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SUSTAINABLE AVIATION FUELS: A DEVELOPMENT OVERVIEW AND PERFORMANCE EVALUATION ON AERONAUTICAL ENGINES

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Abstract. *This paper conducts an in-depth exploration into the paradigm shift occurring within the aviation industry, marked by an imperative to enhance efficiency and reduce its environmental footprint. Central to this transformation are sustainable aviation fuels (SAFs), which serve as a promising alternative to traditional petroleum-based fuels. The research delves into the challenges posed by the industry's dependence on fossil fuels, emphasizing the economic and environmental drawbacks. Subsequently, it analyzes a spectrum of potential alternative fuels, including biofuels and synthetic options, and underscores the necessity of adhering to stringent quality standards. Furthermore, the paper evaluates the environmental and economic implications of transitioning to SAFs, elucidating the strategic investments being made by key industry players. Methodologically, the study employs the real Brayton model to analyze performance metrics, including thrust, thrust-specific fuel consumption (TSFC), and overall efficiency, offering insights into the viability of biofuel blends. This comprehensive analysis sheds light on the transformative potential of SAFs and paves the way for a sustainable trajectory in the aviation sector.*

Keywords: *decarbonization, sustainable aviation fuel, gas turbines, efficiency analysis*

1. INTRODUCTION

Aviation, like other industries throughout its development, has been under pressure to become increasingly efficient and clean, to the extent that the technologies currently being researched are geared toward solving this demand. New engine designs and increasingly better aerodynamic wings are among the major changes resulting from the need for extreme efficiency (Neste/IATA, 2021). Besides the environmental issue, aviation's dependence on oil is extremely harmful to the industry in the economic sense as well, since oil products fluctuate rapidly in price and have a high cost. Thus, one of the directions that aviation technology will have to take is to find new fuels, not derived from petroleum, but from clean and renewable sources.

Developing researches shows that there are numerous alternative fuel options to be tested further in aviation. Among these are options such as biofuels (biodiesel, biokerosene, ethanol), hydrogen, synthetic fuels or even made from the reuse of products, such as the one produced from burnt cooking oil used in several tests by airlines in recent years (Ng *et al.*, 2021). In addition to efforts to find a replacement for gasoline and kerosene in engines, there are research lines working on the electrification of fleets, using existing technologies in other industries, but making the necessary modifications to make them viable in aviation.

Since these are new and developing fuels, any new hydrocarbon-based compound must be standardized according to the current control and quality standards, i.e., they must conform to defined rules and protocols. Such standards involving tests, procedures and research for a new type of fuel are defined by ASTM D4054 (ASTM International, 2022). After this initial validation, the fuel is then specified in ASTM D7566 (ASTM International, 2021), which covers its production process and that of any other aviation fuel containing synthesized hydrocarbons. By the year 2020, there were 7 production chains approved to ASTM D7566.

Among the various classifications of aviation kerosene, it can be identified as Jet A-1 (or QAV-1), when it comes from fossil energy sources, alternative Jet (or alternative QAV), for when the fuel is derived from alternative and sustainable sources, and as Jet C (or QAV-C) when alternative Jet is mixed with Jet A-1 in certain proportions defined by the ANP (National Agency of Petroleum, Natural Gas and Biofuels) for Brazil (Petrobras, 2021). Therefore, based on this nomenclature, it can be said that different types of Jet C fuels will be addressed and treated.

In aviation, the strong dependence on fossil fuels is the bottleneck to make this means of transportation more sustainable, given that approximately 2% of greenhouse gas emissions come from aviation (Litt *et al.*, 2013). Furthermore, the dependence on oil derivatives becomes an economic and geopolitical problem, since the production and distribution of this resource are strategic issues and can be strongly affected by various problems unrelated to several consumer countries (Boehm *et al.*, 2021). Big companies are investing in the development and production increase of SAFs (Sustainable Aviation Fuels) (Boeing (2022) and Embraer (2022)). Moreover, many airlines are working with these companies and testing flights with higher percentages of sustainable fuel every year (Zschocke *et al.* (2012)), showing that this technology is a short-term bet. These facts justify the relevance of this work, since it is of utmost importance to evaluate and analyze viable alternatives to aviation in the face of these obstacles, in order to also contribute to its growth and ascension.

