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Master of Philosophy

Innovation in micro gas turbines for aeronautical applications

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I, Jody Anfossi, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Jody Anfossi

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Abstract

Innovations in propulsion systems have been a main driver of progress in aviation. The current dependence on fossil fuels and their increasing use due to the continuous growth of air transport suggest that alternative solutions must be considered to reduce emissions as well as alleviate shortage issues that may arise in the future. To tackle these issues, innovative solutions including novel cycle arrangements for higher efficiency and the use of alternative, potentially zero emissions fuels have been investigated in recent years.

With regards to the low cycle efficiency affecting small power rating gas turbines, recovery of waste heat from the exhaust gases represents a possible remedy, typically used in ground applications. Further remedies have been identified: the adoption of an intercooler, for instance. The implementation of these remedies has the potential to improve the efficiency of the power plant. However, they usually lead to reduce the specific installed power, mainly due to the added weight of extra components needed. As the weight is a key parameter for aeroengines, an analysis that addresses the performance trade-off between the improved power plant efficiency and its larger weight on the fuel economy is required to determine if the added complexity is justified for typical flight missions.

As far as alternative fuels are concerned, liquid hydrogen is considered an appealing energy carrier for aeronautical applications. In fact, its amount of energy per unit mass is about three times greater than jet fuel. Moreover, the non-pressurized liquid state allows hydrogen the highest amount of energy per unit volume, which results in relatively moderate size and weight of the storage tanks. These aspects suggest there could be a case to take advantage of this weight saving to introduce cycles that can reach higher efficiency despite a more complex, thus heavier configuration.

During the upcoming months of this research project, part of the European project NextMGT, trade-off studies will be conducted to assess the multi-fuel performance of propulsion systems based on novel cycles obtained by modification of a simple cycle micro gas turbine. To this extent, a numerical model simulating design and off-design steady state operation of an aeronautical engine will be developed and integrated with aircraft performance and mission analysis tools. This simulation framework enables the calculation of the fuel consumption of the different engine arrangements, under a set of defined realistic flight missions.

Finally, the results obtained could be used to provide recommendations for the most beneficial cycles innovations to the overall efficiency of MGT-based aeronautical propulsion systems, improving engine performance and minimizing environmental impact.

Nomenclature

Acronyms

ACARE	Council for Aviation Research and innovation in Europe
ASME	The American Society of Mechanical Engineers
BEV	Battery-electric vehicle
CMC	Ceramic matrix composite
CNC	Computer numerical control
CVT	Continuous variable transmission
ESA	Energy storage array
ESR	Early stage researcher
EU	European Union
FADEC	Full authority digital engine controller
FC-APU	Fuel cell auxiliary power unit
HALE	High-altitude long-range
HC	Hydrocarbons
HR	Hydrogen recuperated
IFSD	In-flight shutdown rate
KR	Kerosene recuperated
KS	Kerosene simple
LCA	Life Cycle Assessment
LH2	Liquid hydrogen
MGT	Micro gas turbine
MGU	Motor-generator unit
NATO	North Atlantic Treaty Organization
PM	Particulate matter
PMU	Power management unit

RC	Radio-controlled
RE	Reciprocating engine
REEV	Range-extended vehicle
SAF	Sustainable aviation fuel
STP	Standard temperature and pressure
TIT	Turbine inlet temperature
TSFC	Thrust specific fuel consumption
UAV	Unmanned aerial vehicle
WP	Work package

Subscripts

∞	Polytropic
aux	Auxiliary
b	Combustion chamber
be	Breakeven
c	Compressor
ds	Design point
HEX	Heat exchanger
in	Inlet
m	Mechanical
MR	Main rotor
out	Outlet
p	Parasitic drag
ps	Primary surface
req	Required
t	Turbine
tank	Tank
TR	Tail rotor
tub	Tubular

Greek Symbols

ϵ	Heat exchanger effectiveness
η	Efficiency

γ	Ratio of specific heats
τ	Temperature ratio

Other Symbols

Δp	Relative pressure losses
c_p	Constant pressure specific heat
SiC	Silicon carbide
CO	Carbon monoxide
r	Pressure ratio
T	Temperature
t	Time
w	Work per unit mass

Chapter 1

Project Background

1.1 Introduction

1.1.1 Micro Gas Turbines

It is more than twenty years since Micro Gas Turbines (MGTs), or *microturbines*, entered the commercial market, in the distributed generation at first. Despite this, the scientific community still does not agree completely on the features a small-scale powerplant must have to be defined as MGT. According to the most used definition in literature the term micro gas turbine refers to units producing shaft up to 500 kW, although the main commercial machines are in the range 30 to 500 kW. Beyond the power rating, others consider additional requirements, such as having a gas generator with a single stage compressor and a single stage turbine (both typically radial in design) and the electrical generator mounted on the same axis. Rotational speed is extremely high, usually greater than 40.000 rpm, therefore power electronics are used to match the output frequency to the grid [16]. MGTs can achieve high power-to-weight ratios (up to 2500 W/kg, 2 to five times that of a piston engine, depending on the power rating), while their electrical efficiency remains low, around 15%.

Advantages compared to other technologies in the small-scale power production (e.g., reciprocating engines) have been known for more than twenty years. As long as the simple Brayton-Joule cycle is considered, micro gas turbines offer a small number of moving parts, compact size and light weight, multi-fuel capabilities, and opportunities for greater energy efficiency, and lower emissions [14]. These advantages and their power-to-weight ratio make MGTs attractive for aviation applications.

Simple cycle

Micro gas turbines in their most basic form use the Brayton-Joule cycle to produce power. The working fluid goes through compression, heating and expansion to convert the energy it contains in the mechanical energy that drives a shaft. Ideal cycles consider isentropic compression and expansion, while the heating as isobaric. However, actual processes involve losses of various kinds (aerodynamic, leakage, thermal, etc.) that are responsible for the deviation of the real cycle efficiency to lower values. At a preliminary stage, compression and expansion are considered adiabatic, but irreversible. Consequently, the concept of isentropic efficiency for compressor and turbine is introduced to assess the "distance" of the real transformation from the ideal one. In addition, considering pressure losses along other components, such as the combustion chamber, enables more accurate performance prediction.

The thermal efficiency of the cycle is defined as the ratio between the net power

Table 1.1: Assumptions to the real cycle are related to the efficiency of compressor, turbine, friction between mechanical components, combustion chamber and pressure losses in the combustion chamber.

$\eta_{\infty,c}$	$\eta_{\infty,t}$	η_m	η_b	Δp_b
0.80	0.85	0.99	0.98	0.05

delivered by the shaft and the heat added in the combustion. The thermal efficiency (η) of an ideal Brayton simple cycle depends only on the pressure ratio of the compressor (r), the higher the better (cf. Eq. (1.1)). As regards the power output, both TIT and pressure ratio have influence, as described in Eq. (1.2). Indeed, it is clear since this point of the analysis that the major parameters affecting the system performance are r and TIT.

$$\eta = 1 - \left(\frac{1}{r}\right)^{(\gamma-1)/\gamma} \tag{1.1}$$

$$\frac{w}{c_p T_1} = \tau\left(1 - \frac{1}{r^{(\gamma-1)/\gamma}}\right) - (r^{(\gamma-1)/\gamma} - 1) \tag{1.2}$$

where T_1 is the compressor inlet temperature, w is the net specific power output and t is the temperature ratio between TIT and T_1. However, for a real cycle the efficiency depends on several factors, such as the performance of the components, the cycle arrangement and the conditions of the surrounding environment. The diagrams in Fig. 1.1 and 1.2 display: the sensitivity of simple cycle performance to TIT; the conflict between the optimal compression ratio for maximum efficiency and maximum power output, both for the ideal and the real case. The assumptions that characterize the real case are outlined in Tab.1.1.

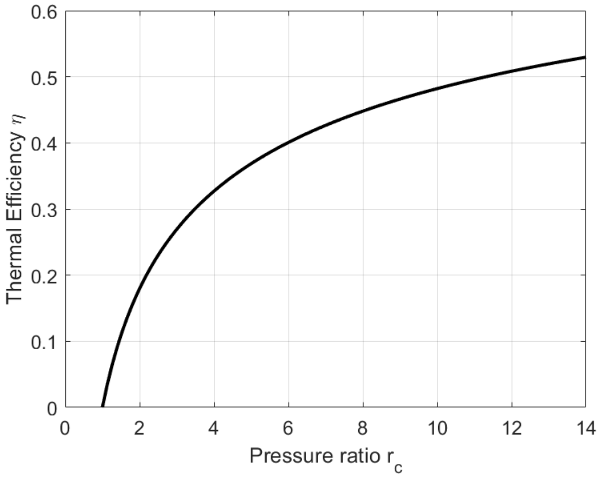
Recuperated cycles

With regards to the low cycle efficiency affecting small power rating gas turbines, recovery of waste heat from the exhaust gases represents a possible remedy, typically used in ground applications. The implementation of a recuperated cycle allows for improved efficiency of the power plant. However, it leads to reduction in the specific installed power, mainly due to the added weight of the heat exchanger.

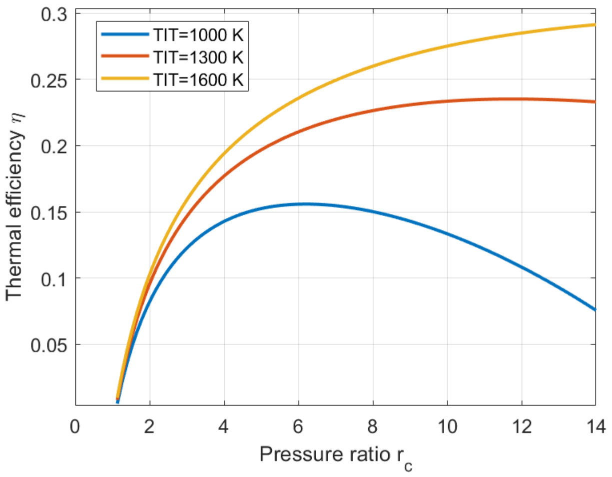
Whilst the improvement of aerodynamics and the investigation of internal heat and leak losses have marked the last two decades of research, the use of recuperators has granted a simple offset to the lacking electric efficiency of MGTs. This is so true that recuperated cycles have made possible the commercial success of micro gas turbines, albeit mediocre. All the most well-known commercially available MGTs are recuperated, indeed (Tab. 1.2). Simple Joule Brayton cycle MGTs are just not present on the market, a niche application is reported in Subsection 2.1.1.

Losses: scalable and not

Micro gas turbine cycles are affected by lower values of efficiency, with respect to larger power rating systems. This means that for the same amount of fuel, they deliver a lower amount of mechanical power. Inherent causes of poor efficiency of micro scale engines are listed below:

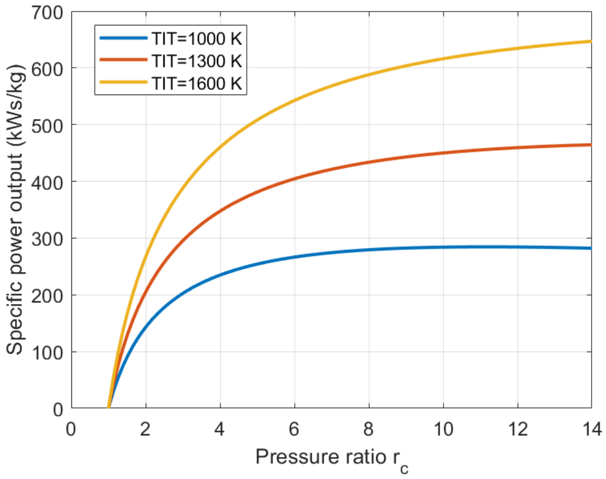


(a) *Ideal*

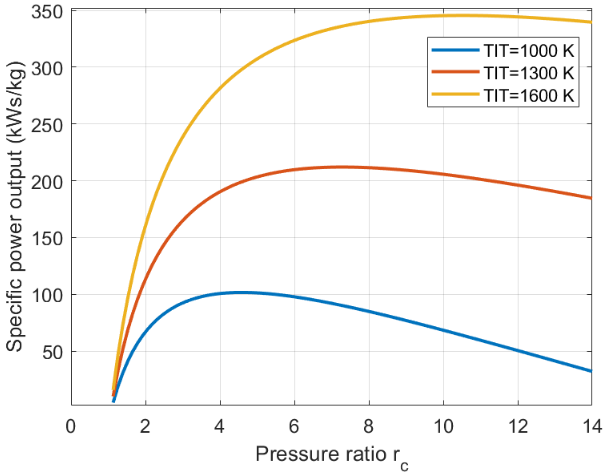


(b) *Real*

Figure 1.1: Thermal efficiency for a Brayton simple cycle.



(a) *Ideal*



(b) *Real*

Figure 1.2: Specific power output for a Brayton simple cycle.

Table 1.2: Well-known commercially available MGTs for distributed power production. All engines use single shaft recuperated configuration with radial turbomachinery.

Model	Manufacturer	Output (kW)	η_{cycle}	TIT (°C)	Speed (krpm)
C30	Capstone	30	0.28	870	96
TA45	Elliot Energy	45	0.30	870	116
C65	Capstone	65	0.29	870	85
Parallon 75	Honeywell	75	0.30	870	85
TA80	Elliot Energy	80	0.30	870	68
T100-NG	Ansaldo	100	0.30	950	70
TA200	Elliot Energy	200	0.30	870	43
C200	Capstone	200	0.33	870	45
MT 250	Ingersoll-Rand	250	0.30	900	45

- Low Re. Laminar flow for compressor stages, so high drag. Limits for efficiency [24].
- Skin friction losses more relevant: higher surface roughness compared to surface area of components [46], [24].
- Geometric restrictions from manufacturing and material properties [24].
- Tip clearance effects [46].
- Compressor cannot be modelled simply as adiabatic [24].
- Configuration related causes. Internal flow leakage: up to 1.5% efficiency loss per 1% flow leakage (33 kW MGT) [22]. Internal heat transfer, which is enhanced by the use of SiC ceramics due to their high thermal conductivity [46]. Outwards heat losses: up to 26% of the net power due to convection/radiation (1 kW MGT) [46].
- Turbine erosion and compressor fouling induce performance degradation that are qualitatively similar to the effects due to leakage on the thermal efficiency [22].

