

GT2025-153997

DESIGN SPACE EXPLORATION OF GEARED TURBOFANS USING ALTERNATIVE FUELS

Nabila Cava, Pavlos Rompokos, Christos Mourouzidis, Ioannis Roumeliotis

Centre for Propulsion and Thermal Power Engineering, Cranfield University,
Bedford, UK

ABSTRACT

This paper explores the design space of UHBPR geared turbofan engines for the short-to-medium range market, focusing on the comparative performance of engines powered by conventional Jet A-1, Hydroprocessed Esters and Fatty Acids (HEFA), and liquid hydrogen accounting for the thermal management effect of the cryogenic fuel. Utilizing a multi-point design approach, the research aims to optimize engine configurations for each fuel type, considering the anticipated entry into service in 2035 (EIS2035). The study investigates key parameters such as engine performance, size and weight.

The findings reveal that HEFA-optimised engines show a moderate 0.16% improvement in energy-specific fuel consumption (ESFC) and exhibit minimal changes in engine performance, size, and weight compared to the Jet-A baseline, confirming its feasibility as a retrofitted fuel in existing Jet-A engines. This positions HEFA as a practical short-term solution. In contrast, hydrogen-optimised engines that utilise fuel preheating, demonstrate an increase in specific energy consumption by nearly 5.6% mainly attributed to the fuel conditioning, but can enable more compact designs with a reduction of 1.9% in bare engine weight. Furthermore, a retrofitting analysis indicates that Jet A-1-optimised design can adequately accommodate both HEFA and H₂ but with decreasing ESFC differences of -0.1% and 6.9% for HEFA and Hydrogen.

Keywords: UHBPR Turbofans, Alternative fuels, Hydrogen, HEFA

NOMENCLATURE

B	Biot Number
BPR	Bypass Ratio
EIS	Entry Into Service
EoR	End of Runway
ESFC	Energy-Specific Fuel Consumption
FAR	Fuel-to-Air Ratio
FN	Net Thrust
FPR	Fan Pressure Ratio

HP	High Pressure system
HPC	High Pressure Compressor
HPT	High Pressure Turbine
IPC	Intermediate Pressure Compressor
K _{cool}	Cooling flow factor
LP	Low Pressure system
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
MCR	Mid Cruise
PGB	Power Gearbox
PR	Pressure Ratio
SFC	Specific Fuel Consumption
sFN	Specific Thrust
TET	Turbine Entry Temperature
ToC	Top of Climb
UHBPR	Ultra-High By-Pass Ratio
WF	Fuel Flow
ε	effectiveness

1. INTRODUCTION

Today's aircraft are 75% more fuel efficient than aircraft from the early jet age. However, despite these advancements, the environmental emissions from aviation still fall short of the targets set by the Paris Agreement [1] due to the predicted rise in air traffic in the next few years [2]. It is envisaged that if all other sectors meet their emission reduction targets, aviation will constitute the overriding majority of mankind's carbon budget by mid-century [3]. The IPCC report states with high confidence that to limit an overshoot of 1.5°C, global net anthropogenic CO₂ emissions are required to be reduced by about 45% from 2010 levels by 2030, reaching net zero around 2050 [4]. Similar

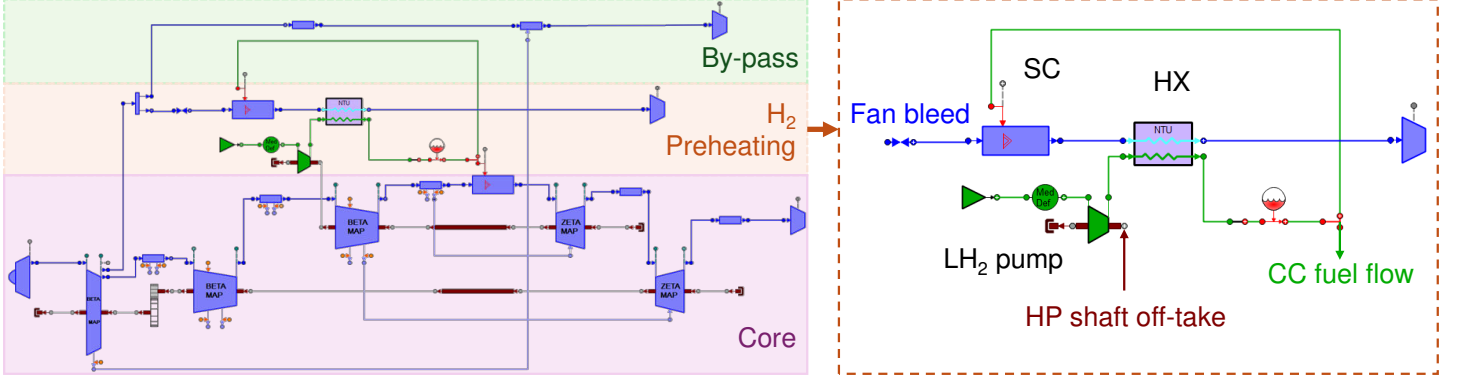


FIGURE 2: Two spool geared turbofan engine model with integrated LH₂ preheating system

used for the Jet A-1 and HEFA designs, but it is fitted with an LH₂ preheating system. This comprises a gas line and a fuel line. The gas line utilises bleed from the engine, which is then directed to the secondary combustor (SC) to increase its heat transfer potential and in turn preheats the fuel via the heat exchanger (HX) to a set temperature. The fuel line accounts for the LH₂ pump to adequately pressurise the fuel before combustion and after it has been heated via the HX is directed to the SC and the combustion chamber (CC) of the engine.

2.2 Cycle Design Process

The cycle design process defines the thermodynamic cycle of the engine, specifying all performance parameters. For the design space exploration generic maps are used, that are representative of the application of the turbomachinery components, and then these are scaled based on the performance requirements of the design point, according to the approach proposed by Kurtzke [13]. In addition, to address requirements and cycle constraints across different operating conditions, a multi-point design approach is utilized.

Three critical points are considered for the design cycle: Mid Cruise (MCR) as the design point, and Top of Climb (ToC) and End of Runway (EoR) as the off-design points. MCR is chosen as the design point because it represents the largest phase of the flight envelope, ensuring a minimum SFC at MCR will lead to the lowest SFC at a mission level. At that condition, the turbomachinery maps and the nozzle areas are scaled. At ToC the fan and the compressors are sized as they operate at the highest non-dimensional conditions. Finally, the EoR accounts for the maximum conditions at take-off and is where the highest temperatures are reached during the mission.

For an SMR application similar to the Airbus A320 or the Boeing 737, the thrust requirements and ambient conditions are presented in Table 1, as discussed by Alexiou et al. [14]. These were derived using methodologies from [15] and [16].

In addition, for an EIS of 2035, the MCR values for component efficiencies, pressure drops, and the EoR temperature limits are based on Klein and Staudacher [17]. These parameters are constrained by current material capabilities and turbine cooling technologies, which limit cycle operating temperatures

at critical points within the gas path. Additionally, manufacturing capabilities significantly influence component efficiencies. Achieving the desired technology level for this timeframe involves carefully targeting these efficiency values. The main requirements and constraints are summarized in Table 2.