This paper represents a comprehensive exploration of the cutting-edge developments in aviation technology, with a particular emphasis on the pivotal role of SAFs. The scope of this work encompasses an in-depth analysis of the performance and environmental impact of SAFs in aviation engines, examining critical parameters such as thrust, thrust-specific fuel consumption (TSFC), and overall efficiency. Furthermore, it delves into the significance of adhering to stringent quality standards, as established by ASTM D4054 and ASTM D7566, to ensure the reliability and safety of these innovative fuels. This research not only contributes to the academic understanding of aviation technology but also holds practical implications for the aviation industry's ongoing transformation towards sustainability and efficiency.

For the analysis of SAFs in engines, the real Brayton model was chosen as a reference, because it is suitable for gas turbines and also because it can be adapted analytically for turbojet, turbofan and turboprop engines, which are the objects of present interest.

Both El-Sayed (2017) and Mattingly (2005) provide a clear and objective methodology to model these engines through the Brayton cycle, and several modeling variations are addressed in these two references, such as whether the engine has an afterburner or not, whether the bypass ratio is being optimized, among other possible variations. However, in this paper the approach available in El-Sayed (2017) will be used for each of the three engines mentioned for the case without afterburner and corresponding to the real Brayton cycle.

The analysis have focus on net thrust, thrust specific fuel consumption (TSFC) and overall efficiency. In order to maintain the engine performance and, consequently, the aircraft performance, alternative fuels must supply enough to have approximately the same thrust as Jet A-1 provides. Also, TSFC is other important parameter since fuel costs represents nearly 30% of the total expenses of a airline in Brazil and approximately 25% in USA (ABEAR (2015) and Kahn and Nickelsburg (2016)). Finally, analyze the overall efficiency was a choice to embrace both thermal and propulsive efficiency and represents the conversion of heat generated by fuel burning into thrust force (El-Sayed, 2017). The analysis will be at 5 of the 7 engine performance parameters presented in El-Sayed (2017).

As for the biofuels analyzed, 6 different blends were chosen with Jet A-1, all of which are in the maximum proportions allowed by ASTM D7566, except for the fuels CHJ (Catalytic Hydrothermolysis Jet) and ATJ-SKA (Alcohol to Jet - Synthetic Paraffinic Kerosene). The ATJ-SKA was not yet approved by the standard, so the same percentage as ATJ-SPK (Alcohol to Jet - Synthetic Paraffinic Kerosene) was used due to their similarity. Furthermore, data was only found for CHJ at a maximum proportion of 25%. The blends chosen are arranged as presented in Table 1.

Table 1. Fuel mixtures analyzed.

Name	**Acronym**	**% in the mixture with Jet A-1**
Alcohol to Jet - Synthetic Paraffinic Kerosene	ATJ-SPK	50
Synthesized Iso-Paraffins	SIP	10
Hydrotreated Esters and Fatty Acids	HEFA	50
Fischer-Tropsch	FT	50
Catalytic Hydrothermolysis Jet	CHJ	25
Alcohol To Jet - Synthesized Kerosene with Aromatics	ATJ-SKA	50

Of these, only ATJ-SKA have not yet been approved by ASTM D7566 and is being tested. Thus, all the other 5 fuels have already been approved and can be classified as "drop-in", i.e. it is possible to use them without the engines needing to undergo modifications.

2. METHODOLOGY

Studies on alternative energy sources and their feasibility are extremely complex, requiring considerations about engine efficiency, durability, maintainability, construction aspects and the economic possibility of fuel development and supply. Therefore, the analysis will be restricted to the performance of turbojet, turbofan and turboprop engines, as well as comments on the level of maturity of new fuels being developed and modifications in aircraft systems required for the application of the changes.

Regarding fuels, a presentation will be made of different compounds mixed into the Jet A-1 currently used, showing from a review perception how advanced each development is. Also, the energy qualities of the new fuels will be scored in order to determine, later, the approximate performance of the engines consuming each of them.

For the engine simulations will be used the PEA-GT software (Gama, 2020). The software uses as input data the component model presented in El-Sayed (2017), based on their polytropic and isentropic efficiencies and pressure and temperature relationships at the inlet and outlet of each of them. For the calculation of the complete cycle, the real Brayton cycle is used as a basis, relying on the input data as being the airflow rate at the design point, chosen as 35000 ft and Mach 0.8, conditions that approximate the condition in cruise flight, and ISA (International Standard Atmosphere) temperature, considering air bleed for cooling components, total pressure ratio in the high pressure compressor, temperature at the combustor outlet, fan pressure ratio (for the turbofan engine), component efficiencies, and fuel calorific power. The cycle calculates from the component models the inlet and outlet pressure and temperature data, and at the end presents the propulsive and thermal efficiencies, total efficiency, traction, and specific consumption for each of the engines. The values for the parameters used in PEA-GT were based on the CFM56, whose data were taken from Baptista (2017), Gunston (2017) and EASA (2021). The core specifications are the same for the 3 engines, in order to have a good comparison basis. The mass energy densities and the densities for each of the fuels present in the Table 2 were collected from Zschocke *et al.* (2012).