Measures to improve efficiency

Ceramics use in MGTs The need to cool the hot parts of a micro gas turbine cannot source directly remedies from larger turbines. The small scale involves implementation difficulties which may hinder the use of thermal barrier coatings and air cooling for the blades receiving hot air from the combustor. The former tends to increase weight and thickness of the blades generating higher mechanical stresses. The latter generally shows manufacturing obstacles due to the dramatically small dimension of the ducts and holes required in the blades. As a consequence, the use of uncooled conventional metallic materials for the turbine inevitably limits the TIT around 900 °C and therefore the overall cycle efficiency.

Ceramics fit into this context as an alternative material with the mechanical and thermal properties to replace metals in the construction of turbine blades and parts of the engine case exposed to high temperatures without cooling. Doubts have been raised about life, reliability and cost obstacles of ceramics in engines for aeronautical propulsion. Some major criticism regarding ceramic turbines is the need for a heat exchanger made of ceramic as well for a recuperated cycle, with a consequent sharp rise of the system cost and its lack of competitiveness. This is due to the use of higher TIT allowed by the ceramic stages, which generally leads to such high TOT ($> 700\,^{\circ}$C) that stainless steel recuperators cannot sustain [43].

Massive research and development in the last fifteen years have allowed the entry of ceramics in aeronautical powerplants for components like Ceramic Matrix Composites (CMCs) shrouds of the CFM LEAP engine. Ceramic matrix materials are indeed appreciated for their lightweight, stiffness and resistance to high temperature and corrosion. However, the application of ceramics to rotating parts looks like being still limited to the automotive turbochargers, which work at the temperature of reciprocating engines (REs) exhaust gases and relatively low speeds compared to MGTs context, where rotations are of the order of 10^5 and $900\,^{\circ}$C temperatures. While seeking for higher performance ceramic materials, adjusting the engine environment to better accommodate existing ceramics may be a successful strategy to exploit their potential today. In this regard, in his detailed study Vick concluded that ceramic turbines are ready for application in long-life, high-effectiveness recuperated small engines designed for low blade speeds and pressure ratios [47]. Reliability would be enhanced by two aspects:

- High-effectiveness recuperated engines allow for reduced ceramic blades erosion rate, since they operate at lean air/fuel ratios, produce less water vapor in the exhaust.
- Low blade speeds and pressure ratios help to prevent fast fracture and slow crack growth.

Finally, a further aspect that would promote the suitability of ceramics for small-scale turbomachinery is the statistically distributed material defects in a small volume that reflects on the survival probability and reliability of small parts, as supported in [4].

3D printed blades: future design opportunities The effort of research in additive manufacturing has led to technologies that could be game changing for both stationary and rotating components of micro gas turbines. HiETA Technologies declares to have designed and tested a lightweight and internally air-cooled radial turbine wheel, operating up to $1200\,^{\circ}$C turbine inlet temperature. Thus, the overall efficiency of the engine system is increased, being equal the pressure ratio. Moreover, actively cooling the turbine wheel, increases the component life and by light-weighting the wheel, as well as reducing wear on bearings. Mass reductions of 22% have already been realized, with the potential to increase to 40-50% depending on the application [17]. The light weight is a clear advantage that provides further support to the implementation of this technology to aeronautical engines. Finally, the technology developed by HiETA enables small scale turbomachinery with a feature that has been exclusive prerogative of large scale gas turbine up to now. This widens the opportunities in micro gas turbine cycle design.

1.1.2 Aeronautical applications

Many aspects that are inherent to micro gas turbines found interest in aviation applications of small aircraft propulsion for business and military jets, as well as unmanned aerial vehicles (UAVs)

MGTs for aircraft propulsion

MGTs seem to possess a range of desirable qualities for an aircraft propulsion system, which are not fully encountered today by the competitors, mainly reciprocating engines. The interest in MGTs is growing especially for small UAVs. In fact, micro gas turbine based propulsion could enable augmented speed and altitude performance, thus operational scenarios, which are reserved only to larger unmanned systems today.

Reliability and life The small piston engines in current UAVs are replaced every 100 hours or less of service and could experience an in-flight shut down rate (IFSD) worse than 5-10 in every 100 hours of flight. Gas turbines are capable of achieving roughly 10 times the reliability and 10 times the life of reciprocating engines [41]. Micro gas turbines may not match such results but are expected to do far better than small piston engines.

Noise and vibrations Reciprocating engines generate noise at the exhaust, the intake, and by vibrations which are transmitted into the aircraft structure. Qualitatively, it may be said that internal combustion engines are the noisiest propulsion system; electric motors are the quietest; and turboprop engines are between the two. Noise mitigation is more difficult for REs than for turboprop engines because they generate lower frequency sound. Turboprop engines and electric motors produce high-frequency noise that naturally damps out quickly in the atmosphere.

Cooling Micro gas turbines do not need the cooling systems that are typical of reciprocating engines. Any cooling requirements are disadvantageous for a propulsion system, because cooling represents wasted energy, it adds weight and drag to the vehicle. Cooling adds complexity to the propulsion system and is another potential cause of failure.

Lubrication REs feature rotating bearings, sliding surfaces and seals that need lubrication. MGTs have lower lubricating requirements, since the moving parts just rotate, so bearing lubrication only is needed. Innovative bearing designs for MGTs may avoid lubrication completely: purely fuel-lubricated bearings, air bearings, and magnetic bearings.

High altitude operations MGTs are inherently able to operate at high altitude as well as sea level. REs typically require additional hardware, such as turbocharger, to guarantee acceptable performance beyond a certain altitude. Conversely, the power output would deteriorate remarkably, limiting the operative range of the engine itself.

Control Being a steady-flow device, a turbine requires only a few simple sensors and only one controlled variable, typically the fuel flow rate, to adjust the power output. This makes the control logic simple than the one of electronically fuel injected reciprocating engines.

Fuel flexibility MGTs are capable of running on various fuels without particular adjustments to the combustion chamber. This is a real asset that can ensure regular operation in war scenarios or in emergency after a natural disaster, where the access to a specific fuel may be difficult or impossible.

Conclusions

Although the technological advantage of micro gas turbines is solid when it comes to aircraft propulsion, reciprocating engines remain the dominant choice for small aircraft, especially for UAVs. In fact, they represent an acceptable compromise for fuel consumption and power-to-weight ratio. They do not shine for performance but for high availability on the market and limited capital cost, typically at the expense of life and reliability. Thus, given this compromise, the small piston engines attractiveness may be explained by the lack of availability of high-performance gas turbines in very small sizes.

Alternative propulsion concepts may only be desirable when suitable gas turbines are not available. Indeed, simple cycle micro gas turbines are available in the hobby market, and have excellent power-to-weight ratios, but due to their very high SFC and capital cost they are rarely used for small aircraft propulsion.

This analysis does not imply that gas turbines, or alternatives propulsion systems (e.g., fuel cells) should be abandoned. But instead, it suggests that they can begin to supplant REs in small propulsion systems, if their power-to-weight ratio and SFC evolve towards values that allow to achieve the endurance and range required by the most common civil and military missions.

1.2 Research objectives

This work is part of the EU Horizon 2020-funded NextMGT project [12], which aims at enabling a significantly improved understanding of the fundamental design and operational aspects of MGT technology and the requirements for successful commercialization. This specific research work focuses on the investigation of cycle innovations that could lead MGTs to set a new performance standard in terms of power-to-weight ratio and specific fuel consumption for aeronautical propulsion applications. Innovations may refer to components of the micro gas turbine, such as the adoption of a heat exchanger, as well as the use of unconventional fuel.

Various powerplant configurations will therefore be obtained, depending on the innovation implemented. These engine configurations will undergo an evaluation of their performance when used as the main propulsion system of a selected aircraft on defined flight missions. The fixed aircraft and missions will allow to have a common testbed and determine which innovation, or combination of innovations, allows to achieve the best performance.

Matching and outperforming other prime movers of similar power rating in aviation propulsion would eventually support the commercial success of micro gas turbines. The knowledge this PhD aims to develop and share could help define what are the promising innovations to MGT-based propulsion systems for the achievement of high efficiency, while improving aircraft performance and minimizing the impact on the environment. To achieve this goal, four research objectives have been identified. They can be summarized as follows:

1. Develop a simulation framework that integrates the aircraft performance model and the MGT thermodynamic model to assess the cycle efficiency and the power-to-weight ratio. By developing the MGT thermodynamic model in a modular way, further components can be added to the cycle easily.

2. Evaluate the consequences of running the MGT on hydrogen with respect to conventional fuels, such as jet fuel. This could impact specific fuel consumption, power-to-weight ratio and aircraft performance. In fact, the tanks required for hydrogen storage may differ remarkably from kerosene tanks for volume and weight, therefore aerodynamics and weight of the aircraft could be altered.

3. Examine the performance of the different powerplant configurations over the same set of representative missions. This common test bed enables a consistent comparison of the obtained values for the specific fuel consumption and the power-to-weight ratio among the various configurations.

4. Develop a mission analysis model able to quantify the environmental impact in terms of polluting and greenhouse emissions (e.g., NO_x, CO_2, etc.). This estimation

should be the result of a life cycle assessment (LCA) of clean aviation fuels to make the study sounder and more accurate.

The way these four objectives have been designed leads to address the main research question present work. In fact, they cover the main aspects needed to perform a comprehensive exploration of innovative cycles for an aeronautical application in terms of performance and environmental impact. First, achieving objective #1 is fundamental for the integration of thermodynamic model of the engine and the aircraft performance model. This allows to calculate the fuel consumption in various flight conditions. Second, objective #2 has a direct impact on the aircraft performance model when hydrogen feeds the MGT engine, pointing out the most evident difference with a traditionally fuelled propulsive system. Third, the different cycle configurations proposed can be explored and compared consistently only over a common testing ground, which is the goal described by objective #3. Finally, the assessment of the environmental impact of a particular MGT innovative cycle is based on the calculation of the amount of emissions produced during a given mission. Moreover, an LCA can improve the results and add research value, helping to identify the net advantage of using alternative fuels. These last items are included in objective #4.

1.3 The NextMGT project

The Next Generation of Micro Gas Turbines for High Efficiency, Low Emissions and Fuel Flexibility (NextMGT) is an EU funded project, which started in January 2020, under the Marie Skłodowska-Curie Actions framework [12]. The project objective is to enable an improved understanding of: the fundamental design and operational aspects of micro gas turbine technology; the requirements for their successful commercialization. The participants to the projects are organized in a consortium that includes seven beneficiary members and twenty partners under the coordination of City, University of London [30]. The work of the author of the present report, Early Stage Researcher 1 (ESR1), lies in the *Work Package 1 (WP1) - Cycle Innovations and System Optimisation*, which is led by the Aristotle University of Thessaloniki. WP1 main goal is to examine the possible cycle innovations to achieve high overall MGT efficiency to match other prime movers of similar power range and to optimize MGT systems for several applications, such as aeronautical propulsion. The small power rating of micro gas turbines put them in direct competition with electric motors, REs and hybridized forms of these two. Key parameters in the challenge among these different approaches to propel aircraft are the power-to-weight ratio, the capital cost per kilowatt and the overall efficiency. ESR1 is expected to explore optimum trade-offs between high efficiency and size/weight reduction of an MGT based propulsion systems to determine if and at which condition they can allow more attractive performance, capital and operating costs than the mentioned competitors.

1.4 Report outline

The present report is aimed at developing a comprehensive understanding of the subject of the ongoing work as a Marie Curie Early Stage Research Fellow at City, University of London within the NextMGT project funded from the European Union's Horizon 2020 Research and Innovation Programme. A critical analysis of previous work, key parameters in the performance and design will follow. In the first part, a review of the most relevant applications of MGTs to aeronautical propulsion is presented to identify the weaknesses still affecting these systems nowadays. In the second part, various alternative fuels are investigated in view of their compatibility with MGTs. A conclusion on the findings of this review is presented at the end, where some decisions are also explained.

The project plan is illustrated through the tasks that have been considered necessary to achieve the project objectives. A timeline for the completion of these task is proposed together with a risk management strategy to mitigate the effects of undesirable events that might jeopardize the compliance with the established deadlines. Finally, an update of the current research status is also provided. The main results are described and contextualized with respect to the research plan.

Chapter 2

Literature Review

In this chapter aeronautical propulsion systems powered by micro gas turbines are presented in two sections, 2.1 and 2.2. The first section deals with contributions and challenges related to micro gas turbines through published studies. In the following section, alternative fuels for aviation, such as SAF and hydrogen are investigated, given the fuel flexibility of MGTs. Final considerations about the literature survey are then presented, the research gaps are highlighted, and new possible directions to fill them are outlined.

2.1 MGTs for aeronautical propulsion

In this section the most common applications of micro gas turbines in aeronautical propulsion are presented. The niche use of MGTs often leads to adapt already existing devices to the aeronautical application to hold costs down. The typical result is a non-optimized solution affected by high fuel consumption, which typically reflects on high operational expenditures and limited range capability. However, literature shows some attempts to introduce MGTs to aero-propulsion, but none of those moved past the prototype phase or was commercially successful after years. All the examples included in these sections should represent the starting point for further cycle innovations in directions that have been unexplored so far. In fact, it is speculated that the full potential of micro gas turbine technology for small aircraft propulsion, especially for UAVs, has not been explored yet [25].