TABLE 1: Main Operating Conditions

Operating Point	Altitude (m)	ΔT_{ISA}	Mach Number	Thrust (N)
MCR	10668	0	0.78	20100
ToC	10668	10	0.78	24100
EoR	0	15	0.25	94700

TABLE 2: Design Inputs and Technology limits for the cycle design

	Parameter	Units	Values
MCR	Fan Polytropic Efficiency	%	95
	IPC and HPC Polytropic Efficiency	%	92
	LPT and HPT Polytropic Efficiency	%	91.5
EOR	Maximum HPC outlet temperature,	K	1030
	Maximum HPT Entry Temperature,	K	1950
	Maximum NGV Metal Temperature	K	1220
	Maximum Turbine Blade Metal Temperature	K	1200

The multi-point design is an iterative approach that aims at maximising the MCR TET and OPR for a given Fan Pressure Ratio (FPR) and BPR so that the maximum TET and HPC exit temperature (T3) are satisfied at EoR. In addition, the cooling flow fractions are also determined based on cooling efficiency and the maximum blade metal temperature for the turbine at EoR. The workflow of the multi-point cycle design process followed in this paper is presented in Figure 3.

For a given BPR and FPR, an initial TET and OPR are assumed at MCR. Based on the scaled engine model, the EoR is simulated at off-design and the resulting TET and T3 are checked if they match the maximum limits, alternatively, the MCR TET and OPR are corrected accordingly and the whole process is repeated until convergence is reached. Then the ToC is simulated

to establish the performance requirements for the gas path geometry sizing.

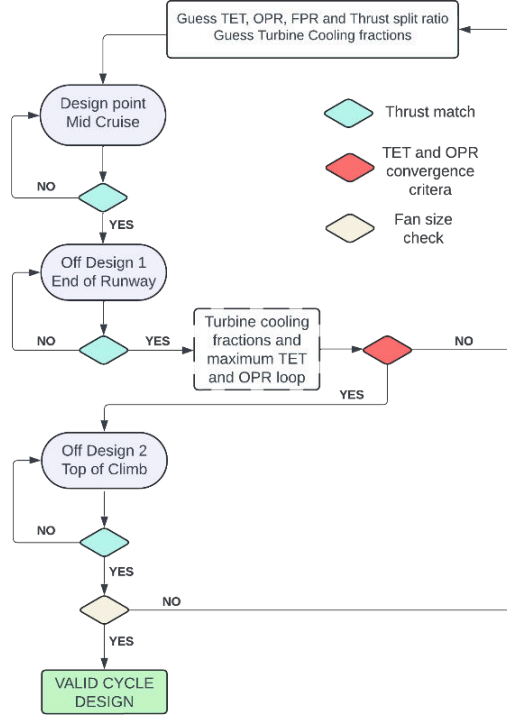


FIGURE 3: Multi-point cycle design workflow

2.3 Turbine Cooling Method

To establish the turbine cooling flows, the following turbine cooling method is used which includes convective and film cooling but also film cooling considering Thermal Barrier Coating (TBC).

Young and Wilcock [18] modified the method detailed by Holland and Thake [19] to account for the effects of thermal barrier coating. A simplified expression (Eq. 1) to determine the turbine cooling flow fraction is proposed in [20]. Where w_g refers to the gas flow rate just before the introduction of the cool air and w_c refers to the cooling gas flow rate.

$$\frac{w_c}{w_g} = \frac{K_{cool}}{(1+B)} \frac{\varepsilon_0 - \varepsilon_f(1 - \eta_{c,int}) - \varepsilon_0 \varepsilon_f \eta_{c,int}}{\eta_{c,int}(1 - \varepsilon_0)} \quad (1)$$

Where,

$$B = B_{TBC} - \frac{\varepsilon_0 - \varepsilon_f}{1 - \varepsilon_0} B_{met} \quad (2)$$

$$\varepsilon_0 = \frac{T_{gi} - T_{bl}}{T_{gi} - T_{ci}} \quad (3)$$

The parameters B_{TBC} and B_{met} are the Biot Number of the TBC and metal respectively, $\eta_{c,int}$ is the cooling efficiency, ε_0 and ε_f are the overall cooling effectiveness and film

effectiveness respectively, T_{gi} is the initial gas temperature, T_{ci} is the inlet temperature of the cooling gas and T_{bl} is the blade temperature. K_{cool} is known as the cooling flow factor.

The values of K_{cool} , B_{TBC} , B_{met} , $\eta_{c,int}$ and ε_f are based on the technology level. For the aim of this research, the values for advanced technology defined by Wilcock et al. [20] are selected and summarised in Table 3.

TABLE 3: Values for advanced cooling technology level

K_{cool}	0.045
B_{TBC}	0.4
B_{met}	0.15
$\eta_{c,int}$	0.75
ε_f	0.45

The needed temperatures for ε_0 are obtained in PROOSIS during the cycle design (T_{gi} , T_{ci}) or given as a technology limitation (T_{bl}). In addition, w_g is also determined with PROOSIS.

2.4 Fuel Properties

To capture the effect of the alternative fuels on engine performance the LHV and combustion product properties are set. For conventional Jet A-1 as well as HEFA SPK and Hydrogen, the fuel composition and LHV are presented in Table 4, as discussed by Lokesh et al [21] and Dash et al [22]. The main properties are gathered in Table 4.

TABLE 4: Fuel composition and LHV

Fuel	Jet A-1	HEFA SPK	Hydrogen
Empirical form	$C_{12.5}H_{24.4}$	$C_{11.2}H_{24.5}$	H_2
H/C ratio	1.952	2.178	-
LHV (MJ/kg)	43.12	44.3	120

TABLE 5: HEFA and Hydrogen relative difference to Jet A-1 averaged between 500 – 2000 K

Fuel	HEFA SPK (FAR 2%)	Hydrogen (FAR 0.75%)
γ	-0.022%	0.38%
R	0.24%	4.6%
C_p	0.32%	3.94%

The different molecular compositions affect combustion product properties. In the context of modelling gas turbine performance, key parameters of interest include specific heat capacities (C_p), the heat capacity ratio (γ), and the gas constant (R). In two different studies by Rompokos et al. [12],[23] the relative differences between HEFA and Hydrogen compared with Jet A-1 are deeply analysed and detailed. The results for the

relative differences between the alternative and the conventional fuels found in the studies are summarized in Table 5.

As expected, alternative fuels show an increase in C_p , primarily due to their higher hydrogen content and the resulting increase in water vapour in the combustion products. HEFA presents an average relative increase of 0.32%, while C_p for hydrogen increases by 3.94% compared to Jet A-1.

Considering the power balance between interconnected gas turbine components, a higher C_p value will enhance thermal efficiency because, for the same amount of work done by the compressor, a smaller temperature drop in the turbine is required. Additionally, the significant increase in the LHV of hydrogen compared to kerosene will reduce the core mass flow, as less fuel mass is needed to generate the same amount of energy. This reduction in core mass flow can lead to smaller and more compact engine cores, which, in turn, allows for the development of engines with a higher bypass ratio (BPR) while maintaining approximately the same fan diameter. Finally, an improvement in specific fuel consumption is anticipated, as less fuel will likely be required to generate the same thrust, as previously mentioned. All these effects will be more profound for engines designed for hydrogen since the difference with conventional fuel is higher.

