *EU Emissions Trading System (EU ETS).* Downloaded from: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en. [Accessed: September 7 2024].

[7] European Commission. *ReFuelEU Aviation*. Downloaded from:: https://transport.ec.europa.eu/transport-modes/air/environment/refueleu-aviation_en. [Accessed: September 10 2024].

[8] European Commission. *Renewable Energy Directive.* Downloaded from: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en. [Accessed: September 10 2024].

[9] ICAO. *CORSIA eligibility framework and requirements for sustainability certification schemes*. ICAO: 2024.

[10] IATA. *CORSIA*. IATA: 2024.

[11] ASTM International. *Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons (ASTM D7566).* ASTM International: 2023.

[12] Oehmichen K., Majer S., Müller-Langer F., Thrän D. *Comprehensive LCA of Biobased Sustainable Aviation Fuels and JET A-1 Multiblend.* Applied Sciences 12, no. 7,5: 2022.

[13] Mattingly J. D. *Elements of Gas Turbine Propulsion.* New York: McGraw-Hill, 1996.

[14] Gensel P. *Types Of Jet Engines.* Downloaded from: https://aviationoiloutlet.com/blog/types-of-jet-engines/. [Accessed: September 15 2024].

[15] Hünecke K. *Jet Engines Fundamentals of Theory, Design and Operation*. England: Air Life, 2012.

[16] Čavka T. *Projektiranje i izrada automatiziranog sustava za upravljanje radom turbomlaznog motora malog potiska.* Zagreb: Fakultet prometnih znanosti, 2017.

[17] JetJoe.com. *JJ-1400*. Downloaded from: http://www.jetjoe.com/cp_detail.html?pd=pd2. [Accessed: September 17 2024].

[18] Hill P.G. and Peterson C. R. *Mechanics and Thermodynamics of Propulsion, 2nd Edition.* Reading, Massachusetts: Addison-Wesley, 1992.

[19] Bioenergy, European Technology and Innovation Platform. *Fatty Acid Methyl Esters (FAME) Fact Sheet.* Downloaded from: https://www.etipbioenergy.eu/fact-sheets/fatty-acid-methyl-esters-fame-fact-sheet. [Accessed September 17 2024].

[20] Graboski M.S., McCormick R.L. *Combustion of Fat and Vegetable Oil Derived Fuels in Diesel Engines.* Amsterdam: Progress in Energy and Combustion Science, Elsevier, 1998.

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In Zagreb, 23 September 2024

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