2.1.1 Micro turbo engines for RC models

Various companies (e.g., JetCat, AMT, evoJet, Jets Munt) produce micro gas turbines meant to be mounted on radio-controlled aircraft models since the early 90's. They are usually single shaft, single stage centrifugal compressor, single stage axial turbine produced with CNC manufacturing. This MGTs are able to power both turbojet and turboprop solutions. The range of thrust proposed for the former range from 20 N to 1500 N. The turboprop solutions can provide up to 15 kW shaft power. They run on a mixture of jet kerosene with 5% oil.

A market analysis was performed on the basis of the data sheets available from the manufacturers. This gives the opportunity to highlight how the various micro turbojet line-ups are close to each other in terms of fuel consumption and weight, as shown in Fig. 2.1. The data provided by the figure points out that micro turbojets on the market can easily double the Thrust Specific Fuel Consumption (TSFC) of one of the smallest turbofans, the Williams FJ33, which powers the smallest single-engine light Cirrus SF50 jet. To conclude, this kind of engines has powered some exotic solutions, without ever

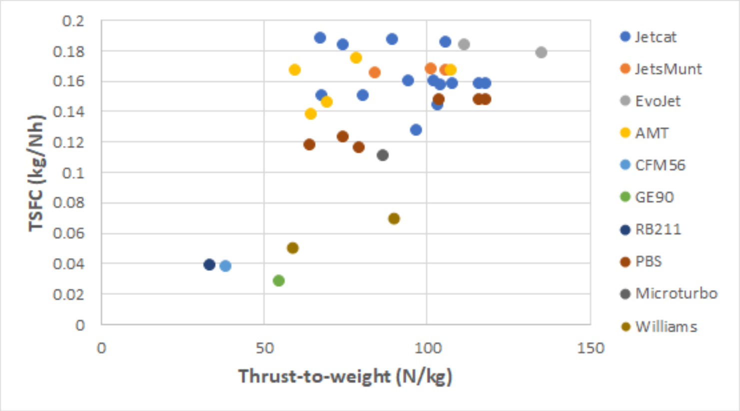


Figure 2.1: RC-Hobby Models MGT engines and large airliners engines.

encountering large scale applications. For instance, JetCat engines power the Jet Suit concept by Gravity Industry, founded in 2017. This jet pack integrates five JetCat power turbojets, for a 1050 bhp total power [18]. Richard Browning, founder of Gravity Industry, reached the fastest speed with his body-controlled jet-engine-powered suit ($136\,\mathrm{km\,h^{-1}}$) in 2019. Finally, a micro turbojet has been used also as bring-home device for gliders [15].

2.1.2 Micro turbofan

Losses related to their small scale make MGTs less competitive than RE, especially at low power rating, where the reciprocating engine is king, especially for affordability. The lack of valid jet alternatives has limited NATO class I and II mainly to low altitude and short endurance missions. In fact, micro turbojet up to 1 kN is dominated by relatively simple engines manufactured for hobbyists (cf. 2.1.1). Some innovative solutions have been studied to increase the MGTs performance in aeronautical applications, so their competitiveness. They consist in converting an existing hobby micro turbojet into a micro turbofan by mounting the fan on the same shaft for compressor and turbine by means of a CVT gearbox. The continuous variable transmission is able to change gear ratios while maintaining the core running at its optimum [19]. This is a crucial aspect especially for MGTs, whose efficiency at design point is already low and off-design operations should be avoided when possible. Moreover, CVT is now a mature and reliable technology that has been studied and widely deployed for decades in the automotive field and for a myriad of further uses. Pratt & Whitney Canada patented a continuously variable transmission coupled to the shaft for transmitting power to a propulsion load in 2012 [51]. The results obtained about micro turbojet to micro turbofan conversion are not remarkable in terms of reduction of fuel consumption, which remains pretty the same of the baseline. However, a sensitive increase of thrust is achieved. Consequently, mission profile can widen for those UAVs converted from propeller to this kind of powerplant, enabling features still unavailable today for NATO classes I and II, especially for cruise speed and altitude [24].

2.1.3 Hybrid-electric MGT powertrains

Innovative solutions have been studied to cope with the poor efficiency in off-design operating conditions. UAV Turbines has developed a hybrid-electric powertrain, which consists in a MGT working at design point to power an electric motor that drives a

Table 2.1: Sentient Blue Maui 8500 key technical specifications.

Continuous/Peak Power (kW)	8.5/16
Dry System Weight (kg)	3.63
Brake-Specific Fuel Consumption (g/(kWh))	450
Electrical efficiency (%)	17.2

propeller, while any excess power is shunted to batteries for storage. The electric motor allows for flexible management of the shaft rotating speed, bypassing the need for a complex and heavy gearbox to shift from 10^5 rpm of the micro engine shaft to 10^3 rpm of the propeller shaft. On top of that, this hybrid solution enables effective operating strategies to tackle noise pollution, such as a fast transition to silent full electric mode if needed. Hybrid cargo drones, for instance, will be able to take off and land with quiet electrical power (only prop noise, almost no engine noise) and use turbogenerators during cruise. In this regard, certification requirements (cf. [32]) and regulations about dB limitations are strict (cf. [36]), especially for operations over residential areas.

Within the 20 kW power rating, the Italian American Sentient Blue is developing a hybrid solution to tackle the limited endurance of Li-Po battery powered drones (cf. Tab. 2.1). In fact, they observed an average of 20 minutes flight time for a fully charged battery, which can reduce to 10 minutes in cold winter days, given the sensitivity of Li-Po batteries energy density with respect to low temperatures. Thus, to face a typical 8 hours working day, a pilot should carry up to 10 batteries per drone, a generator to recharge them and the fuel to run the generator itself. All this may turn to be very expensive and impractical. Sentient Blue's solution (Fig. 2.2) in this regard is a hybrid arrangement that includes:

- Micro Gas Turbine, with a two-stage compressor.
- Motor-Generator Unit (MGU), bespoke device and primary source of electrical power for the UAV.
- Full Authority Digital Engine Controller (FADEC), to ensure peak efficiency and safety in all flight conditions.
- Power Management Unit (PMU) manages the electrical power from the MGU and the ESA.
- Energy Storage Array (ESA), a small installation of lithium polymer batteries or super capacitors.

The PMU check the power demand from the UAV and uses the ESA for load smoothing and peak power demand up to an extra 7.5 kW in the case of their *Maui 8500* product. Endurance may be extended up to 2 h. On top of that, a patented oil system design is implemented to extend the life of the bearings and the inspection intervals as well. Flight tests are expected by September 2021.

2.1.4 MGTs as range extenders

A range extender is defined as a device used to make the range of a battery-electric vehicle (BEV) longer. Well-known commercial applications of range extenders belong mainly to the automotive industry. The B-segment hatchback BMW i3 is proposed on the US market in BEV or range-extended vehicle (REEV). The latter was equipped with

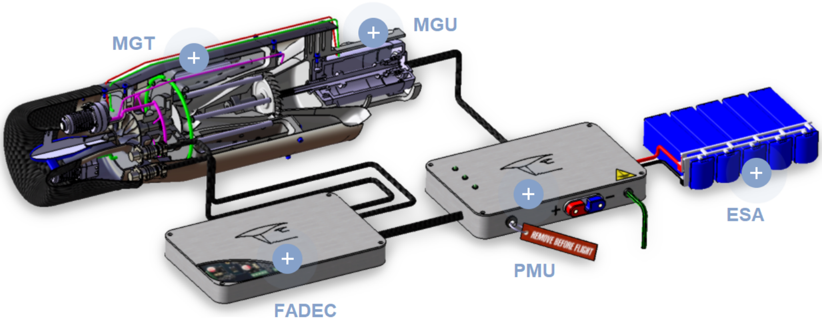


Figure 2.2: Sentient Blue's hybrid technology [5].

a two-cylinder gasoline engine as range extender.Remarkable examples about commercial aeronautical range extenders are lacking. Automotive parts supplier Ricardo announced the development of a two-cylinder 2.3 kW engine designed to use heavy fuel in 2010, for instance. With that being said, both the ground and the air range extender share the requirement to be compact and lightweight. This conclusion is commonly accepted, also considering their occasional use and the vehicle efficiency penalty of carrying dead weight they introduce. On top of that, low noise and vibrations and little maintenance are desirable as well. A recent study highlighted a linear growth of fuel consumption with vehicle mass and showed that Micro gas turbines have the potential to suit the role of auxiliary power unit (APU) for REEVs [20]. In fact, since the APU is decoupled from the road (or flight) load, its operation can be optimized to produce power at high efficiency and low exhaust emissions for best battery charging performance.

2.1.5 Recuperated aeroengines

Successful demonstrations of recuperator employment in aeroengines date back to the 1960s, when the low cost of fuel and the limits of heat exchanger technology of that era hindered further work in this direction [26]. The intermittent research of the following years culminated in a 3 kW turboshaft engine equipped with an annular ceramic recuperator. It was designed at the U.S. Naval Research Laboratory for a UAV application and tested without cracks or leakage. However, it never moved past the prototype phase [48].

The advancements in materials and manufacturing technology have led to the current generation of recuperators, which shows improved thermal performance and compactness. These are crucial aspects for microturbine applications in the aeronautical field, since fuel economy and high power-to-weight ratio are significant performance requirements for aircraft powerplant integration. It is clear that the incorporation of a recuperator increases the system weight, impacting negatively the power-to-weight ratio of the gas turbine, and to even outbalance the fuel saving allowed by the recuperated cycle. Only a quantification of the compromise between parasitic recuperator weight and saved fuel weight can determine how reasonable this complex engine configuration may be. The importance of the break-even point, at which the recuperator added weight is compensated by reduction in fuel burn was highlighted by Ali in [3]. The economic viability of a regenerative helicopter is reached only if the fuel carrying capacity is reduced by an amount greater than or equal to the weight added by the installed heat exchanger(s). An extensive work has been published recently in this regard with the aim to assess the abovementioned trade-off for a light helicopter powered by two microturbines over a set of realistic missions for a wide range of recuperator effectiveness [53]. The obtained results suggest that the deployment

Table 2.2: Tech specs of the most relevant MGTs for aeronautical propulsion in literature.

	Power (kW)	Fuel	Cycle	Status
Jetcat	6-15	Jet	Simple	Market
Vick	5.26	Jet	Recuperated	Prototype
Sentient Blue	8.5	Jet	Hybrid-Electric	Prototype
Marcellan	77	Jet	Simple	Concept
Turbotec	100	Hydrogen	Recuperated	Concept
PBS	160	Jet	Simple	Market
Zhang	313	Jet	Recuperated	Concept

of a recuperator may not be beneficial for short haul or duration missions, especially for highly effective recuperators that tend to be bulkier, exacerbating even more the weight penalty associated with their incorporation.

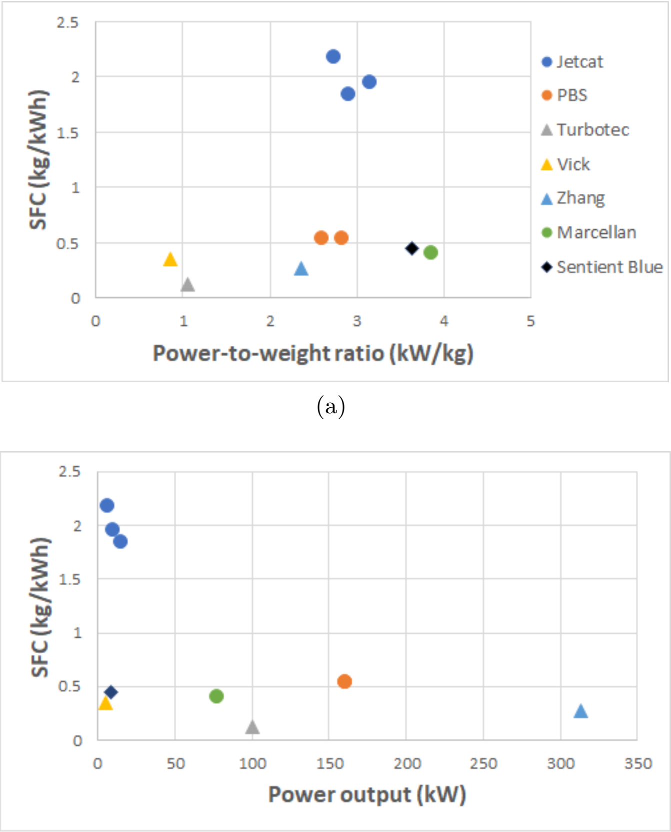
The concept of improving fuel economy by increasing the complexity, thus the weight, of the powerplant configuration has been analyzed from a similar perspective by Roumeliotis [38]. In this case, the power rating is higher, and the rotorcraft original engine is upgraded to a thermoelectric powerplant, so it includes a recuperator and an electric motor supplied by batteries. The results indicate that sensible fuel economy may be achieved despite the weight penalty within certain limits of hybridization. Moreover, the reduced specific power and the throttle response change due to the heat exchanger addition can be compensated by the electric motor addition.

2.1.6 Summary

Examples of commercialized, concept and prototypal MGTs for aeronautical propulsion have been presented so far. Some of them use the simple Brayton-Joule cycle described in 1.1.1, others use a regenerative cycle thanks to the adoption of a heat exchanger. A list of them with their main specifications is reported in Tab. 2.2.