2.5 LH₂ preheating and engine integration

Apart from the aforementioned properties, specifically for hydrogen, the pure substance properties are also included in the performance modelling as retrieved by NIST [24]. These affect the pump and HX performance.

The modelling approach for the integrated engine-fuel conditioning simulation is discussed in detail in [11] and is outlined by the following assumptions:

1. The pump delivery pressure is set as a function of the HPC delivery pressure to allow for adequate pressure margin across the fuel line. This determined the power off-take from the HP shaft.
2. The HX is modelled assuming a constant effectiveness of 25% across all operating points. This is a first-order approximation to determine the top-level requirements of the fuel conditioning unit.
3. Across all conditions, the hydrogen delivery temperature is set constant at 250 K, which determines the bleed flow requirement.
4. Across all conditions, the delivery temperature of the secondary combustor is set to 1000 K, which determines the secondary combustor fuel flow.

2.6 Bare engine weight estimation

The bare engine weight estimation methods are critical in the preliminary design phase, providing essential data for performance and feasibility assessments. Cranfield University's in-house tool ATLAS, developed based on the work of Lolis for aero engine weight estimation, is used. This follows a component-based approach and a thorough description and validation of which can be found in [25]. It is noted that the

combustion geometry for hydrogen follows a similar sizing approach to that of conventional kerosene ones and more detailed geometries specifically associated with hydrogen combustion are not yet included in the calculation

3. DESIGN SPACE EXPLORATION

This chapter presents and discusses the key findings of the design space exploration using alternative fuels, focusing on aspects of engine design, performance and operation.

3.1. Cycle design and engine performance

One of the main objectives during the engine design process is to minimize SFC at MCR. Before moving to a more complex and time-consuming multi-point design methodology, this paper evaluates whether the minimum SFC was at a TET lower than the maximum one (see Table 2).

Maximising MCR TET

A parametric study for Jet A-1 was conducted varying the TET at MCR for different FPR while maximising OPR at MCR based on the T3 maximum value at EoR. The different engine designs were then assessed at EoR to determine the TET at that condition. The results are presented in Figure 4 in terms of MCR specific fuel consumption (SFC) against MCR TET. For increasing MCR TET there is a continuous decrease in SFC, however, there is an upper limit in MCR TET associated with the maximum allowable TET at EoR. That limit is decreasing with increasing FPR. Nevertheless, this suggests that the TET at MCR should be maximised to minimise SFC.

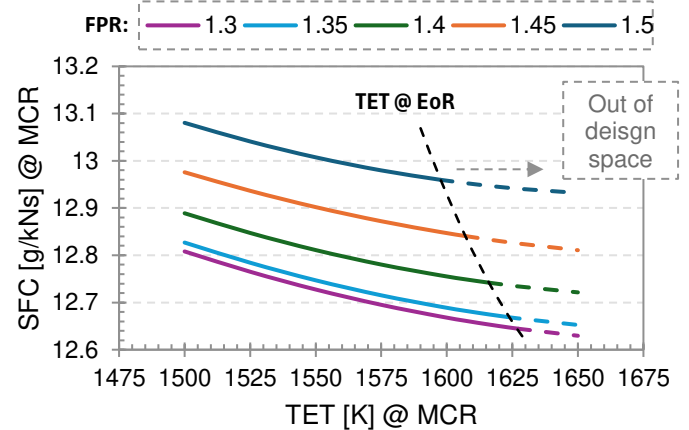


FIGURE 4: SFC over TET at MCR for varying FPR

Optimising MCR BPR

As the three fuels have different LHV, the SFC is not a representative metric of efficiency and instead the ESFC is used which is defined as the ratio between the thermal energy released during combustion and the total net thrust of the engine, as shown by eq. 5.

$$ESFC = \frac{WF \cdot LHV}{FN} \quad (5)$$

Based on the previous discussion the multi-point design approach described in section 2.2 is followed. Next is to determine the optimum BPR that will minimise the MCR SFC for every FPR design. For that, the jet velocity ratio is used as a direct input, which in turn determines the BPR and a parametric analysis is conducted for different FPRs. In Figure 5, the ESFC against the Jet Velocity Ratio is presented for different FPRs using Jet A-1. As observed, for every FPR there is an optimal value of jet velocity ratio, which allows for the optimal line identification.

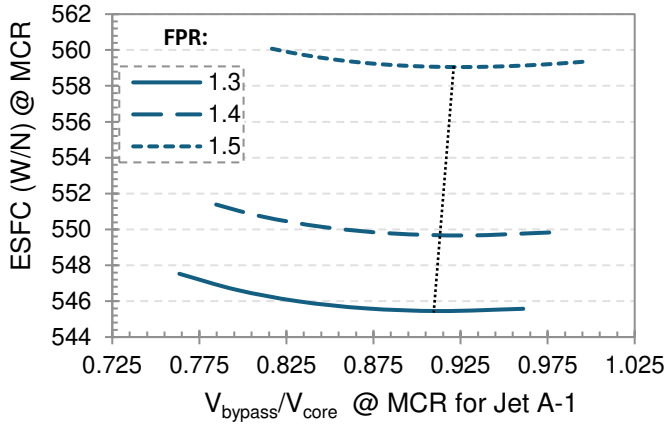


FIGURE 5: ESFC over jet velocity ratio for varying FPR engine designs for Jet A-1

Design exploration for Jet A-1, HEFA and LH₂

In the following analysis, several engine designs are created over varying MCR FPR. Via the multi-point approach, the TET and OPR are maximised and at the same time, the jet velocity ratio is optimised based on minimum MCR SFC. The results are presented in Figure 6 in terms of BPR (plot a), propulsive efficiency, $\eta_{\text{propulsive}}$, (plot b), thermal efficiency, η_{thermal} , (plot c) and ESFC (plot d) over the specific thrust of the designs at MCR. In addition to the three fuels, a fourth scenario is presented where hydrogen is delivered to the engine already conditioned and the thermal management requirement is not accounted for in the engine design.

Between HEFA and Jet A-1, the differences are not significant. As for both fuels, all the FPR designs are optimised based on the jet velocity ratios, the propulsive efficiency is virtually the same. This is also evident in the case of the hydrogen design when the fuel conditioning is not accounted for in the engine sizing. However, when accommodating the thermal management of hydrogen with the proposed configuration, a 0.5% penalty in propulsive efficiency can be observed since the bleed flow extracted from the fan section does not contribute to the thrust generation of the engine.