Table 2. Data of mixtures and Jet A-1.

Fuel	**Jet A-1**	**ATJ-SPK (50%)**	**SIP (10%)**	**HEFA (50%)**	**FT (50%)**	**CHJ (25%)**	**ATJ-SKA (50%)**
Energy density [MJ/kg]	43,073	43,672	43,160	43,597	43,488	43,111	43,287
Density [kg/m³]	818,6	788,2	814,1	787,8	789,9	815,1	791,7

2.1 Turbojet engine

Table 3 presents input data for the turbojet engine. These inputs are the core data for all three engines.

Table 3. Input data for the Turbojet engine.

Input	**Value**
Airflow at the design point [kg/s]	60
Percentage of air used for cooling the high pressure turbine	0,05
Total pressure ratio in the high pressure compressor	15
Total pressure ratio at air inlet	0,995
Total pressure ratio in the combustion chamber	0,95
Combustor outlet temperature [K]	1700
Isentropic efficiency of the high pressure compressor	0,90
Isentropic efficiency of the combustion chamber	0,999
Isentropic efficiency of the high pressure turbine	0,90
Isentropic efficiency of the exhaust nozzle	0,97

The PEA-GT software calculate the net traction (T_{net}) using Eq. (1) for turbojet engine.

$$T_{net} = \dot{m}_a \left[(1+f) V_9 - V \right] + (P_9 - P_a) A_9, \tag{1}$$

where $\dot{m}_a$ is the mass airflow, f is the fuel-to-air ratio, V_9 is the air velocity at the exhaust nozzle exit, V is the flight air speed, P_9 is the pressure at the exhaust nozzle exit, P_a is the ambient pressure and A_9 is the cross-sectional area of the exhaust nozzle exit.

The thrust-specific fuel consumption (TSFC) is calculated using Eq. (2).

$$TSFC = \frac{f}{T_{net}/\dot{m}_a} \tag{2}$$

Thermal efficiency (η_{th}) is given by Eq. (3).

$$\eta_{th} = \frac{(1+f) V_{9_{eq}}^2 - V^2}{2 f h_{PR}} \tag{3}$$

where $V_{9_{eq}}$ is the equivalent velocity at the exhaust nozzle exit, depending of the condition of the nozzle throat (choked or unchoked) and h_{PR} is the energy density of the fuel.

Propulsive efficiency (η_p) is computed using Eq. (4).

$$\eta_p = \frac{T_{net}V}{\dot{m}_a\left[(1+f)\,V_{9_{eq}}^2/2 - V^2/2\right]} \tag{4}$$

Finally, the overall efficiency (η_O) is given by Eq. (5).

$$\eta_O = \eta_{th} \cdot \eta_p \tag{5}$$

2.2 Turbofan engine

Table 4 presents input data for the turbofan engine in addition to the core inputs.

Table 4. Additional input data required for the Turbofan engine.

Input	Value
Bypass ratio	5,0
Pressure ratio of the fan	1,7
Total pressure ratio in the fan duct	0,97
Isentropic efficiency of the fan	0,90
Isentropic efficiency of the low pressure turbine	0,90

For the turbofan engine, PEA-GT computes the T_{net} using Eq. (6)

$$T_{net} = \dot{m}_{ah}\,(1+f)\,V_9 + \dot{m}_{ac}V_{19} - \dot{m}V + (P_9 - P_a)\,A_9 + (P_{19} - P_a)\,A_{19}, \tag{6}$$

where $\dot{m}_{ah}$ is the mass airflow through engine core, $\dot{m}_{ac}$ is the mass airflow through fan duct, V_{19}, P_{19} and A_{19} are the air velocity, pressure and cross-sectional area at the fan duct exhaust nozzle exit, respectively.

TSFC for turbofan engine is given by the same equation for turbojet, but using $\dot{m}_{ah}$ instead of $\dot{m}_a$.