Specific fuel consumption and power-to-weight ratio represent effective performance indicators to understand the technology level of the engines considered in the present section. Data are rarely available in a direct form, so they might have been derived from the information found on manufacturer websites and publications. Fig. 2.3a shows that that pursuing low values of SFC conflicts with achieving high compactness levels, due to the necessity of a heat exchanger to knock down fuel consumption. The turboprop designed by Marcellan in [25] looks the only exception, since it keeps SFC low at a remarkably high power-to-weight. However, a possible explanation to this optimistic result may lie in the preliminary weight estimation model that was used in the MGT design process, which consists in the downscaling of an existing engine. A closer look to Fig. 2.3b seems to reveal that the recuperated cycle, eventually combined with hydrogen (Turbotec), is effective at reducing the SFC for power ratings up to 150 kW, if Marcellan case is neglected. Similar considerations apply to the Sentient Blue case, the innovative hybrid-electric configuration of this powerplant looks rewarding from the fuel economy point of view for such a low power rating. This further highlights how much innovations to the MGT cycle are needed to achieve attractive fuel consumption levels in the 0-50 kW segment.

Finally, the present research work aims to explore MGT cycle innovations to populate the right bottom corner of the chart of Fig. 2.3a.



(a)

(b)

Figure 2.3: MGTs for aeronautical propulsion below 350 kW. Triangle markers represent recuperated engines, while diamond refers to hybrid-electric cycles.

2.2 Fuel flexibility

One of the main advantages of gas turbines is their fuel flexibility. This means they can run with fuels having different specifications, without requirements for design modifications, extending the operating capability. Micro gas turbines carry with them this advantage, which represents a trusted workhorse in the competition with analogous power rating reciprocating engines. All this enables the extension to MGTs of the current discussion about *alternative fuels* for large aviation applications. Among alternative fuels, *sustainable aviation fuels* will play a pivotal role in containing the impact of aviation related carbon emissions, which are due to a fast-growing number of people flying forecast for the upcoming years. In fact, although cutting-edge technology allows for the highest fuel efficiency ever seen on aircraft, the aviation environmental impact is set to become heavier unless other measures to tackle emissions are taken. In the transition to a carbon-free aviation, the technology to power a commercial aircraft on anything other than liquid fuel does not currently exist and, while this is hoped to become feasible in the future, aviation must concentrate on increasing aircraft fuel efficiency, as well as developing SAF.

In a few decades short-haul electric flight will be commercially feasible, no matter if battery or fuel cell based. In this regard, ZeroAvia represents one of the most promising pilot projects to bring hydrogen-electric aviation systems to reality [52]. Long-haul air transport, on the contrary, seems incompatible with electric flight. Hydrogen may be the ultimate sustainable solution to this scope. However, even if hydrogen can be already burned in a turbine engine for aviation, there are significant unsolved technical challenges in designing a LH_2-powered aircraft and in producing enough hydrogen in a sustainable way to supply the industry's needs worldwide.

2.2.1 Alternative fuels: the alternative to fossil-based fuels

In the aeronautical field, alternative fuel is any fuel that has the potential to generate lower carbon emissions than conventional kerosene on a life cycle basis, according to the ICAO definition [33]. This term is also used to describe any alternative to fossil fuels in general. Actually, alternative fuels allow for an offset of CO_2 rather than a reduction, since ideally most of the carbon dioxide released in their combustion is supposed to be absorbed by their production process.

Aviation alternative fuels are often confused with *sustainable aviation fuels* (aka "SAF"). The fact that a fuel is "alternative" to kerosene does not imply its own sustainability. It better refers to the possible use of this fuels in turbine engines without making technological and functional modifications to the engine itself, while ensuring stable operation and performance without jeopardizing its integrity [11]. In fact, the production process and the feedstock needed for some alternative fuels may cause depletion of natural resources, create damages to the environment and hinder the socio-economic growth of the people involved in the supply chain. Some examples of feedstock for alternative fuels may shed a light on the contrast alternative vs. sustainable:

- Households and businesses solid waste, such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, etc.
- Cellulosic waste the excess wood, agricultural, and forestry residues.
- Used cooking oil comes from animal or vegetal fat that has been used for cooking and cannot be used further.

- Camelina primarily an energy crop, with high lipid oil content. The leftover from the oil extraction can also be used as animal feed.
- Algae is potentially the most promising feedstock for producing large quantities of SAF, since they can be grown at high rate in polluted or salt water and other inhospitable places. Moreover, they are ideal for carbon sequestration.
- Non-biological alternative fuels are created involving electric power, water and CO_2. This example can turn sustainable if the inputs are by-products of some other manufacturing processes and the power used is generated from renewables.

Thus, it is important to stress that fuels based on these feedstocks can be both sustainable and unsustainable. The distinction depends on the methods used to produce the feedstocks and the process used to create the fuel itself.

Finally, in the light of the list above, the production of alternative fuels can be tailored to the resources and the opportunities offered in different locations around the globe, unrelated to the drilling sites of fossil fuel. This is an advantage that enables a more diverse geographic supply and subsequent higher energy security.

2.2.2 Biofuels: alternative fuels from biological feedstocks

Biofuels identify a class of non-fossil based fuels produced from biological feedstocks. They can be therefore considered as alternative fuels, but again, their sustainability is not granted. Main examples of biofuels are biodiesel and bioethanol. They are derived from crops such as rapeseed, sugarcane, corn, palm oil, and soybean, which are typically used as food for humans and animals. Consequently, the production of this type of biofuel can compete with the food production and raise several concerns, such as land and water use, deforestation, the effect on food prices, the impact of irrigation, pesticides and fertilizers on local environments. All these issues can be immediately related to the scalability of production of biofuels, which readily appears unsustainable with a view to complete substitution of the jet fuel used in commercial aviation. The use of biofuel can eliminate CO_2, but not NO_x and particulate.

2.2.3 Synthetic Fuels

Synthetic fuels, or *synfuels*, are mixtures of H_2, CO and often CO_2. Their name is due to their use as intermediate products in the synthesis of other fuels. Synfuels are typically used when the locally available hydrocarbon (e.g., methane, coal, etc.) cannot be used directly for a certain application, such as powering an aircraft engine, eliminating the need of importing that specific fuel. For instance, the feed stock available is transformed chemically into synfuel, and finally into jet fuel, *synjet*, an alternative fuel solution that avoids any redesign of engines, airframes or fuel delivery systems. These steps require typically pure CO_2, which can be obtained from the burning of coal for energy production, for instance. In doing so, that energy produced by fossil sources would then become carbon neutral, highlighting their carbon-capture potential.

Truth to be told, the steps required for the chemical transformation of synthetic fuels into synjet imply higher costs compared to more conventional techniques of jet fuel refinement, up to twice the price or more according to [40]. However, global life cycle cost analysis might still confirm the advantage of synjet in terms of energy security, environmental and economic costs, especially for those countries with large reserves of both coal and natural gas [9].

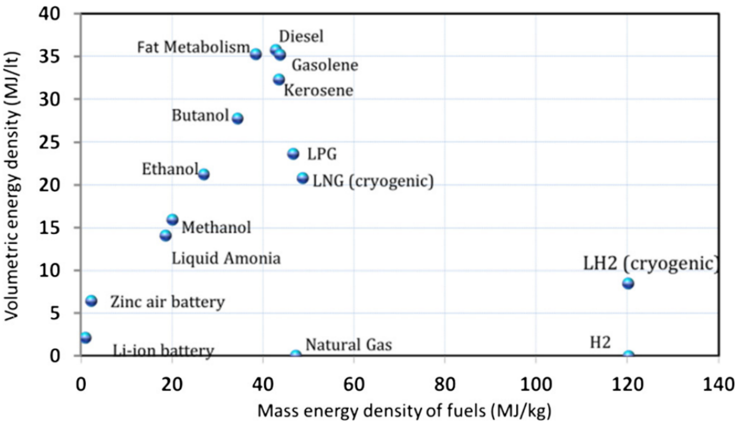


Figure 2.4: Comparison of various energy sources for aviation [50].

2.2.4 Hydrogen

Airbus reports a 4.3% global annual air traffic growth for the next 20 years [2]. This will aggravate the climate impact of the aviation industry [35], which currently contributes 2% to 3% of the world's manmade carbon emissions. The Advisory Council for Aviation Research and innovation in Europe (ACARE) set ambitious goals about emissions reduction: a 75% cut to CO_2 and a 90% to NO_x by 2050 compared to 2000 technology. The strategy to hit this target ranges from innovative aircraft design and novel powerplant arrangements to the use of alternative fuels.

The current dependency on fossil fuels and their increasing use due to the continuous growth of air traffic suggest that alternative solutions must be considered to alleviate shortage issues that may arise in the future as well as reduce emissions. In fact, the ever-growing demand of fuel expected in the next years due to the increase in air traffic will create a discrepancy between demand and offer, which will lead to rise the fuel cost. On top of that, as long as the conventional fuel is in use, the goal of reducing CO_2 emission significantly remains illusory, hindering the certification of new engines that must comply with more and more stringent emissions standard. Hence, alternative fuels will play an important role [50].

With regards to alternative, potentially zero-emissions fuels, hydrogen is considered an appealing energy carrier for aeronautical applications. In fact, its amount of energy per unit mass is about three times greater than jet fuel, as shown in Fig. 2.4. This aspect suggests there could be a case to take advantage of this weight saving to introduce cycles that can reach higher efficiency despite a more complex, thus heavier configuration, such as a recuperated cycle, to the benefit of the fuel economy. However, the low energy density is the critical aspect. Although the non-pressurized liquid state allows hydrogen the highest amount of energy per unit volume, this results in relatively moderate size and weight of the storage tanks. To enable an effective use of hydrogen in aviation, viable cryogenic storage seems the way to go to provide limited volume, so low weight storage, especially for long-haul applications [21].

Hydrogen in aviation applications

Although hydrogen as aeronautical fuel has returned on top recently on the wave of the ecological transition of our society, its first application dates back about eighty years ago. In fact, an experimental aeroderivative turbine running on hydrogen, the Heinkel-Strahltriebwerk 1 (HeS-1), was tested for the first time in 1937 in Germany. About twenty years later the US Air Force started a series of ground and altitude tests to assess the potential of hydrogen fuel injection, which culminated with US B-57B bomber, which was able to switch to liquid hydrogen in flight [29]. In 1988, the Soviets tested the Tupolev TU-155, a TU-144 that was modified to run one out of the three engines with hydrogen. The cryogenic fuel is kept in a fuel tank installed in a special compartment in the rear portion of the passenger cabin. A large flight-testing program was fulfilled. To use cryogenic fuel, the airframe and some standard systems were modified, cryogenic fuel charging, storage and feeding systems were installed that ensured fire/explosion safety. The '90s were marked by a joint venture between German, Russian and American teams to study the eventual production of a large subsonic passenger aircraft in the class of Airbus A310 and powered by Pratt & Whitney engines to be fueled by either liquefied hydrogen or natural gas [13].

Finally, between 2000 and 2002 the European Commission provided funding of about 3 million for the CRYOPLANE project under the coordination of AIRBUS Deutschland GmbH. This project was intended to assess the relevant aspects for the introduction of hydrogen in the commercial aviation environment, including both aircraft and airport facilities related aspects: fuel systems simulation, NO_x reduction techniques, infrastructures for hydrogen production and distribution, just to name a few [37]. As regards the LH_2 fuel system, the study concluded that for an equivalent amount of energy density, liquid hydrogen requires 4 times the volume of conventional aviation fuel. Hence, the fuel tanks must be 4 times larger when compared to conventional aircraft fuel storage. Due to this excessive surface area of the tanks, consumption of energy would increase from 9% to 14%. Overall operating costs of hydrogen fueled aircraft would increase from 4% to 5% based on fuel alone [21]. Despite the criticality of liquid hydrogen storage, the final report of CRYOPLANE corroborated the technical feasibility and safety of LH_2 to fuel aircraft for commercial airline service, and its potential to reduce the impact of civil aviation upon the atmosphere [49].

To conclude, important structural modifications are needed to enable an airliner to run on hydrogen. The bulky tanks for its storage represented a solid obstacle to the transition to hydrogen-fueled aircraft in the past, by damaging the aerodynamic efficiency and/or reducing the payload available aboard. Nowadays, the development of composite materials technology and cryogenic storage techniques may represent the solution to make carbon-neutral flight possible.

Current trends in aviation for H_2 application

As regards small aircraft, especially UAVs, examples of LH_2 used as a fuel for air-breathing engines are lacking. Between 2007 and 2014 Boeing demonstrated the readiness of a hydrogen propulsion system based on a Ford-developed engine by testing the Phantom Eye, a High-Altitude Long-Endurance (HALE) unmanned air vehicle, a natural evolution of Boeing's earlier success with the piston-powered Condor [6, 7, 8]. This is probably the most remarkable application of hydrogen of this kind. Most of the applications concern fuel cells indeed. In 2005 AeroVironment built and tested the Global Observer, the world's first liquid-hydrogen powered UAV of HALE type. The aircraft fuselage contains the liquid-hydrogen fuel-cell propulsion system, which powers eight motors mounted along a 50-feet wing [28].

Other relevant applications concern the concept of Fuel Cell Auxiliary Power Unit (FC-APU), which is one of the most investigated hybrid solutions for hydrogen in aviation. With a view to increasing electric power demand on future aircraft, APU could be used not only as secondary/emergency power source. In fact, in the More Electric Aircraft

Table 2.3: Types of hydrogen storage.

Type	Temperature (K)	Pressure (atm)	Density ($kg\,m^{-3}$)
Compressed Gaseous	298	350-700	25-39
Cryo-Compressed	20-270	250-500	25-70
Liquid H2	20	1	70

framework, more and more systems will run on electric power in the near future, so APU could play the role of continuously running device and lighten the load on main engines. The FC-APU is expected to be heavier than the traditional APUs, but more efficient, which can make the overall system mass (which includes fuel and water masses) lower especially for long duration operations. NASA's target for specific power of SOFC hybrid systems is $0.5\,kW\,kg^{-1}$, while it is about $2\,kW\,kg^{-1}$ for conventional simple cycle APU. The efficiency of the hybrid systems is higher than 50% (some predictions even approach 80%), compared to around 15% of the simple cycle APUs [39].