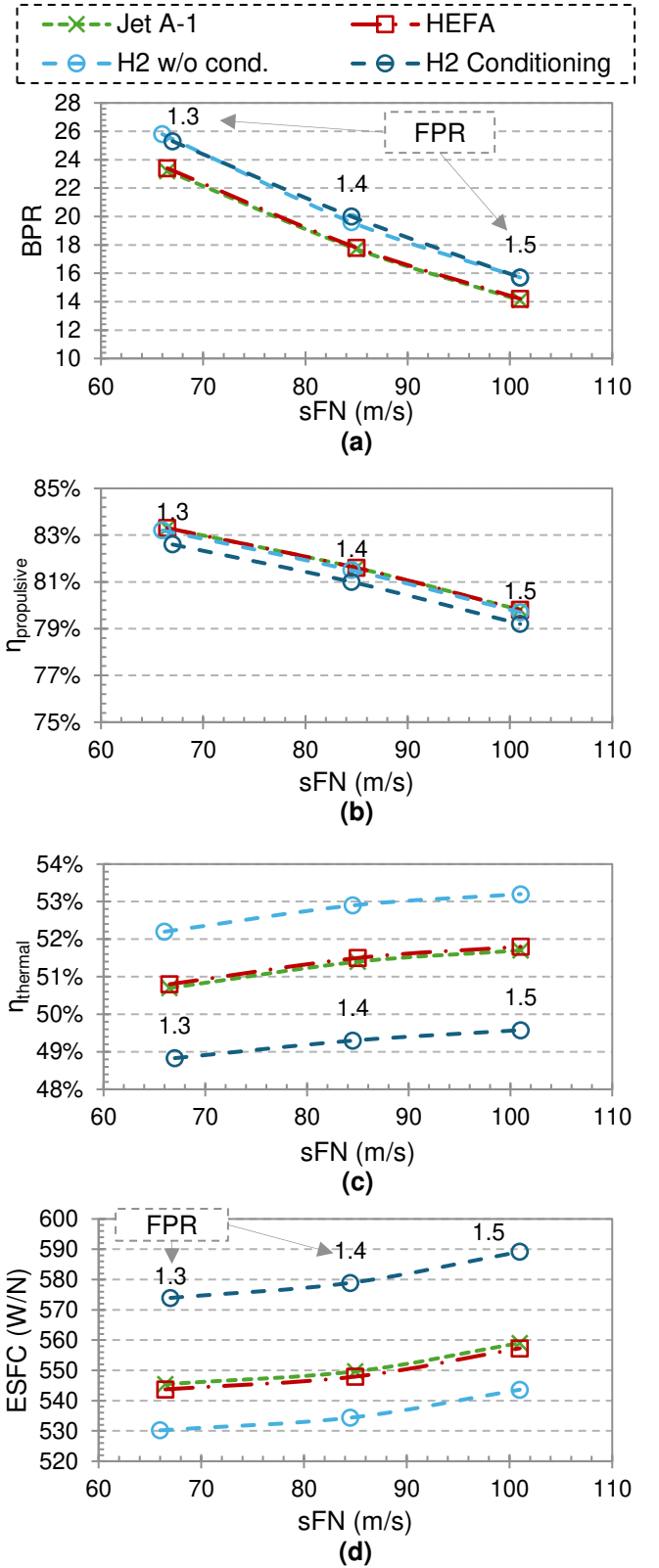


FIGURE 6: (a) BPR, (b) propulsive efficiency, (c) thermal efficiency and (d) ESFC over specific thrust for optimised FPR designs for JET A-1, HEFA and H₂ at MCR

The biggest difference between Jet A-1, HEFA and H₂ comes from the effect on the thermal efficiency. This is due to the increased C_p (shown in TABLE 4) in the hot section of the engine. I.e. the turbines can provide the same power with the same temperature drop with a reduced mass flow, allowing for a small increase in BPR for HEFA and an even bigger increase for both H₂ design scenarios. However, for the H₂ designs that accommodate the fuel conditioning system, the decrease in thermal efficiency compared to all other cases is to a great extent attributed to the additional fuel consumption of the secondary combustor and to a lesser extent to the bleed flow requirement of the fuel conditioning unit and to the power requirement of the LH₂ pump. In total, these are summarised by the ESFC evolution, where the HEFA and H₂ with the fuel conditioning designs present a small reduction and increase respectively.

To better illustrate the effect of the LH₂ preheating on the engine design, the fan bleed, SC fuel flow and pump power requirements at MCR over the fuel flow of the main engine combustor are presented in Figure 7. As can be observed bleed flow (less than 0.5% of the by-pass flow) and pump power requirements are relatively small. For increasing FPR designs the engine fuel flow demand is increasing driving an increase in pump power and the heating requirements, which in turn demand higher bleed flows from the fan.

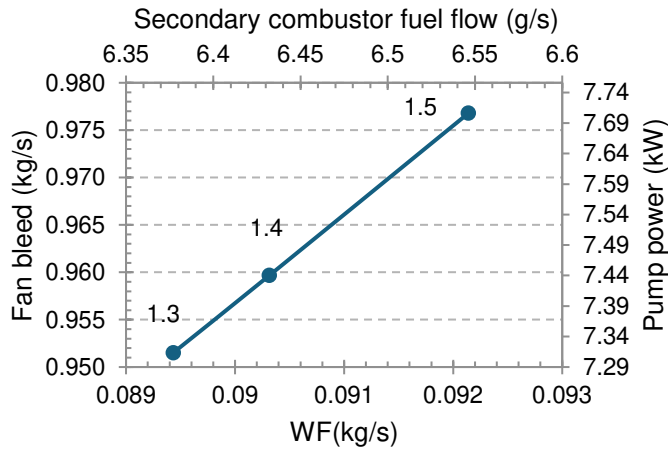


FIGURE 7: By-pass bleed feed, H₂ pump power and secondary combustor fuel flow over main combustor fuel flow across optimised FPR designs at MCR

Optima for Jet A-1, HEFA and H₂ with fuel conditioning

The last constraint of the design space is the fan diameter dictated by ground clearance requirements. Ideally, the design would move to low FPRs, since they generally lead to lower SFC. However, if for a certain design, the core produces the same amount of the total thrust, moving to a lower FPR increases the BPR, which translates into larger fan diameters. Therefore, the fan size limits the design space in terms of FPR. To calculate the fan diameter, it is necessary to introduce the Mach number the fan face will encounter and the hub-to-tip ratio of the fan blades.

Also, the fan size limitation, which is selected to be similar to the Airbus 320neo. These values are gathered in Table 6.

TABLE 6: Fan size assumptions and limit.

Parameter	Units	Values
Fan Face Mach Number @ ToC	-	0.65
Hub-to-tip ratio	-	0.255
Fan maximum diameter	m	2.05

Following the abovementioned multi-point design process, the optimal engine design and performance for Jet A-1, which is considered the baseline engine, is obtained. For Jet A-1, the results are presented in Table 7 for the three sizing points. The selected Jet A-1 model has an FPR of 1.39 at MCR, which corresponds to a BPR of 18. At this operating point, the Fuel-to-Air Ratio (FAR) is 2.28% and the engine provides an ESFC of 547.7 W/N.

Analogously, the optimum engines are obtained for HEFA and hydrogen with the LH₂ preheating. The performance results along with the relative differences to the baseline are presented in Table 8 (HEFA) and Table 9 (Hydrogen). For the HEFA engine, at MCR, the engine has an FPR of 1.39, corresponding to an optimal BPR of 18.1. The ESFC is 546.8 W/N at Cruise and the fuel-to-air ratio (FAR) is 2.23%. As for the Hydrogen design, the FPR that minimises the SFC at MCR is 1.4, corresponding to a BPR of 19.8. The ESFC is increased to 578 W/N, approximately and the FAR to 0.88%. Note how the three models reach the maximum EIS2035 temperatures for TET and T₃, demonstrating the proper functioning of the multi-point cycle design.