The η_{th} is calculated using Eq. (7).

$$\eta_{th} = \frac{(\dot{m}_{ah} + \dot{m}_{ac})\left(V_{9_{eq}}^2 - V^2\right)/2}{\dot{m}_{ah} f h_{PR}} \tag{7}$$

η_p is given by Eq. (8).

$$\eta_p = \frac{2T_{net}V}{(\dot{m}_{ah} + \dot{m}_{ac})\left(V_{9_{eq}}^2 - V^2\right)} \tag{8}$$

Finally, η_O is the product between η_{th} and η_p, as for the turbojet engine.

2.3 Turboprop engine

Table 5 presents input data for the turboprop engine. In addition to core data, the turboprop engine has the same efficiency for the low pressure turbine that turbofan and a smaller efficiency for the exhaust nozzle (0,90 instead of 0,97).

Table 5. Input data for the Turboprop engine.

Input	Value
Ratio of total exhaust pressure to atmospheric pressure	1,1
Isentropic efficiency of the propeller at the design point	0,50
Isentropic efficiency of the propeller reduction gearbox	0,97

PEA-GT calculates T_{net} for the turboprop engine using Eq. (9).

$$T_{net} = \dot{m}_a\left[(1+f)\,V_9 - V\right] + (P_9 - P_a)\,A_9 + \frac{P\eta_{prop}}{V}, \tag{9}$$

where P is the shaft power and η_{prop} is the propeller efficiency.

TSFC is calculated using the same equation for turbojet engine (Eq. (2)).

The η_{th} is given by Eq. (10).

$$\eta_{th} = \frac{P}{\dot{m}_a f h_{PR}} \tag{10}$$

η_O is computed using Eq. (11).

$$\eta_O = \frac{T_{net}V}{\dot{m}_a f h_{PR}} \tag{11}$$

Finally, the η_p is given by Eq. (12).

$$\eta_p = \frac{\eta_O}{\eta_{th}} \tag{12}$$

2.4 SAFs overview

ATJ-SPK represents fuels whose feedstock comes from biomass from ethanol or isobutanol production, starchy and sugary crops, lignocellulosic residues and industrial flue gases. Some organizations working on the development of ATJ-SPK are Gevo, Cobalt, Honeywell UOP, Lanzatech, Swedish Biofuels and Byogy. The use of blends of ATJ-SPK with Jet A-1 in a 50-50% ratio was approved by ASTM D7566 (ASTM International, 2021) in 2016 for the use of ethanol as feedstock, and for the use of isobutanol as feedstock the approval occurred in 2018. In addition, this blend is characterized as "drop-in," so no mechanical changes to engines are required before it can be used as a fuel.

SIP's main feedstocks come from hydroprocessed fermented sugars, biomass used for sugar production, sugarcane and any type of vegetal sugar. Its main developers and producers are the companies Amyris and Total. The use of a blend of SIP with Jet A-1 was approved by ASTM D7566 (ASTM International, 2021) in 2014, with the maximum percentage allowed for SIP being 10%. The reason for this lower percentage in the blend is due to the fact that SIP is composed of only a single compound, called farnesane, unlike other fuel types such as ATJ-SPK or HEFA, for example. In addition, SIP is also considered to be "drop-in".

Hydroprocessed esters, fatty acids, bio-oils, animal fat and recycled oils are used as feedstocks for HEFA. The main companies involved in the production and development of HEFA are World Energy, Honeywell UOP, Neste Oil, Dynamic Fuels and EERC. The use of blends of HEFA with Jet A-1 was approved by ASTM D7566 (ASTM International, 2021) in 2011, considering a maximum blend ratio of 50%, then it is also a "drop-in" fuel up to this ratio. There is currently a demand in the market for higher blend ratios to be approved, mainly by Boeing (Zschocke *et al.*, 2012).

FT's main feedstock sources are coal, natural gas and biomass, all of which can be used to produce synthetic gas, the production of which is the initial step in the FT production pathway. Leading organizations in the development and production of FT fuel are Fulcrum Bioenergy, Red Rock Biofuels, SG Preston, Kaidi, Sasol, Shell and Syntroleum. In 2009 it was approved by ASTM D7566 (ASTM International, 2021) to use a mixture of FT and Jet A-1 with the maximum percentage of FT being 50%. Thus, FT was the first fuel to be approved, that is, it was one of the reasons for the creation of ASTM D7566. Like the fuels already treated, FT is also classified as "drop-in".