Impact on plant performance

When a turbine deigned to run on fossil fuel is fueled with hydrogen, the increased reactivity and higher flame speeds of hydrogen force new combustion and fuel injection designs to be adopted. This means that core gas turbine combustion module needs replacement in case of retrofit of a plant, but weight and volume should not go through stay the same.

The different composition of the combustion products leads the gases to have different thermophysical properties. The predominance of water vapor, the marginal presence of NO_x and the almost absence of CO_2 in the products affect the specific heat and the heat transfer coefficient with a clear effect on the enthalpy drop in the turbine and the heat transfer of the turbine blades respectively. Finally, given the higher heating value of hydrogen compared to natural gas, the fuel flow rate at turbine inlet is expected to be lower with effects on the matching between turbine and compressor [10].

Types of hydrogen storage

Storage represents a design challenge when hydrogen is used as a fuel in transport applications, given its density that is about ten times less than kerosene under standard conditions [31]. Three types of storage have been identified by Aceves [1] for different storage temperature and pressure, as reported in Tab. 2.3. The type of storage influences directly the requirements of the tank in terms of materials, wall thickness and weight of the tanks.

Aircraft tanks for liquid hydrogen Among the main hurdles in utilizing liquid hydrogen for air applications, there is the storage, as it has four times the volume compared to kerosene which in turn increases the weight of the tank [21]. At room temperature, hydrogen will be in a gaseous form. At atmospheric pressure, H_2 can be maintained at liquid state under 20.4 K which is the cryogenic temperature below the critical temperature 33 K, 1.29 MPa. However, LH_2 storage tanks are designed for lower pressures, so that the wall thickness and the weight can be reduced.

2.2.5 Life cycle assessment

When alternative fuels are considered for an aeronautical application, it is important to make an evaluation not only based on energy consumption or emission of few pollutants, but also develop a wider analysis including an evaluation of different environment and social costs. In fact, The analysis of one or two pollutants only can easily lead to results of a distorted reality. To avoid that, the broad literature about life cycle assessments suggests to include CO, PM, HC, beyond the hot debated CO_2 and NO_x [34].

LCAs consider environmental and social costs of the fuel, from its production to its use, in other words "well-to-wake", in contrast with the simpler "tank-to-wake" approach, which is common to many mission analysis studies. The latter is a mere quantification of the emissions related to the sole burning, therefore is not sensitive to the various production methods of alternative fuels, missing part of the picture. Finally, Pereira concludes that hydrogen is the less polluting solution among alternative fuels. Its advantages in terms of environmental costs over jet fuel increase especially when renewable sources are used for its production.

2.2.6 Summary

Fuel flexibility has been widely considered an asset of micro gas turbines over their competitors in the existing literature. An investigation of the possible alternatives has been presented in this report to highlight limits and opportunities.

While SAF and their blends are considered pivotal in the transition to aviation decarbonization, hydrogen is the energy carrier that many consider as the ultimate solution to tackle CO_2 emissions related to air transport. The research efforts of the main players in the industry are in that direction. In this respect, storage of hydrogen looks like the main challenge at the moment, due to the low content of energy per unit volume. Conversely, the amount of energy per unit mass of hydrogen is outstanding, about three times greater than jet fuel. The latter is the most interesting characteristic of this unconventional fuel and might open to a wide range of opportunities in cycle innovation.

Power rating being equal, the power-to-weight ratio of engines does not seem to be affected by the fact of running on hydrogen rather than on other more conventional fuels. However, as regards aeronautical applications, where jet fuel has to be beamed aboard, the higher mass energy density of hydrogen enables the reduction of the mass of fuel needed for a defined mission. This aspect suggests there could be a case to take advantage of this weight saving to implement cycles that can reach higher efficiency despite a more complex, thus heavier configuration, due to additional components, such as a recuperator and/or an intercooler. Although the new configuration would show a lower power-to-weight ratio, the payload might remain constant or improved, since the extra weight of the new engine would be compensated by hydrogen replacing jet fuel.

2.3 Conclusions

A critical analysis of the main applications of MGTs to aeronautical propulsion is presented, among simple cycle, recuperated cycle and hybrid-electric configurations. SFC and power-to-weight ratio have been identified as key parameters to assess the technology level. Propulsive systems driven by micro gas turbines simple cycle with a very low power rating ($< 100\,\mathrm{kW}$) emerge as the ones featuring attractive power-to-weight ratios, but mediocre SFC values. At the same time, the adoption of recuperators, eventually combined with the capability of burning hydrogen, enables a reduction of SFC to values that resemble those of larger gas turbines. This reduction is obtained at the expenses of power-to-weight ratio, which is knocked down due to the additional weight of the heat exchanger.

The analysis concludes that the improvement of SFC and the preservation of the power-to-weight ratio are conflicting goals. However, a compromise may be still made to allow a significant reduction of the fuel consumption, without deteriorating excessively the attractive power-to-weight ratio, which is a recognized asset of micro gas turbines running on simple Brayton-Joule cycle.

Novel technologies and materials, currently studied or implemented in other applications, transferred to the small scale of MGTs seem to have the potential to reach that compromise:

- adoption of an intercooler in the cycle to reduce the power needed to drive the compressor;
- integration of the MGT with an electric motor in a hybrid-electric configuration;
- adoption of lightweight high-compactness heat exchangers obtained by additive manufacturing and innovative materials, such as CMCs and compressed metal foams;
- additive manufacturing techniques applied to the turbine wheel may enable internal cooling, therefore higher TIT (cf. paragraph 1.1.1);
- the use of hydrogen instead of kerosene or similar fossil fuels.

The investigation of the last item has been the main focus of the research in the last months, as described in Chapter 4.

Chapter 3

Project Plan

This chapter describes the way the project is meant to achieve its aim. To this extent, the research methods that have been used so far are explained. Moreover, the tasks expected to be completed in the upcoming months are presented and a timeline is proposed.

3.1 Research methodology

This research project aims to define what are the most promising innovations to the MGT cycle for the achievement of the highest efficiency, minimizing the impact on aircraft performance and the environment. The approach followed to pursue this aim is to set up a numerical model simulating engine design and off-design steady state operation integrated with aircraft performance and mission analysis tools, as depicted in Fig. 3.1. This enables the calculation of power and fuel consumption of engines running on various fuels, under a defined flight mission. The obtained results allow for the exploration of engine innovations, compare them and identify the most promising ones.

3.1.1 Aircraft performance model

The aircraft performance model previously developed by Zhang [53] is used in the present study (Fig. 3.2). It predicts the power necessary to allow an MBB Bo 105, a multipurpose light rotorcraft, to operate at a given weight, altitude and flight speed, namely z and v in Fig. 3.1. This helicopter is powered by two RR Allison 250-C20B turboshaft engines

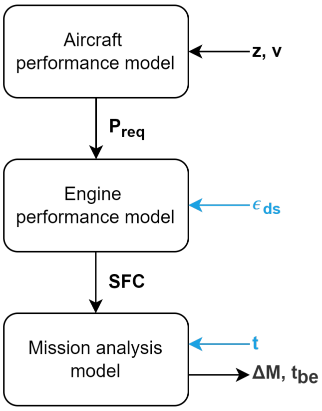


Figure 3.1: The relationship among the components included in the numerical model (variable parameters in blue).

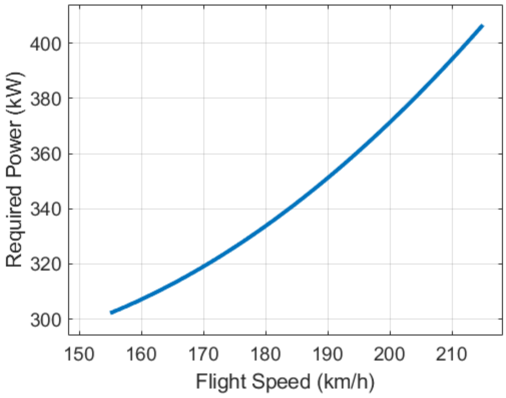


Figure 3.2: Power required for level flight at 500 m altitude.

Table 3.1: Reference helicopter specifications.

Design Parameters	
Engines	2× Allison 250-C20B
Engine Power (kW)	Elliot Energy
Empty Weight (kg)	2× 313
Max Take-Off Weight (kg)	1276
Max Fuel (kg)	460

and its relevant design parameters are shown in Tab. 3.1. Three key assumptions are made in the model:

- The integration of recuperators does not affect the aerodynamics of the helicopter.
- The integration of any tank does not affect the aerodynamics of the helicopter.
- The MTOW is considered a constant across all the configurations selected.

The model is based on momentum theory and takes into account different contributions that build up the total power needed: main rotor power, tail rotor power, power to overcome the parasitic drag and the power related to auxiliary systems, as described in (3.1). Momentum theory-based methods are the simplest available and easy to implement for normal operations, far from the limitations of the flight envelope.

$$P_{req} = P_{MR} + P_{TR} + P_p + P_{aux} \tag{3.1}$$

3.1.2 Engine performance model

Test case engines

The simple cycle kerosene-fueled engine is based on the 300 kW micro gas turbine simple cycle of Allison 250-C20B, which is used as baseline and referred as “Kerosene-Simple” (KS) in Tab. 3.2. This engine consists of a gas generator and a two-stage free power turbine. The performance maps of the compressor, the gas generator turbine and the free power turbine are obtained from a GasTurb model that had been previously validated using available experimental data [54]. Under the assumption of maximum efficiency

Table 3.2: Test case engine definition.

	KS	KR	HR
Fuel	Jet Fuel	Jet Fuel	Liquid Hydrogen
Cycle	Simple	Recuperated	Recuperated

operation at any rotating speed, correlations can be extracted from the performance maps between the corrected mass flow, the efficiency and the pressure ratio for each component. Finally, cycle efficiency and SFC can be calculated for the power required to perform the mission, P_{req}, which is defined in the rotorcraft model.

Afterwards, a heat exchanger is incorporated in the baseline configuration for heat recovery. The recuperated cycle performance is assessed first for 100% jet fuel, "Kerosene-Recuperated" (KR) engine, then for 100% liquid hydrogen, "Hydrogen-Recuperated" (HR). Thus, three configurations are investigated and are presented in Tab. 3.2.

Recuperators

The heat exchangers are modeled over a wide range of thermal effectiveness ($0.6 < \epsilon_{ds} < 0.9$) both in their performance and in their weight. As far as the first point is concerned, part-load operation of the heat exchanger is modeled as suggested in the GasTurb Manual. It provides a correlation to compute off-design effectiveness and pressure losses, given the mass flow [23], according to Eqs. (3.2)-(3.4), where the subscript ds refers to the design point conditions. In off-design conditions the heat transfer surface is considered to remain constant.

$$\epsilon = 1 - \frac{m}{m_{ds}}(1 - \epsilon_{ds}) \tag{3.2}$$

$$\frac{p_{in} - p_{out}}{p_{in}} = \left(\frac{p_{in} - p_{out}}{p_{in}}\right)_{ds} \frac{\left(\frac{m_{in}}{p_{in}}\right)\frac{T_{out}^{1.55}}{T_{in}^{0.55}}}{\left(\frac{m_{in}}{p_{in}}\right)_{ds}\frac{T_{out,ds}^{1.55}}{T_{in,ds}^{0.55}}} \tag{3.3}$$

$$\frac{p_{in} - p_{out}}{p_{in}} = \left(\frac{p_{in} - p_{out}}{p_{in}}\right)_{ds} \frac{m_{in}^2 T_{in}}{(m_{in}^2 T_{in})_{ds}} \tag{3.4}$$

The pressure losses term at the design point assumes constant, but still conservative values according to the geometry of the recuperator, between 3% and 5%. A tubular recuperator shows average pressure drops that are typically lower than a primary surface.

As regards the weight estimation, McDonald presented a work based on the existing data in the open literature on recuperator specific weight [27]. The research portrays how sensitive specific weight for a gas-to-gas heat exchanger is to thermal effectiveness. Two surface geometries of metallic recuperators are considered for possible applicability to aeroengines: tubular and primary surface. Zhang started from McDonald's results and describes the correlation for tubular and primary surface heat exchangers according to Eq. (3.5) (valid for $0.60 < \epsilon_{ds} < 0.75$) and Eq. (3.6) (valid for $0.80 < \epsilon_{ds} < 0.90$) in [53].

$$m_{HEX_{tub}} = (3.19\epsilon_{ds}^3 - 5.93\epsilon_{ds}^2 + 3.74\epsilon_{ds} - 0.79) \times 10^3 \tag{3.5}$$

$$m_{HEX_{ps}} = (2.82\epsilon_{ds}^3 - 6.77\epsilon_{ds}^2 + 5.44\epsilon_{ds} - 1.46) \times 10^4 \tag{3.6}$$

Where m_{HEX} is the recuperator weight for unit of mass flow rate, while ϵ_{ds} is the heat exchanger design effectiveness, see Fig. 3.3.

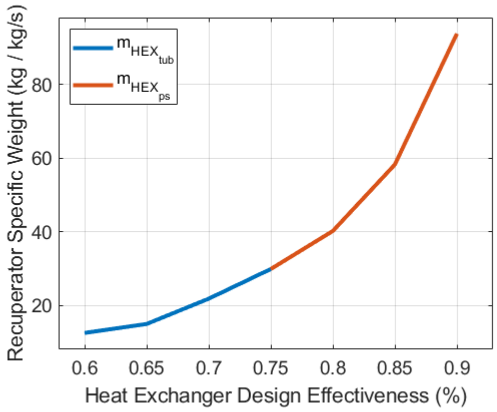


Figure 3.3: The specific weight of recuperator for tubular and primary surface geometries.