As for the fuel flow (WF), a moderate reduction of 2.81% for HEFA and a notable reduction of 64.98% for Hydrogen is observed, approximately matching the LHV ratio between the baseline engine and the alternative fuels. This reduction propagates to other fuel-dependent measures such as the FAR and the SFC.

TABLE 7: Jet A-1 baseline performance results

Parameter	Units	Values		
Operating Point		MCR	ToC	EoR
OPR	-	63.52	70.54	58.51
FPR	-	1.39	1.45	1.38
BPR	-	18	17.4	17.5
TET	K	1621	1806	1950
T ₃	K	861	942	1030
WF	kg/s	0.255	0.313	0.806
W ₁	kg/s	238.2	242.2	573.2
W _{core}	kg/s	12.5	13.07	30.83
FAR	%	2.28%	2.67%	2.92%
V _{BP} /V _{core}	-	0.86	0.77	0.88
SFC	g/(kNs)	12.7	12.99	8.51
sFN	m/s	84.83	99.51	165.23
ESFC	W/N	547.7	560.2	367.0

TABLE 8: HEFA performance results and relative differences to baseline engine

Parameter	Units	Values		
Operating Point		MCR	ToC	EoR
OPR	-	63.55	70.84	58.42
rel diff.		0.05%	0.07%	-0.03%
FPR	-	1.39	1.45	1.38
		0.00%	0.00%	-0.04%
BPR	-	18.1	17.6	17.7
		0.96%	0.96%	0.98%
TET	K	1622	1807	1950
		0.06%	0.04%	0.00%
T _{t3}	K	861	944	1030
		0.02%	0.04%	0.00%
WF	kg/s	0.248	0.304	0.783
		-2.81%	-2.83%	-2.91%
W _l	kg/s	238.9	242.9	574.4
		0.27%	0.28%	0.21%
W _{core}	kg/s	12.42	12.98	30.61
		-0.63%	-0.63%	-0.71%
FAR	%	2.23%	2.61%	2.85%
		-2.24%	-2.26%	-2.25%
V _{BP} /V _{core}	-	0.87	0.78	0.89
		1.13%	1.10%	1.17%
SFC	g/(kNs)	12.34	12.62	8.26
		-2.81%	-2.83%	-2.91%
sFN	m/s	84.15	99.24	164.88
		-0.27%	-0.28%	-0.21%
ESFC	W/N	546.8	559.2	366.1
		-0.16%	-0.18%	-0.26%

TABLE 9: Hydrogen performance results and relative differences to baseline engine

Parameter	Units	Values		
Operating Point		MCR	ToC	EoR
OPR	-	64.13	72.38	58.79
rel diff.		0.97%	2.60%	0.48%
FPR	-	1.40	1.46	1.38
		0.72%	0.81%	0.44%
BPR	-	19.8	18.8	19.4
		10.17%	7.91%	10.66%
TET	K	1641	1800	1950
		1.21%	-0.33%	0.00%
T _{t3}	K	863	941	1030
		0.27%	-0.04%	0.00%
WF	kg/s	0.097	0.119	0.303
		-62.03%	-62.10%	-62.42%
W _l	kg/s	238.3	242.8	574.3
		0.03%	0.27%	0.20%
W _{core}	kg/s	11.46	12.25	28.22
		-8.27%	-6.20%	-8.47%
FAR	%	0.88%	1.01%	1.12%
		-61.37%	-62.28%	-61.68%
V _{BP} /V _{core}	-	0.87	0.77	0.90
		1.10%	0.59%	2.06%
SFC	g/(kNs)	4.82	4.92	3.20
		-62.03%	-62.10%	-62.42%
sFN	m/s	84.36	99.24	164.89
		-0.03%	-0.27%	-0.20%
ESFC	W/N	578.7	590.9	383.8
		5.65%	5.47%	4.58%

Overall for HEFA a decrease in ESFC is observed mainly due to the properties of the fuel as well as the increase in BPR. The hydrogen engine on the other hand is penalised in terms of efficiency mainly due to the SC fuel flow. A better view of the ESFC breakdown can be obtained from Figure 8 and Figure 9. If an H₂ engine were to be designed without any fuel conditioning considerations, then the very properties of the fuel together with a reduction in core size would provide a 2.6% increase in thermal efficiency. Accounting for the impact of the bleed that feeds the preheating module and the power requirement of the pump, the thermal efficiency is ever so slightly penalised. At the same time since the associated bleed is not contributing to thrust generation the propulsive efficiency is penalised more. Finally, the biggest penalty comes from the SC fuel flow which eventually leads to an increase in ESFC of 5.6%.

3.2 Engines size, weight and inertias

ATLAS utilises PROOSIS performance results as inputs, to deliver engine preliminary annulus diagrams and weight estimations for all major engine modules. Engine components design criteria and constraints, as well as material properties, refer to current state-of-the-art technology levels with EIS 2025-2035.

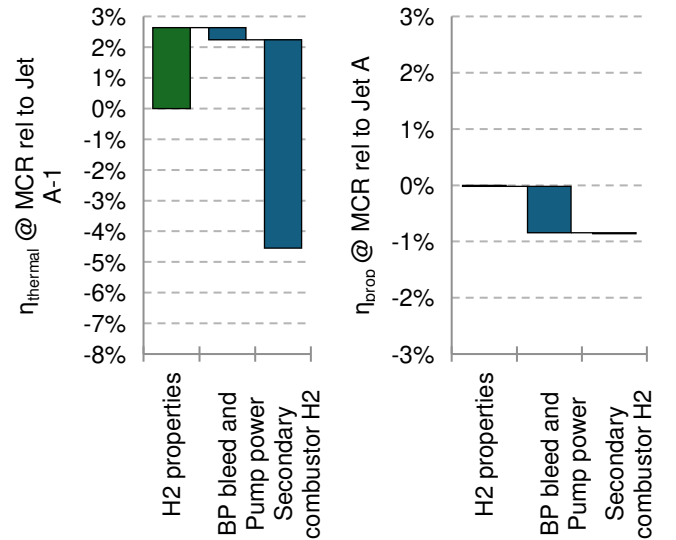


FIGURE 8: Thermal and propulsive efficiency difference breakdown for the optimum H₂ design relative to Jet A-1 at MCR

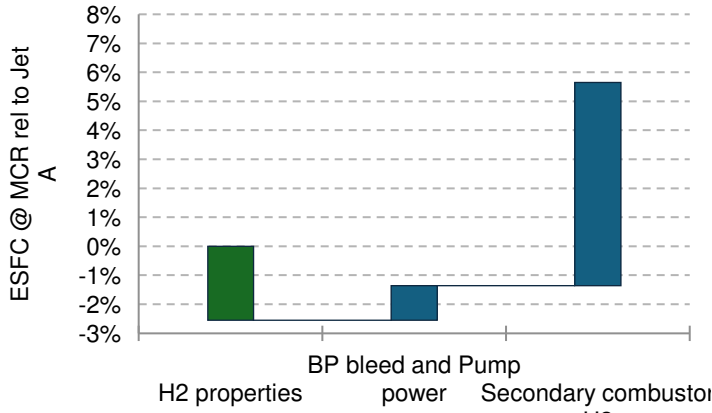


FIGURE 9: ESFC difference breakdown for the optimum H₂ design relative to Jet A-1 at MCR