CHJ's main feedstock comes from vegetable oils, waste fats, oils, greases and triglycerides such as soybean oil, jatropha oil, camelina oil, carinata oil and tung oil. Currently, the main organizations working on CHJ development are Applied Research Associates (ARA) and Chevron. The use of blends containing CHJ was approved by ASTM D7566 (ASTM International, 2021) as recently as 2020. The maximum approved percentage of CHJ in the blend with Jet A-1 was 50%, but for engine performance analysis a blend containing 25% CHJ will be considered. In addition, like the previous fuels, CHJ is also classified as "drop-in".

ATJ-SKA is similar to the ATJ-SPK, with the main difference being the presence of aromatics in the composition of the ATJ-SKA. Therefore, the feedstock sources are essentially the same as for the ATJ-SPK. The main organizations developing it are Swedish Biofuels and Byogy. Unlike the other fuels treated so far, ATJ-SKA is not yet listed as approved by ASTM D7566, but is already in progress. Therefore, due to its similarity to ATJ-SPK, it was also chosen to consider a 50% blend of ATJ-SKA with Jet A-1 for performance analysis.

3. RESULTS

The analysis of the results will be made from the total efficiency, traction and thrust specific consumption of the engines with each type of fuel presented, comparing two situations: the data of the same fuel for different engines and between engines of the same type for different fuels.

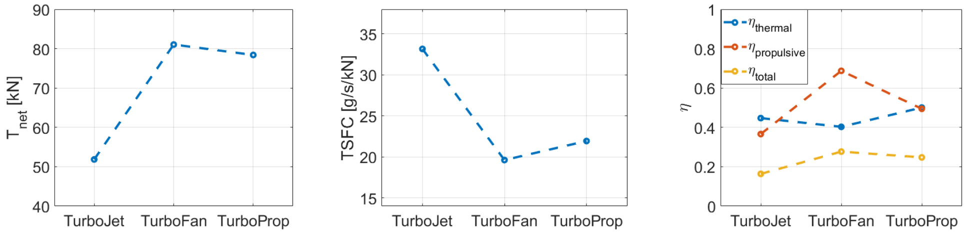
In tables and figures, T_{net} is the net thrust, TSFC is the thrust specific fuel consumption, η_O is the overall efficiency, η_{th} is the thermal efficiency and η_p is the propulsive efficiency.

3.1 ATJ-SPK (50%)

Results for the ATJ-SPK performance analysis is presented for the three types of engines in Table 6 and Figure 1.

Table 6. Performance Parameters for ATJ-SPK (50%).

Parameter	Turbojet	Turbofan	Turboprop
T_{net} [N]	51855,4	81043,4	78399,8
TSFC [g/s/kN]	33,1660	19,6185	21,9368
η_O	0,1638	0,2769	0,2476
η_{th}	0,4472	0,4028	0,5008
η_p	0,3662	0,6873	0,4944



(a) Net Traction (b) TSFC (c) Efficiencies

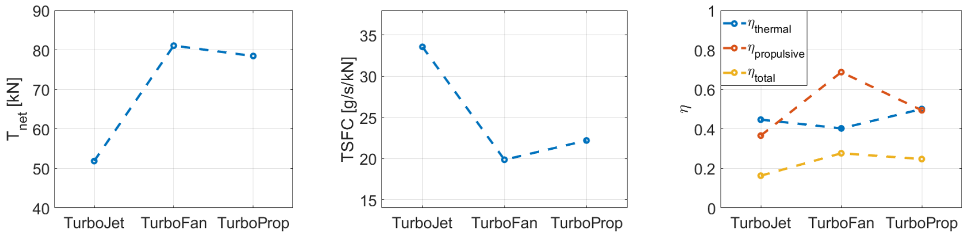
Figure 1. Parameters using ATJ-SPK (50%) for each of the engines.

3.2 SIP (10%)

The performance results on the engines using the Jet A-1 mixture with 10% SIP is shown in Table 7 and Figure 2.

Table 7. Performance Parameters for SIP (10%).