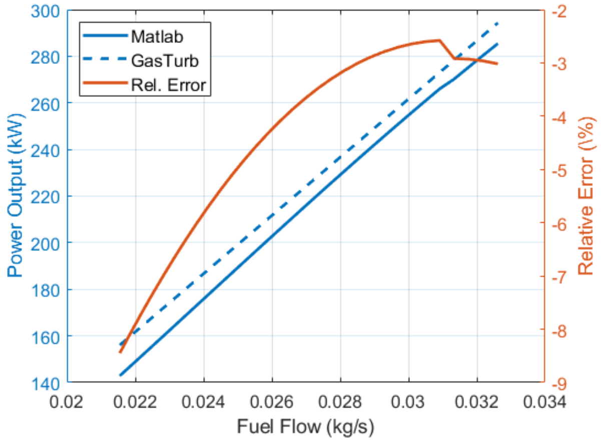


Figure 3.4: Comparison between the GasTurb and MATLAB simple cycle models (STP conditions).

Model verification

The engine model is set up in MATLAB environment under the same operating conditions used by Zhang in [54]. Zhang's model is developed by means of the commercial software GasTurb. The engine model is verified for the kerosene case in both simple and recuperated cycles. As regards the simple cycle, few thermodynamic data are available from the reference simulation conducted in GasTurb. However, a representative comparison for the correlation between fuel flow and output shaft power can be obtained, as shown in Fig. 3.4. The relative error encountered here seems to be mainly related to the higher level of accuracy of the GasTurb software, which adjusts the thermodynamic properties of the working fluid according to its temperature, pressure and chemical composition across the whole simulation.

3.1.3 Mission analysis model

The mission analysis model calculates the amount of fuel consumed over a defined mission duration. The mission considered here consists of cruising in horizontal flight at 500 m altitude at a speed of 180 km/h. This resembles the typical cruise condition of the reference helicopter. The duration of the mission, t in Fig. 3.1, is a variable parameter, which is limited between zero and three hours. The mass of fuel injected in the combustion

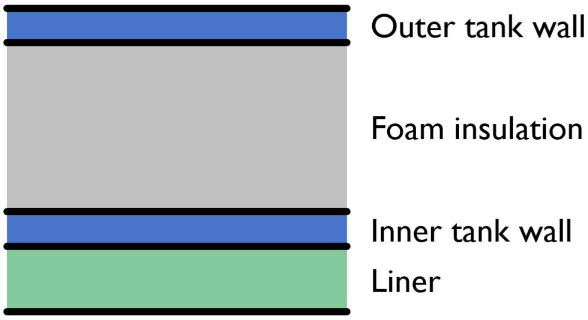


Figure 3.5: Structure of the LH2 multilayer tank wall.

chamber is obtained by multiplying the SFC, which derives from the engine performance model, by the power required and the duration of the mission.

Storage tanks for liquid hydrogen

As regards the case of a LH2-fueled powerplant, the LH2 tank mass is calculated according to the amount of fuel required to perform the selected mission and a multilayer wall tank model based on a study by Sekaran [42]. This research study considers tank structure, geometry, materials and other physical phenomena, typical of liquid hydrogen storage, such as boil-off and permeation, for an aeronautical application. The mentioned multilayer wall consists of the four components presented in Fig. 3.5 and listed below:

- liner made of Al 5086 alloy for avoidance of the hydrogen permeation problem;
- polyethylene inner wall;
- polyurethane foam for effective thermal insulation and low weight;
- outer polyethylene outer wall.

Sekaran concludes that, for a fixed tank length of 2 m, the tank mass increases linearly with the mass of LH2 to be stored and proposes a set of correlation for a multitude of different insulation materials. Both Sekaran and Verstraete [45] agree that the use of polyurethane foam insulation leads to a higher gravimetric storage density and thus a lightweight tank. Consequently, the polyurethane insulation is selected in the present work. The linear correlation obtained by Sekaran for the polyurethane foam insulation allows to extract Eq. (3.7) easily. This equation is used for the mass estimation of the tank, being accepted the constraint on the length for this specific rotorcraft application.

$$m_{tank} = 0.2498 \times m_{LH2} + 16.89 \tag{3.7}$$

3.1.4 Life cycle assessment

The design of the method to perform the life-cycle assessment for the specific application of the present project is still ongoing, as pointed out in section 3.2. However, in a sound life cycle assessment, different stages of the life cycle of a product are considered and their associated inputs and outputs are determined: raw material extraction followed by material processing, manufacturing, distribution, usage, and disposal. The combination of two approaches for fuel LCA "well-to-pump" and "pump-to-wake" in the well-to-wake is used in the present study, as suggested in [44]. This type of analysis considers the phases of feedstock production, followed by fuel production, its transport, dispensing and usage in the aircraft engine.

3.2 Research plan

Objectives 1 to 4 (cf. section 1.2) have driven the research progress so far. However, they have not been fully achieved. In fact, further innovations are expected to be added to the MGT cycle in order to use the developed simulation framework to produce results for a wide selection of engine arrangements, to examine and compare them. The following list contains detailed tasks meant to be completed in the next months to respond to the four research objectives of the present work.

(a) Investigate cycle efficiency improvement through the use of an intercooler. Given the aim of improving the cycle efficiency by means of novel engine configurations, intercooled cycles can be used to improve the net power produced by the Brayton-Joule cycle. By improving the efficiency of compression, the adoption of an intercooler represents an unusual solution for aeronautical propulsion powertrains.

(b) Implement innovative heat exchanger technologies into the thermodynamic cycle. The benefits of recuperated cycles for aeronautical propulsion have been recognized. The next generation of recuperated micro gas turbine should be able to define new performance standards: additive manufacturing allows unique matrix structures that can lead to attractive values of compactness, weight and effectiveness for heat exchangers. These improvements are supported by the use of innovative materials, such as compressed metal foams and CMCs.

(c) Explore hybrid-electric configuration. An electric motor could be added and support the micro gas turbine in the power generation. It could be supplied with electrical power by a battery.

(d) Consider a turbine obtained through additive manufacturing. This technology applied to the small power turbine of an MGT, can enable key features, which usually belong to large scale gas turbines, such as blade air cooling. Thus, a higher turbine inlet temperature can be reached in the cycle, without damaging the turbine blades. Higher TITs usually lead to high values of cycle efficiency, as already described in 1.1.1.

(e) Develop a tank model that is able to determine the storage tank requirements for varying ambient conditions, including weight of the plumbing. In fact, an accurate estimation of tank volume and weight would improve the prediction of its impact on aircraft aerodynamics and MTOW.

(f) Extend the mission analysis model with the capability of assessing the environmental impact. This can be achieved by calculating the quantity of polluting and greenhouse emissions (e.g., NO_x, CO_2, etc.) produced during the flight, based on available combustion models. The integration of this results with data from existing LCA for hydrogen production would make the study even more comprehensive.

The Gantt chart in Fig. 3.6 indicates the expected timeline of the activities up to the PhD completion.

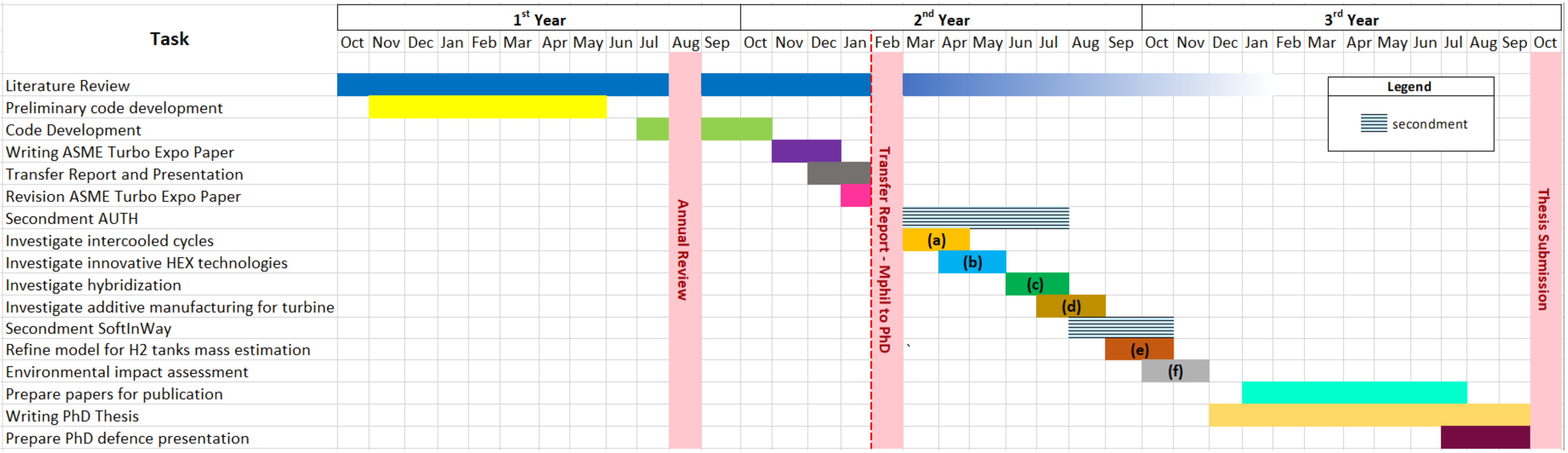


Figure 3.6: Gantt chart of the activities included in the research plan. The red dashed line represents the current research stage.

3.2.1 Risk mitigation

Two categories of risk need mitigation. The first one is related to Covid-19 pandemics and its effect on the measures governments take all around the world to limit the spread of the virus. The second one deals with possible inaccurate allocation of the time needed to carry out the tasks listed in the Gantt in Fig.3.6.

Covid-19 pandemics has hindered the regular development of the present plan since the very beginning. The author could physically reach City only after one year since the actual beginning of the appointment in September 2020. This inevitably held back the familiarization with City facilities and the research team. Fortunately, no experimental work is planned among the activities to be completed. This represents an advantage, protecting the plan from delays related to the closing of laboratories and similar measures taken to contain the pandemics. However, some issues could arise in relation to the secondments to be spent in Greece (AUTH) and Switzerland (SoftInWay) from February to November 2022. In fact, new restrictions might impact the access to the facilities of the partner institutions, hindering networking and collaboration of the candidate with the colleagues on site. Nonetheless, to get the most benefit from the secondments experience remains a prerogative of the candidate, in terms of both personal and professional growth. Wherever possible, alternative ways of interaction will be used, such as video conferences, as they have become a familiar and effective collaboration tool in the last couple of years.

The funding to the present PhD position will end in September 2023, as per the contract between the researcher and City, University of London. Thus, it is early interest of the candidate himself to get to the PhD defense in a timely manner, before the funding stops. To hit this target, it may be necessary to reduce the number of the planned tasks, in case time allocation turns out to be inaccurate. In fact, this is possible, since the activities 1-6 listed above are uncorrelated, offering a good level of flexibility to adjust the research plan to new time constraints and meet the deadlines.

Chapter 4

Research Progress

In this chapter the progress from the MPhil enrollment in October 2020 until now is presented. Research objectives 1, 2 and 3 have inspired the first year and a half at City. In fact, a simulation framework capable of reproducing a turboshaft engine steady state design and off-design operation is built. The fuel consumption of three different engine arrangements is calculated within a parametric study to evaluate the impact of recuperator and hydrogen under a generic reference mission for a light twin engine helicopter. To enable a consistent mission analysis study of the hydrogen fueled rotorcraft, the weight of the tank for liquid hydrogen (LH2) storage is estimated according to a preliminary design model. Finally, the recuperated configurations are compared against the baseline based on a simple cycle, to explore the trade-off between weight and efficiency. This simulation framework has been presented in detail in 3.1. and consists of three numerical models: rotorcraft performance, engine performance and mission analysis.

Part of the work contained within this chapter has been submitted as a conference paper for presentation at the ASME Turbo Expo 2022 under the title *"Performance Assessment of a Recuperated Turboshaft Engine: A Multifuel Case"*, which is attached in Appendix A.

4.1 Results

The models described so far consent to carry out trade-off studies for the different recuperated engine configurations. In fact, The presence of the recuperator allows KR and HR engines to recover heat from the turbine exhaust gases to increase the temperature of the air delivered by the compressor before entering the combustion chamber. Consequently, a lower fuel consumption is expected, which would reflect on a potential reduction of both SFC and emissions with respect to the baseline engine, KS. At the same time, however, the incorporation of the recuperator increases definitely the overall system weight, introducing a weight penalty that grows with the heat exchanger effectiveness. The existence of recuperator geometries other than the ones considered here is well known. In fact, additive manufacturing technologies has recently allowed to achieve attractive values of compactness, so significantly lighter recuperators, effectiveness being equal. This could further support the implementation of regenerative micro gas turbine cycles for aeronautical applications. However, this new generation of recuperators has been excluded by the present study, due to the early stage of their innovative technology, which reflects in high manufacturing costs and perfectible reliability.

HR engine is able to run on potentially carbon-neutral fuel, while it requires properly sized tanks for the storage of liquid hydrogen. This additional piece of equipment entails again a certain increase of the overall system weight, which is related to the amount of fuel needed for a given mission. Further specific components, such as pumps, would be required to replace the existing ones for a full conversion of the helicopter from jet fuel to liquid hydrogen, possibly increasing the weight penalty in these cases. However, for the sake of simplicity of this preliminary study, the hydrogen specific components are considered comparable to the jet fuel ones in terms of weight, so only the additional weight due to the hydrogen tank is considered.