The main outcomes from the engine preliminary design and weight estimation are presented in Table 10 and the Jet A-1 and H₂ designs are compared in Figure 10. These illustrate that all 3 engine variants resulted in very similar weights, regardless of the fuel type. This is something expected since all engines were designed with very similar fan diameters, which along with the PGB dominate the bare engine weight. Furthermore, the effect of the different fuels on the core size resulted to be relatively small, since these are ultra-high BPR engine designs. The core size differences in weight and dimensions between the Jet A-1 and HEFA variants are practically negligible and fall within the error tolerance of the tool. This is expected since these two variants resulted in very similar performance characteristics in terms of core flow capacities, BPR, OPR and TET. However, the H₂ engine variant resulted in having a shorter core by 5.35% as well as a smaller core inlet area by approximately 9% compared to the Jet A-1. These differences made the H₂ engine core lighter by 8.3%, while its overall bare engine only by 1.9%. It is noted, however, that the LH₂ conditioning system weight is not estimated in this analysis.

TABLE 10: Bare engine weight and dimensions for the optima designs of Jet A-1, HEFA and H₂

Fuel	Jet A-1	HEFA	H ₂
Engine weight in kg	2483	2488	2441
Diameter in m	2.05	2.05	2.05
Length in m	2.98	2.98	2.86

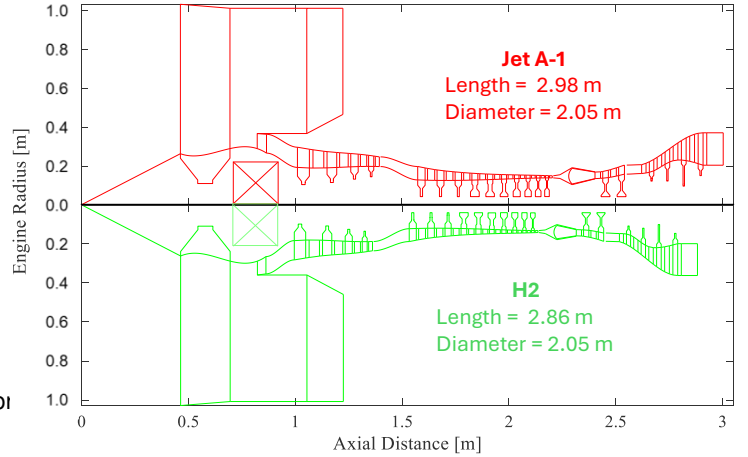


FIGURE 10: Bare engine annulus diagram & weight

The weight breakdown of all 3 engine variants is presented in Figure 11. As discussed previously, the fan and PGB modules dominate the bare engine weight. They comprise 60% of the total engine weight, while interestingly each of them results in having a similar weight proportion. The controls and accessories were assumed to comprise 10% of the total engine weight. The rest of the components that comprise the engine cores resulted in similar proportions for the Jet A-1 and HEFA variants, while for the H₂ engine, all core components presented lower proportions compared to Jet A-1. Although relatively small, such differences can have an impact on the inertia of the spools and thus on the response of the engine during transient operations. Lighter and more compact designs allow for spool inertia reductions. These can enhance the engine response in terms of acceleration and deceleration rates. Nevertheless, lower inertia also increases sensitivity to control inputs, which may lead to instabilities and difficulty in maintaining smooth operations.

4. JET A-1 DESIGN RETROFITTED FOR HEFA AND H₂

Considering that HEFA is designed as a drop-in fuel there is no need for a new engine design, as also demonstrated by the near-zero differences compared to Jet A-1 in ESFC and engine weight, this section will present a scenario where the optimum Jet A-1 design will be retrofitted to operate with HEFA and H₂ with its fuel preheating. The analysis focuses on the engine performance rematching and it is assumed that relevant changes in the combustor will be made to accommodate the new fuels.

As discussed in previous studies published by the authors [11],[23], the optimum Jet A-1, as detailed by its performance in Table 7, is used by maintaining the scaled turbomachinery maps and the nozzle areas. For the H₂ conditioning the relevant fan bypass bleed and pump power off-take are accounted for.

The resulting relative differences to Jet A-1 in terms of performance of the rematched engine at MCR for the two fuels are presented in Table 11. Considering that in all scenarios the thrust requirement is met, both HEFA and H₂ can achieve this with a reduced TET, the reduction of which is primarily related

to the C_p change in the hot section gasses. This leads to a slight increase in core flow, hence the decrease in BPR and subsequently suggests a small penalty in propulsive efficiency due to the change from the optimum jet velocity ratio for the Jet A-1 cycle. Overall, for HEFA the decrease in ESFC is expectedly slightly less than that of the equivalent optimised design. For hydrogen, the penalty in ESFC increases compared to the optimum design scenario mainly (7.1% for retrofit compared to 5.6% for optimum design) since the benefits from an increased BPR are not accrued. A breakdown of the efficiency and ESFC breakdown for the retrofitting scenario are presented in Figure 12 and Figure 13 respectively.