Parameter	Turbojet	Turbofan	Turboprop
T_{net} [N]	51874,3	81068,9	78447,4
TSFC [g/s/kN]	33,5662	19,8563	22,1960
η_O	0,1637	0,2768	0,2476
η_{th}	0,4470	0,4027	0,5008
η_p	0,3663	0,6873	0,4944



(a) Net Traction (b) TSFC (c) Efficiencies

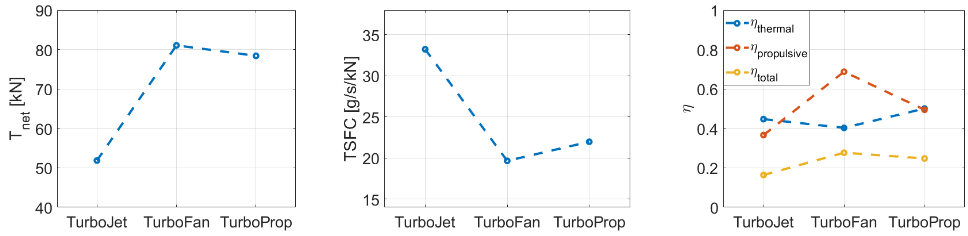
Figure 2. Parameters using SIP (10%) for each of the engines.

3.3 HEFA (50%)

The performance parameters for HEFA (50%) are given in Table 8 and Figure 3.

Table 8. Performance Parameters for HEFA (50%).

Parameter	Turbojet	Turbofan	Turboprop
T_{net} [N]	51858,1	81047,1	78406,7
TSFC [g/s/kN]	33,2241	19,6529	21,9744
η_O	0,1638	0,2768	0,2476
η_{th}	0,4471	0,4028	0,5008
η_p	0,3663	0,6873	0,4944



(a) Net Traction (b) TSFC (c) Efficiencies

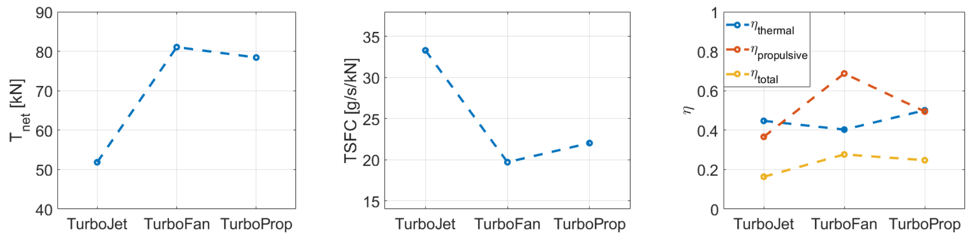
Figure 3. Parameters using HEFA (50%) for each of the engines.

3.4 FT (50%)

The FT at 50% had the results for the 3 engines as presented in Table 9 and Figure 4.

Table 9. Performance Parameters for FT (50%).

Parameter	Turbojet	Turbofan	Turboprop
T_{net} [N]	51862,1	81052,5	78416,7
TSFC [g/s/kN]	33,3087	19,7033	22,0292
η_O	0,1638	0,2768	0,2476
η_{th}	0,4471	0,4028	0,5008
η_p	0,3663	0,6873	0,4944



(a) Net Traction (b) TSFC (c) Efficiencies

Figure 4. Parameters using FT (50%) for each of the engines.

3.5 CHJ (25%)

The results for a mixture of 25% CHJ and 75% Jet A-1 are presented in Table 10 and Figure 5.

Table 10. Performance Parameters for CHJ (25%).

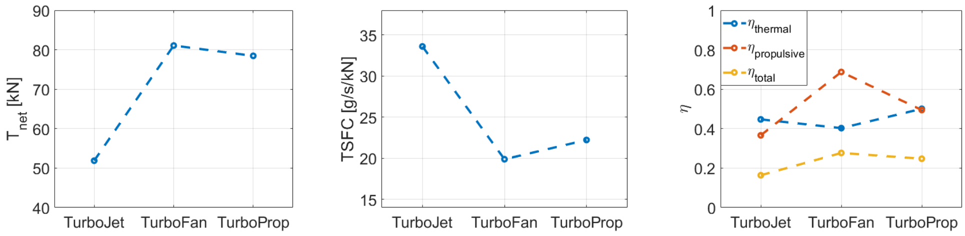
Parameter	Turbojet	Turbofan	Turboprop
T_{net} [N]	51876,1	81071,3	78452,0
TSFC [g/s/kN]	33,6050	19,8793	22,2212
η_O	0,1637	0,2768	0,2476
η_{th}	0,4470	0,4027	0,5008
η_p	0,3663	0,6873	0,4944

3.6 ATJ-SKA (50%)

The results for this fuel mixture containing 50% ATJ-SKA and 50% Jet A-1 for each of the 3 engines analyzed are listed in Table 11 and Figure 6.

3.7 JET A-1 (100%)

Finally, the PEA-GT software was used for a fuel containing 100% of Jet A-1, so that the results obtained could be compared to those of the 6 blends mentioned above. The results for 100% Jet A-1 are presented in Table 12 and Figure 7.