The increased complexity of recuperated and hydrogen-compatible engines would enable reduced SFC and emissions, meanwhile, the combined weight of these configurations is unavoidably higher than the baseline engine. In a specific mission, the point at which the mass of saved fuel equals the mass of the additional equipment for recuperation and/or hydrogen is here defined as "breakeven point". The breakeven point is an indicator to assess whether the adoption of recuperator and hydrogen tanks is beneficial for the given mission. If the breakeven point was not met during this mission, then the lower SFC would not compensate the parasitic weight due to the added complexity of the engine considered. ΔM is the parameter used to mathematically define the problem and identify when the breakeven point is reached, i.e. for a null ΔM. Positive values of ΔM justify KR and HR engine configurations. ΔM is defined as the difference between the saved amount of fuel and the additional equipment for recuperation and/or hydrogen normalized with respect to the MTOW, as shown in Eq. (4.1). The choice of a dimensionless parameter, such as ΔM, is preferable with a view to future work that may deal with comparing different aircraft across various missions.

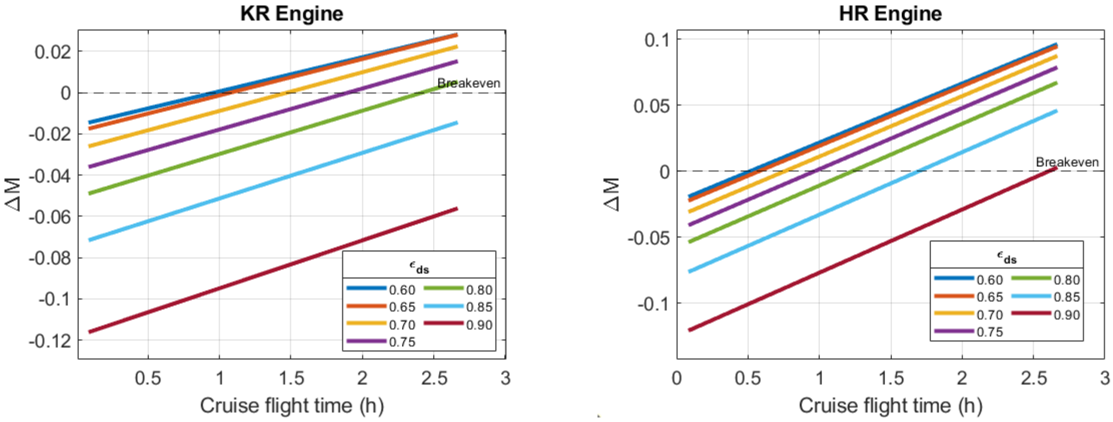
$$\Delta M = \frac{(m_{fuel_{KS}} - m_{fuel}) - (m_{HEX} + m_{tank_{H2}})}{MTOW} \tag{4.1}$$

4.1.1 Cruise mission investigation

Helicopter missions typically include takeoff, climb, cruise, descent, hover and landing. With prime focus on the steady state behavior of the components, the recuperator is considered to operate only during cruise condition. As a consequence, the reference mission that is considered by the present study entails just the cruise phase, therefore horizontal flight condition at fixed speed and altitude: $180\,\mathrm{km\,h^{-1}}$ at $500\,\mathrm{m}$, respectively.

Considering the KR engine, ΔM is negative at the beginning of the cruise, since no fuel has been saved yet at that point, so the recuperator represents just a weight penalty Fig.4.1a. As the cruise flight time increases, ΔM shows a linear trend up to reaching the breakeven point ($\Delta M = 0$), after which it keeps growing at the same rate. A positive ΔM denotes the chance to extend the mission range or increase the payload for the helicopter. For high-effectiveness primary surface recuperators, a longer flight time, which can exceed the 2 h, is needed to save enough fuel to compensate their bulky weight and reach $\Delta M = 0$. The effectiveness of the recuperator is a critical parameter to reach the breakeven point. For instance, a primary surface heat exchanger for a design effectiveness of 75% maybe considered suitable for a mission that includes 1.5 h of cruise, while unsuitable for another one with a shorter cruise flight time.

Consider now the HR engine. The overall trend of ΔM resembles the KR case. In fact, in Fig. 4.1b dependence of ΔM from the cruise flight time remains linear. However, the time needed to reach $\Delta M = 0$ is shorter for all the heat exchanger effectiveness taken into account, if compared to the KR case. On top of that, this reduction is achieved despite the additional weight penalty due to the hydrogen tank, which is specific for the hydrogen engine configuration.



(a) *Kerosene Recuperated Engine* (b) *Hydrogen Recuperated Engine*

Figure 4.1: The variation of ΔM versus cruise flight time.

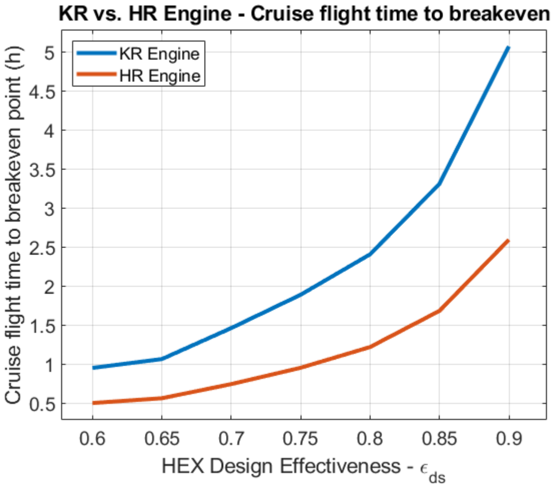


Figure 4.2: Cruise flight time to reach breakeven point for different engine configurations.

The mission analysis shows that the selection of a certain recuperator effectiveness may be suitable in some cases depending on the cruise flight duration. For instance, a recuperated configuration with high-effectiveness primary surface recuperator requires longer cruise times to reach the breakeven point than a low-effectiveness tubular recuperator. Whilst this last consideration is valid both for KR and HR engines, Fig. 4.2 clearly shows a remarkable reduction of the cruise flight time to reach breakeven point, t_{be}, for the HR engine case. In fact, the breakeven point is reached in nearly half of the cruise flight time for any selected effectiveness in the 60-90% range considered, namely less than one hour for lightweight, low effectiveness recuperators, as shown in Fig. 4.1b.

4.2 Conclusions

The obtained results show that the adoption of hydrogen enables sensitive reduction of the breakeven time, making recuperation more attractive for aeronautical applications of micro gas turbines. Moreover, the reduction of the t_{be} to less than one hour of cruise flight may raise interest on low-effectiveness recuperated LH2-fueled micro gas turbines for potentially zero-emission short endurance flight, including light rotorcraft and Urban

Air Mobility applications.

The next steps will include the development of a model to calculate the weight of heat exchangers manufactured with innovative materials (e.g., CMCs and metal foams), as described in activity (b) in the Research Plan 3.2. This model can be directly implemented in the simulation framework used so far and produce results for an easy comparison with the ones of the paper submitted to ASME.

Appendix A

Dissemination

A conference paper with the title *"Performance Assessment of a Recuperated Turboshaft Engine: A Multifuel Case"* has been submitted for presentation at the ASME Turbo Expo 2022, which will take place in June 2022. The paper is currently under review and a copy is attached below.

Proceedings of ASME Turbo Expo 2022
Turbomachinery Technical Conference and Exposition
GT2022
June 13-17, 2022, Rotterdam, The Netherlands

GT2022-80455

PERFORMANCE ASSESSMENT OF A RECUPERATED TURBOSHAFT ENGINE: A MULTIFUEL CASE

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ABSTRACT

The low cycle efficiency of simple cycle micro gas turbines is typically raised by the use of recuperators. The recuperated cycle allows for improved efficiency at low power-to-weight ratio, mainly due to the weight of the added heat exchanger. As weight is considered to be a key parameter for aeroengines, an analysis that addresses benefits and drawbacks of a more efficient, but heavier propulsion system design is required to be carried out. This paper assesses propulsion systems based on simple and recuperated cycle small gas turbine configurations, unusual in aviation, running with conventional jet fuel or hydrogen. An analytical model capable of modelling a turboshaft engine steady state design and off-design operation is developed. The specific fuel consumption of different engine arrangements is therefore calculated to evaluate the performance trade-off between the improved power plant fuel economy and its larger weight under a generic reference mission for a light helicopter. To enable a consistent mission analysis study of the hydrogen fueled rotorcraft, the weight of the tanks for liquid hydrogen storage is estimated according to a preliminary design model. The results obtained suggest that a hydrogen-fueled recuperated powerplant can shorten the flight time to reach the breakeven point, compared to a recuperated jet fuel powerplant of the same power rating.

Keywords: micro gas turbine, liquid hydrogen, aeronautical propulsion, recuperated turboshaft.

NOMENCLATURE

Al	Aluminum
EASA	European Union Aviation Safety Agency
HR	Hydrogen-Recuperated
KR	Kerosene-Recuperated
KS	Kerosene-Simple
LH2	Liquid hydrogen
m	Mass
MGT	Micro gas turbine
MTOW	Maximum Takeoff Weight
P_{req}	Required power
SFC	Specific fuel consumption
t	Cruise flight time
t_{be}	Breakeven time
UAM	Urban Air Mobility
v	Flight speed
z	Altitude
ϵ_{ds}	Heat exchanger design effectiveness

1. INTRODUCTION

Innovations in propulsion systems have been a primary driver for progress in air transportation. The advancements in performance and efficiency of propulsion allow aircraft to travel longer range at high speed while consuming less fuel. Nevertheless, aviation currently contributes 2% to 3% of the world's manmade emissions of carbon dioxide [1]. On top of that, for the next 20 years, the Airbus Global Market Forecast reports a prediction of 4.3% global annual air traffic growth, to which the Urban Air Mobility (UAM) segment will contribute. In fact, the transportation systems able to move people or cargo by air around urban environments is expected to reach a volume of about €4.2 billion in 2030 in terms of European market size. An opportunity that may create approximately 90,000 jobs by 2030, based on the labor needed for constructing related infrastructure and operating the UAM according to the European Union Aviation Safety Agency (EASA) [2].

The current dependence on fossil fuels and their increasing use due to the continuous growth of air traffic suggest that alternative solutions must be considered to reduce emissions as well as alleviate shortage issues that may arise in the future. To meet the growing requirements of the aviation industry, innovative solutions including fuselage designs (e.g., NASA's

Blended Wing Body concept [3]) for enhanced lift-to-drag ratio, novel engine cycles for improved efficiency and the use of alternative, potentially zero CO_2 emissions fuels, such as hydrogen, have been investigated in recent years. Other solutions towards fuel saving and emission reduction rely on alternative arrangements of the propulsion system, such as distributed propulsion. However, when it comes to the employment of many small gas turbines across the aircraft fuselage, fuel consumption seems to reach excessive levels [4].

With regards to the low cycle efficiency affecting small power rating gas turbines, the adoption of a recuperator in the cycle contributes to improved specific fuel consumption and lower carbon emissions. Light helicopters may represent an interesting case since they often feature a twin-engine design due to safety and certification constraints, so that in case of one engine failure, they can be still controlled and landed safely [5]. However, during most of a mission time they operate at part-load, thus far from optimal conditions. Heat recovery by means of a recuperator could improve the system efficiency by reducing the SFC, enabling enhanced mission capabilities, in terms of payload, range or endurance. A substantial temperature difference between the air delivered by the compressor and the exhaust gases is crucial for an effective heat recovery. In this regard, small power rating turboshaft engines are suitable candidates for recuperation due to their low pressure ratio.

Successful demonstrations of recuperator employment in aeroengines based on Brayton cycle date back to the 1960s, when the low cost of fuel and the limits of heat exchanger technology hindered further work in this direction [6]. The intermittent research of the following decades culminated in the design of a 3kW turboshaft engine equipped with an annular ceramic recuperator. It was designed at the U.S. Naval Research Laboratory for a UAV application and was tested without cracks or leakage. However, it never moved past the prototype phase [7].

The advancements in materials and manufacturing technology have led to the current generation of recuperator geometries, namely primary surface and tubular, which show improved thermal performance and compactness. These are crucial aspects for micro gas turbines for airborne applications, since fuel economy and high power-to-weight ratio are significant performance requirements for aircraft powerplant integration. It is clear that the incorporation of a recuperator increases the system weight, impacting negatively the power-to-weight ratio of the gas turbine, and to even outbalance the fuel saving allowed by the increased efficiency of the recuperated cycle. Only a quantification of the compromise between the additional recuperator weight and saved fuel weight can determine the potential benefits of this complex engine configuration. The importance of the break-even point, at which the recuperator added weight is compensated by reduction in fuel burn was highlighted by Ali in [8]. The economic viability of a regenerative helicopter is reached only if the fuel weight is reduced by an amount greater than or equal to the weight added by the installed heat exchanger(s). An extensive work has been published recently in this regard with the aim to assess the abovementioned trade-off for a light helicopter powered by two micro gas turbines over a set of realistic missions for a wide range of recuperator effectiveness [9]. The obtained results suggest that the deployment of a recuperator may not be beneficial for short haul or duration missions, especially for highly effective recuperators that tend to be bulkier, exacerbating even more the weight penalty associated with their incorporation.

The concept of improving fuel economy by increasing the complexity, thus the weight, of the powerplant configuration has been analyzed from a similar perspective by Roumeliotis [10]. In this case, the power rating is higher than those mentioned so far, and the rotorcraft original engine is upgraded to a thermoelectric powerplant, so it includes a recuperator and an electric motor supplied by batteries. The hybridization should tackle the reduced specific power and the change in the throttle response of the system, previously noted in [11], which come with the increased weight and the heat exchanger pressure losses. The results indicate that sensible fuel economy improvements may be achieved despite the weight penalty, albeit within certain limits of hybridization.