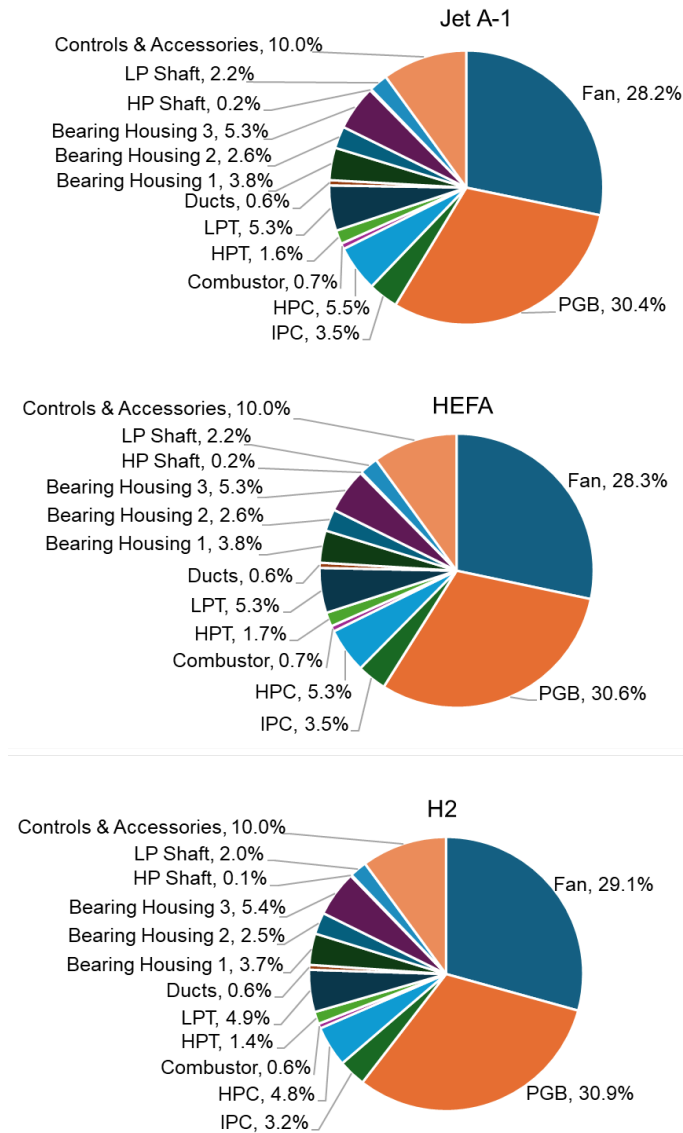


FIGURE 11: Engine modules weight relative to the total engine

In addition, the difference in TET and shaft rotational speed is presented in Table 12. The decrease in TET for both fuels suggests that in the retrofitting scenario, the maximum temperature limits across the hot section are not exceeded, but due to the turbomachinery rematching, a slight increase in rotational speed is to be expected.

TABLE 11: HEFA and H2 performance differences relative to Jet A-1 at MCR – retrofitting scenario

Fuel	HEFA	H ₂
TET	-0.2% (-3 K)	-2.3% (-37 K)
BPR	0.0%	-0.8%
W1	0.0%	0.7%
OPR	0.0%	1.4%
$\eta_{\text{propulsive}}$	-0.11%	-0.89%
ESFC	-0.1%	6.9%

TABLE 12: HEFA and H2 performance differences relative to Jet A-1 at EoR – retrofitting scenario

Fuel	HEFA	H ₂
TET	-0.2%	-3.1%
HP rotational speed	0.1%	0.6%
LP rotational speed	0.0%	0.3%

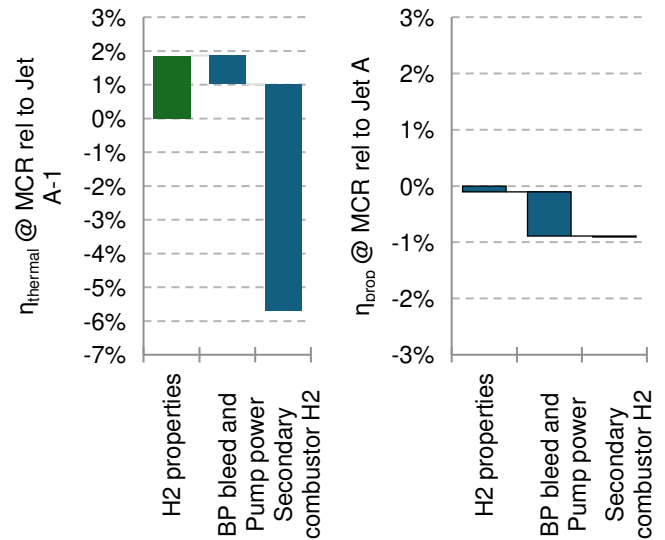


FIGURE 12: Thermal and propulsive efficiency difference breakdown for the H₂ retrofitting scenario relative to the Jet A-1 performance at MCR

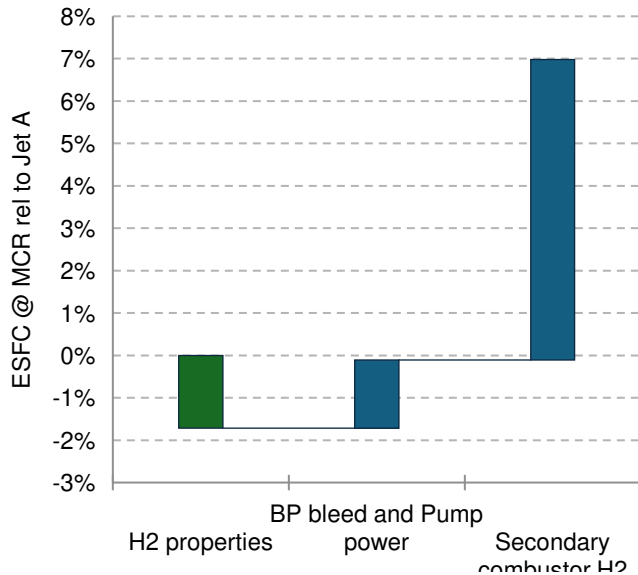


FIGURE 13: ESFC difference breakdown for the H₂ retrofitting scenario relative to the Jet A-1 performance at MCR

CONCLUSIONS

The paper presented the design exploration of UHBPR for Jet A-1, HEFA and hydrogen. For the definition of the engine cycles a multipoint-design approach was followed to maximise the core temperatures, while for all the fuels, the final designs selected were based on minimising the specific thrust.

The engine designed specifically for HEFA does not show great variation compared to the equivalent Jet A-1. The higher hydrogen content of the fuel drives a reduction in fuel flow similar to the increase in LHV, and the increase in C_p allows for higher thermal efficiency which in turn leads to a slightly smaller core size and an increase in the BPR. The overall combined benefit suggests a small increase in energy efficiency of 0.16%. As the differences in the engine cycle are minor, the overall weight of the engine is similar in both cases, hence constituting the need for an individual design of a SAF-powered engine irrelevant.

The H₂ engine shows greater differences than the HEFA case, due to the bigger difference in the properties of the hot section. The core size can be even further reduced allowing for a 10% increase in BPR but due to the engine bleed and power off-take requirements of the fuel preheating system together with the additional fuel of the secondary combustor an overall 5.6% increase in ESFC is observed. The reduction in core size is reflected by a reduction in bare engine weight and length.

In addition, it was demonstrated that a Jet A-1 engine design can adequately rematch to run on HEFA and H₂

across the same thrust requirements. In both cases a reduction in the TET is observed and a slight increase in spool speed in EoR. The ESFC changes are smaller compared to the new engine designs, -0.1% for HEFA and +6.9% for H₂.

ACKNOWLEDGEMENTS

The authors are grateful to Rolls-Royce plc for its guidance during the project and Empresarios Agrupados for their continuous support with PROOSIS. The HEAVEN project is in receipt of funding from the framework programme for research and innovation Horizon Europe under grant agreement No 101102004. The authors confirm that the data supporting the findings of this study are available within the article.