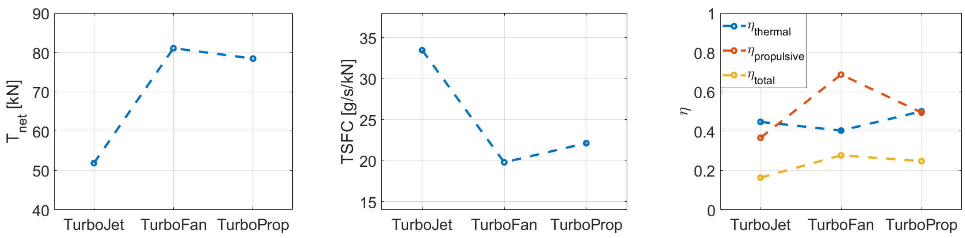


(a) Net Traction (b) TSFC (c) Efficiencies

Figure 5. Parameters using CHJ (25%) for each of the engines.

Table 11. Performance Parameters for ATJ-SKA (50%).

Parameter	Turbojet	Turbofan	Turboprop
T_{net} [N]	51869,5	81062,5	78435,5
TSFC [g/s/kN]	33,4660	19,7967	22,1312
η_O	0,1637	0,2768	0,2476
η_{th}	0,4470	0,4027	0,5008
η_p	0,3663	0,6873	0,4944

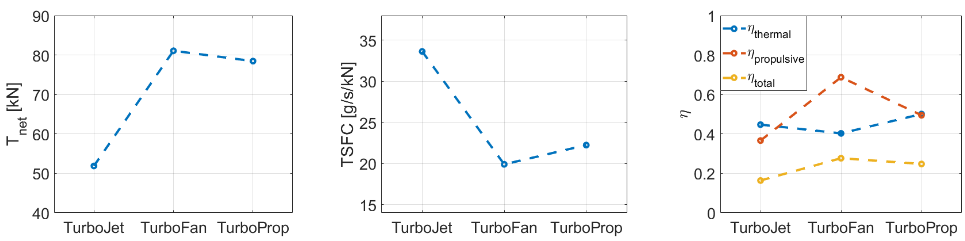


(a) Net Traction (b) TSFC (c) Efficiencies

Figure 6. Parameters using ATJ-SKA (50%) for each of the engines.

Table 12. Performance Parameters for Jet A-1 (100%).

Parameter	Turbojet	Turbofan	Turboprop
T_{net} [N]	51877,5	81073,2	78455,6
TSFC [g/s/kN]	33,6351	19,8972	22,2407
η_O	0,1637	0,2768	0,2476
η_{th}	0,4470	0,4027	0,5008
η_p	0,3663	0,6873	0,4944



(a) Net Traction (b) TSFC (c) Efficiencies

Figure 7. Parameters using Jet A-1 (100%) for each of the engines.

3.8 Comparison between the mixtures for each engine

It can be seen that Jet A-1 is the fuel that presented the best performance in traction. The blends with SAF, however, presented very close values, showing that they are a viable alternative. This behavior was repeated for the three engines.

As expected, the Turbofan engine proved to be the most powerful for the flight condition analyzed. This type of engine is known to have lower net traction at low speeds than the Turboprop, but a higher performance at cruise flight conditions. The Turboprop showed slightly lower traction than the turbofan, but still high for this type of engine at this speed, since Turboprops excel at lower Machs. This behavior may be a deficiency of the PEA-GT program in computing the aerodynamic changes in the propeller at high speeds. Finally, the turbojet engine showed the lowest net traction. The overall engine performance followed the pattern for all fuels, showing that the SAFs are very close to the Jet A-1 in performance characteristics.

Regarding to specific consumption, Jet A-1 (100%) presented the highest value, despite the proximity between all blends, showing that the use of SAFs does not require changes in the aircraft fuel system with regard to tank capacity. This means that the use of biofuels would cause a small reduction in fuel consumption during flight.

Comparing the fuels efficiencies, the variation was negligible, so the general conclusion is that the SAFs do not affect the thermal neither the propulsive efficiency. This behavior corroborates with the conclusion that SAFs are highly feasible in aeronautical operations.

In addition, all the SAFs analyzed have lower density than Jet A-1, as presented in Table 2, i.e., for a fixed volume tank used at its maximum capacity, there would be a reduction in minimum operational weight of the aircraft, with the maximum occurring when replacing Jet A-1 by HEFA (50%), with a reduction of approximately 3.8% in weight.