REFERENCES

- [1] United Nations, "The Paris Agreement", 2024, Available at: <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>
- [2] Airbus, "Global Market Forecast 2019-2038," 2019
- [3] DLR (2020) "Strategic research and innovation agenda - The proposed European Partnership on Clean Aviation" Available at https://www.clean-aviation.eu/files/Clean_Aviation_SRIA_R1_for_public_consultation.pdf
- [4] Masson-Delmotte, V., Zhai P., Pirani A., Connors S. L., Péan C., Berger S., Caud N., Chen Y., Goldfarb L., Gomis M. I., Huang M., Leitzell K., Lonnoy E., Matthews J. B. R., Maycock T. K., Waterfield T., Yelekçi O., Yu R. and Zhou B. (eds.) (2021) "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change", Cambridge University Press. In Press.
- [5] Brewer, G. D., 1991, Hydrogen Aircraft Technology, CRC Press, ISBN 9780849358388.]
- [6] Seeckt, K., and Scholz, D., 2009, "Jet Versus Prop, Hydrogen Versus Kerosene for a Regional Freighter Aircraft," Deutscher Luft- und Raumfahrtkongress, p. 12
- [7] Rompokos, P., Kisooson, S., Roumeliotis, I., Nalianda, D., Nikolaidis, T., and Rolt, A., 2020, "Liquefied Natural Gas for Civil Aviation," Energies, 13(22), p. 5925. DOI 10.3390/en13225925
- [8] Sasi S, Mourouzidis C, Roumeliotis I, Nikolaidis T, Pachidis V, Norman J. (2023). Impacts of Alternative Aviation Fuels on Engine Cycle Design and Aircraft Mission Capability, ASME paper No. GT2023-101114, V002T03A005
- [9] Palmer, C. J., (2024), Hydrogen Fuel Vaporiser, EP 3978738 B1.
- [10] Tacconi, J. and Grech, N. (2023) 'Advanced Hydrogen Cycles to Help Decarbonize the Aviation

- Industry. Part 1: Development of Simulation & Modeling Toolsets', in *Volume 1: Aircraft Engine*. American Society of Mechanical Engineers. doi: 10.1115/GT2023-103505.
- [11] P. Rompokos, V. Kyritsis, C. Mourouzidis, and I. Roumeliotis, 'Assessment of a Liquid Hydrogen Conditioning System for Retrofitting on Kerosene Designed Turbofan', presented at the ASME Turbo Expo 2024: Turbomachinery Technical Conference and Exposition, American Society of Mechanical Engineers Digital Collection, Aug. 2024. doi: 10.1115/GT2024-121997.
- [12] EA Internacional (2023) *PROOSIS - Propulsion Object-Oriented Simulation Software*. Available at: <https://www.ecosimpro.com/products/proosis/> (Accessed: 10 December 2023).
- [13] Kurzke J., (1995), *Advanced User-Friendly Gas Turbine Performance Calculations on a Personal Computer*', in Volume 5: Manufacturing Materials and Metallurgy; Ceramics; Structures and Dynamics; Controls, Diagnostics and Instrumentation; Education; IGTI Scholar Award. Huston, Texas: American Society of Mechanical Engineers. doi: 10.1115/95-GT-147.
- [14] A. Alexiou, N. Aretakis, I. Kolias, and K. Mathioudakis, 'Novel Aero-Engine Multi-Disciplinary Preliminary Design Optimization Framework Accounting for Dynamic System Operation and Aircraft Mission Performance', *Aerospace*, vol. 8, no. 2, Art. no. 2, Feb. 2021, doi: 10.3390/aerospace8020049.
- [15] N. A. Cumpsty, 'Preparing for the Future: Reducing Gas Turbine Environmental Impact', presented at the ASME Turbo Expo 2009: Power for Land, Sea, and Air, American Society of Mechanical Engineers Digital Collection, Feb. 2010, pp. 969–988. doi: 10.1115/GT2009-60367.
- [16] S. M. Jones, W. J. Haller, and M. T.-H. Tong, 'An N+3 Technology Level Reference Propulsion System', E-19373, May 2017. Accessed: Nov. 19, 2024. [Online]. Available: <https://ntrs.nasa.gov/citations/20170005426>
- [17] F. Klein and S. Staudacher, 'Cycle Optimization Potential of Composite Cycle and Turbocompound Aero-Engines', *J. Eng. Gas Turbines Power*, vol. 142, no. 061007, May 2020, doi: 10.1115/1.4046820.
- [18] J. B. Young and R. C. Wilcock, 'Modeling the Air-Cooled Gas Turbine: Part 2—Coolant Flows and Losses', *J. Turbomach.*, vol. 124, no. 2, pp. 214–221, Apr. 2002, doi: 10.1115/1.1415038.
- [19] 'Rotor blade cooling in high pressure turbines | Journal of Aircraft'. Accessed: Nov. 20, 2024. [Online]. Available: <https://arc.aiaa.org/doi/abs/10.2514/3.44668?journalCode=ja>
- [20] R. C. Wilcock, J. B. Young, and J. H. Horlock, 'The Effect of Turbine Blade Cooling on the Cycle Efficiency of Gas Turbine Power Cycles', *J. Eng. Gas Turbines Power*, vol. 127, no. 1, pp. 109–120, Feb. 2005, doi: 10.1115/1.1805549.
- [21] K. Lokesh, V. Sethi, T. Nikolaidis, E. Goodger, and D. Nalianda, 'Life cycle greenhouse gas analysis of biojet fuels with a technical investigation into their impact on jet engine performance', *Biomass Bioenergy*, vol. 77, pp. 26–44, Jun. 2015, doi: 10.1016/j.biombioe.2015.03.005.
- [22] 'Hydrogen Fuel for Future Mobility: Challenges and Future Aspects'. Accessed: Nov. 21, 2024. [Online]. Available: <https://www.mdpi.com/2071-1050/14/14/8285>
- [23] P. Rompokos *et al.*, 'Integrated Performance Assessment and Decarbonising Potential for Aircraft Retrofitted With Sustainable Aviation Fuels', presented at the ASME Turbo Expo 2024: Turbomachinery Technical Conference and Exposition, American Society of Mechanical Engineers Digital Collection, Aug. 2024. doi: 10.1115/GT2024-128858.
- [24] NIST (2020) *Thermophysical Properties of Fluid Systems*. Available at: <https://webbook.nist.gov/chemistry/fluid/> (Accessed: 30 October 2020).
- [25] P. Lolis, P. Giannakakis, V. Sethi, A. J. B. Jackson, and P. Pilidis, 'Evaluation of aero gas turbine preliminary weight estimation methods', *Aeronaut. J.*, vol. 118, no. 1204, pp. 625–641, Jun. 2014, doi: 10.1017/S0001924000009404.
- [26] P. Lolis, 'Development of a preliminary weight estimation method for advanced turbofan engines', Cranfield University, 2014.
- [27] P. P. Walsh and P. Fletcher, *Gas Turbine Performance*. John Wiley & Sons, 2004.
- [28] G. C. Oates, *Aircraft Propulsion Systems Technology and Design*. AIAA, 1989.



DSpace

<https://dspace.org/>

Design space exploration of geared turbofans using alternative fuels

Cava Zamorano, Nabila; Rompokos, Pavlos; Mourouzidis, Christos; Roumeliotis, Ioannis

2025-06-16

American Society of Mechanical Engineers (ASME)

<https://doi.org/10.1115/gt2025-153997>

Cava Zamorano N, Rompokos P, Mourouzidis C, Roumeliotis I. (2025) Design space exploration of geared turbofans using alternative fuels. In: ASME Turbo Expo 2025: Turbomachinery Technical Conference and Exposition, 16-20 June 2025, Memphis, USA, Volume 2: Coal, Biomass, Hydrogen & Alternative Fuels. Paper number GT2025-153997