Despite the results presented, the large usage of SAF is still facing some challenges like the production price and their availability. The price per ton of the sustainable fuels is at least 60% higher than fossil fuels (€600 versus €950) and commercial aviation nowadays demands much higher quantities of fuel than SAF producers can supply, for example, the potential biofuel production capacity in Europe is only about 4% of the required demand, which is a difficult for the wide use of SAF in the market (EASA, 2019).

Furthermore, the maturity level of these fuels are variable. Some of them have enough technology available to achieve higher productions, meanwhile others do not have a well established production chain. Using the NASA technology readiness level (TRL) (Mankins *et al.*, 1995) to analyse the SAFs, HEFA (50%) is in the maximum maturity level (9 of 9), instead ATJ-SPK (50%) is 6 to 7, i.e, between technology demonstration and development for industrial scale. However, despite its high maturity, one of the problems with HEFA is its limited production capacity, since it is also a biofuel used in the road sector, i.e., there is competition between the aviation and road industries, which ends up creating an even greater shortage of this biofuel.

Considering the technical analysis carried out, the scale of production capacity and the certainty of its use for gas turbines, Table 13 presents a classification for the SAFs.

Table 13. Fuel features.

Fuel	**Feature**
ATJ-SPK	“drop-in” fuel, abundant feedstock
SIP	“drop-in” fuel, few producers
HEFA	“drop-in” fuel, ease of production
FT	“drop-in” fuel, low production
CHJ	“drop-in” fuel, fully synthetic kerosene
ATJ-SKA	technology currently being tested

The results presented in Kroyan *et al.* (2022), which emphasize the effectiveness of SAFs in relation to jet engine performance, establish a solid foundation for the analysis conducted in this paper. While the first text highlights SAFs' ability to maintain jet engine performance at levels comparable to fossil fuels, this study delves into the mathematical modeling of fuel properties and their influence on fuel consumption. The connection between these two sets of results is crucial as it demonstrates that not only do SAFs have positive practical performance, but they can also be comprehended and optimized through detailed analyses of fuel characteristics. Therefore, the conclusions of Kroyan *et al.* (2022) validates the results, underscoring the feasibility and potential of SAFs in making aviation more sustainable and efficient.

4. CONCLUSION

In the pursuit of sustainable and eco-friendly solutions within the aviation industry, SAFs have emerged as a prominent contender, presenting a compelling alternative to conventional fossil fuels. The environmental impact of aviation, particularly its substantial contribution to greenhouse gas emissions, necessitates urgent measures to mitigate its effects. SAFs, derived from renewable resources, offer an avenue to significantly reduce the industry's carbon footprint. This study delves into the comprehensive assessment of SAFs, focusing on their performance aspects compared to Jet A-1, a commonly used aviation fuel. Through rigorous analysis and empirical data, this research seeks to shed light on the potential of SAFs in revolutionizing the aviation sector, aligning with global efforts for a sustainable future.

The study's findings highlight the significant potential of SAFs as a viable alternative to traditional fossil fuels in the aviation sector. Notably, SAFs exhibited minimal variations in net traction, with differences as small as 0.1%, demonstrating their comparable power to Jet A-1. Specific consumption also remained stable, showing variations lower than 1.5% when compared to Jet A-1, while consistently maintaining lower specific consumption values overall.

Furthermore, the comparison of SAFs across three different engine types yielded consistent performance results, reinforcing their reliability and adaptability. This uniformity in performance positions SAFs as a compelling solution for achieving substantial reductions in CO2 emissions. This is particularly relevant given the limited technological development of electric and hydrogen propulsion systems for aviation.

The study's proposal to replace Jet A-1 entirely with SAFs, particularly those classified as "drop-in" fuels, emerges as an expedient strategy to achieve the desired greenhouse gas emission reductions without compromising engine thrust. Despite challenges related to pricing and production capacity, the active investment from major aircraft manufacturers and airlines underscores the growing industry interest in SAFs. Among SAF types, HEFA emerges as a recommended choice due to its favorable characteristics, including lower density and well-established aviation technology.

In summary, the study's results firmly establish SAFs as a promising avenue for revolutionizing aviation towards sustainability. The minimal performance differentials observed, combined with their environmental benefits, emphasize the potential of SAFs to play a pivotal role in addressing the aviation industry's sustainability challenges.

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6. RESPONSIBILITY NOTICE

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