As far as alternative fuels are concerned, hydrogen is considered an attractive energy carrier for aeronautical applications. On the one hand, its energy content per unit mass is about three times greater than jet fuel. This aspect suggests there could be a case to take advantage of this weight saving to introduce cycles that can reach higher efficiency in spite of a more complex, thus heavier configuration, such as a recuperated cycle. On the other hand, storage volume requirement is a remarkable drawback for its use as aerospace propellant. In fact, H_2 shows a specific mass that is only a mere fraction of JP-8, at standard temperature and pressure conditions. Cryogenic liquid storage seems a viable solution, since it allows hydrogen to achieve about the 25% of the amount of energy per unit volume of kerosene, so relatively moderate sized tanks [12].

Among the various studies on rotorcraft recuperated powerplants, the use of liquid hydrogen as a fuel has not been assessed in the existing literature. In this work, part of the European project NextMGT [13], the correlation and the trade-off between the fuel saving potential and the weight penalty introduced by the recuperator is estimated over a generic reference mission against various powerplant configurations, including recuperation and both kerosene and liquid hydrogen as fuels. When liquid hydrogen is used, the weight of a properly sized storage system must enter the trade-off study, which is carried out by means of an integrated simulation model.

2. METHODOLOGY

A simulation framework capable of reproducing a turboshaft engine steady state design and off-design operation is built in MATLAB environment. The fuel consumption of three different engine arrangements is calculated within a parametric study to evaluate the impact of tubular and primary surface recuperators over a wide range of effectiveness values (60-90%) under a generic reference mission for a light twin engine helicopter. To enable a consistent mission analysis study of the hydrogen fueled rotorcraft, the weight of the tank for liquid hydrogen (LH2) storage is estimated according to a preliminary design model. The framework consists of three numerical models: rotorcraft performance, engine performance and mission analysis, as depicted in Fig. 1.

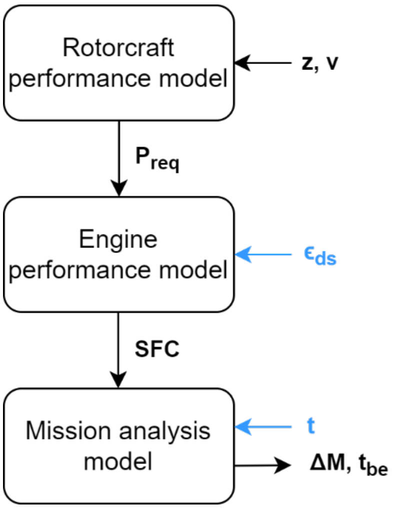

FIGURE 1: THE NTERACTIONS AMONG THE MODELS INCLUDED IN THE SIMULATION FRAMEWORK (VARIABLE PARAMETERS IN BLUE).

2.1 Rotorcraft performance model

The rotorcraft performance model developed by Zhang [9] is used in the present study (Fig. 2). It predicts the power necessary to allow an MBB Bo 105, a multipurpose light rotorcraft, to operate at a given weight, altitude and flight speed, namely z and v in Fig. 1. This helicopter is powered by two RR Allison 250-C20B turboshaft engines and its relevant design parameters are shown in Table 1. Three key assumptions are made in the model:

- The integration of recuperators does not affect the aerodynamics of the helicopter.
- The integration of any tank does not affect the aerodynamics of the helicopter.
- The MTOW is considered a constant across all the configurations selected.

The model is based on momentum theory and takes into account different contributions that build up the total power needed: main rotor power $P_{t,MR}$, tail rotor power $P_{t,TR}$, power to overcome the parasitic drag P_p, and the power related to auxiliary systems P_{aux}, as described in Eqn. (1). Momentum theory based methods are the simplest available and easy to implement for normal operations, far from the limitations of the rotorcraft flight envelope.

$$P_{req} = P_{t,MR} + P_{t,TR} + P_p + P_{aux} \qquad (1)$$

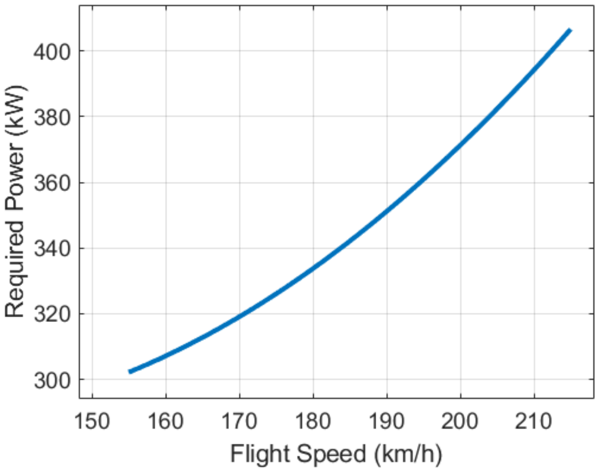

FIGURE 2: POWER REQUIRED FOR LEVEL FLIGHT AT 500 M ALTITUDE.

TABLE 1: REFERENCE HELICOPTER SPECIFICATIONS.

Design Parameters	
Engines	2× Allison 250-C20B
Engine Power (kW)	2× 313
Empty Weight (kg)	1276
Max Take-Off Weight (kg)	2400
Max Fuel (kg)	460

2.2 Engine performance model

Test case engines: The simple cycle kerosene-fueled engine is based on the 300kW micro gas turbine simple cycle of Allison 250-C20B, which is used as baseline and referred as “Kerosene-Simple” (KS) in Table 2. This engine consists of a gas generator and a two-stage free power turbine. The performance maps of the compressor, the gas generator turbine and the free power turbine are obtained from a GasTurb model that had been previously validated using available experimental data [14]. Under the assumption of maximum efficiency operation at any rotating speed, correlations can be extracted from the performance maps between the corrected mass flow, the efficiency and the pressure ratio for each component. Finally, cycle efficiency and SFC can be calculated for the power required to perform the mission, P_{req}, which is defined in the rotorcraft model.

Afterwards, a heat exchanger is incorporated in the baseline configuration for heat recovery. The recuperated cycle performance is assessed first for burning 100% jet fuel, “Kerosene-Recuperated” (KR) engine, then for 100% liquid hydrogen, “Hydrogen-Recuperated” (HR). Thus, three configurations are investigated and are presented in Table 2.

TABLE 2: TEST CASE ENGINES DEFINITION.

	KS	KR	HR
Fuel	Jet fuel	Jet fuel	Liquid Hydrogen
Cycle	Simple	Recuperated	Recuperated

Recuperators: The heat exchangers are modeled over a wide range of thermal effectiveness ($0.6 < \epsilon_{ds} < 0.9$) both in their performance and in their weight. As far as the first point is concerned, part-load operation of the heat exchanger is modeled as suggested in the GasTurb Manual. It provides a correlation to compute off-design effectiveness and pressure losses, given the mass flow [16], according to Eqs. 2-4, where the subscript ds refers to the design point conditions. In off-design conditions the heat transfer surface is considered to remain constant.

$$\epsilon = 1 - \frac{m}{m_{ds}}(1 - \epsilon_{ds}) \tag{2}$$

Cold side:

$$\frac{p_{in} - p_{out}}{p_{in}} = \left(\frac{p_{in} - p_{out}}{p_{in}}\right)_{ds} \frac{\left(\frac{m_{in}}{p_{in}}\right)^2 \frac{T_{out}^{1.55}}{T_{in}^{0.55}}}{\left(\frac{m_{in}}{p_{in}}\right)_{ds}^2 \frac{T_{out,ds}^{1.55}}{T_{in,ds}^{0.55}}} \tag{3}$$

Hot side:

$$\frac{p_{in} - p_{out}}{p_{in}} = \left(\frac{p_{in} - p_{out}}{p_{in}}\right)_{ds} \frac{m_{in}^2 T_{in}}{(m_{in}^2 T_{in})_{ds}} \tag{4}$$

The pressure losses term at the design point assumes constant, but still conservative values according to the geometry of the recuperator, between 3% and 5%. A tubular recuperator shows average pressure drops that are typically lower than a primary surface.

With regards to weight estimation, McDonald presented a work based on existing data in the open literature on recuperator specific weight [15]. The research portrays how sensitive specific weight for a gas-to-gas heat exchanger is to thermal effectiveness. Two surface geometries of metallic recuperators are considered for possible applicability to aeroengines: tubular and primary surface. Zhang started from McDonald's results and describes the correlation for tubular and primary surface heat exchangers according to Eqs. (5) (valid for $0.60 < \epsilon_{ds} < 0.75$) and (6) (valid for $0.80 < \epsilon_{ds} < 0.90$) in [9].

$$m_{HEX_{tub}} = \left(3.19\epsilon_{ds}^3 - 5.93\epsilon_{ds}^2 + 3.74\epsilon_{ds} - 0.79\right) \times 10^3 \tag{5}$$

$$m_{HEX_{ps}} = \left(2.82\epsilon_{ds}^3 - 6.77\epsilon_{ds}^2 + 5.44\epsilon_{ds} - 1.46\right) \times 10^4 \tag{6}$$

Where m_{HEX} is the recuperator weight for unit of mass flow rate, while ϵ_{ds} is the heat exchanger design effectiveness, see Fig. 3.

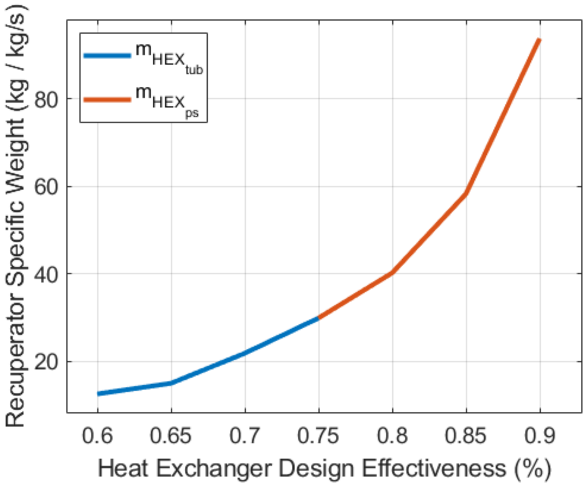

FIGURE 3: THE SPECIFIC WEIGHT OF RECUPERATOR FOR TUBULAR AND PRIMARY SURFACE GEOMETRIES.

2.3 Mission analysis model

The mission analysis model calculates the amount of fuel consumed over a defined mission duration. The mission considered here consists of cruising in horizontal flight at 500 m altitude at a speed of 180 km/h. This resembles the typical cruise condition of the reference helicopter. The duration of the mission itself is a variable parameter, which is limited between zero and three hours. The mass of fuel injected in the combustion chamber is obtained by multiplying the SFC, which is derived from the engine performance model, by the power required and the duration of the mission.

LH2 storage tank: the LH2 tank mass is calculated according to the amount of fuel required to perform the selected mission and a multilayer wall tank model based on a study by Sekaran [17]. This research study considers tank structure, geometry, materials and other physical phenomena, typical of liquid hydrogen storage, such as boil-off and permeation, for an aeronautical application. The mentioned multilayer wall consists of the four components presented in Fig. 4 and listed below:

- liner made of Al 5086 alloy for avoidance of the hydrogen permeation problem;
- polyethylene inner wall;
- polyurethane foam for effective thermal insulation and low weight;
- outer polyethylene outer wall.

Sekaran concludes that, for a fixed tank length of 2 m, the tank mass increases linearly with the mass of LH2 to be stored and proposes a set of correlation for a multitude of different insulation materials. Both Sekaran and Verstraete [18] agree that the use of polyurethane foam insulation leads to a higher gravimetric storage density and thus a lightweight tank. Consequently, the polyurethane insulation is selected in the present work. The linear correlation obtained by Sekaran for the polyurethane foam insulation allows to extract Eqn. (7) easily.

This equation is used for the mass estimation of the tank, being accepted the constraint on the length for this specific rotorcraft application.

$$m_t = 0.2498 \times m_{LH2} + 16.89 \tag{7}$$

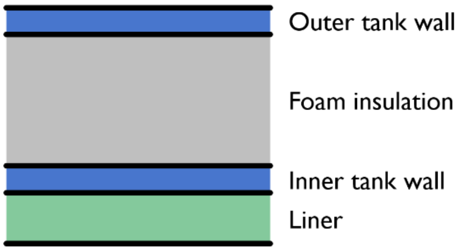

FIGURE 4: STRUCTURE OF THE LH2 TANK WALL.

3. RESULTS AND DISCUSSION

The presence of the recuperator allows KR and HR engines to recover heat from the turbine exhaust gases to increase the temperature of the air delivered by the compressor before entering the combustion chamber. Consequently, a lower fuel consumption is expected, which would reflect on a potential reduction of both SFC and emissions with respect to the baseline engine, KS. However, the incorporation of the recuperator increases the overall system weight, introducing a weight penalty that increases with the heat exchanger effectiveness. The existence of recuperator geometries other than the ones considered here is well known. In fact, additive manufacturing technologies has recently allowed to achieve attractive values of compactness, hence, significantly lighter recuperators for the same effectiveness. This could further support the case for implementation of regenerative micro gas turbine cycles for aeronautical applications. However, this new generation of recuperators has been excluded in the present study, due to the early stage of their innovative technology, which leads to high manufacturing costs and improvable reliability.

The HR engine is able to run on potentially carbon-neutral fuel, while it requires properly sized tanks for the storage of liquid hydrogen. This additional piece of equipment entails again a certain increase of the overall system weight, which is related to the amount of fuel needed for a given mission. Further specific components, such as pumps, would be required to replace the existing ones for a full conversion of the helicopter from jet fuel to liquid hydrogen, possibly increasing the weight penalty in these cases. However, for the sake of simplicity of this preliminary study, the hydrogen specific components are considered comparable to the jet fuel ones in terms of weight, so only the additional weight due to the hydrogen tank is considered.

The increased complexity of recuperated and hydrogen-compatible engines would enable reduced SFC and emissions, meanwhile, the combined weight of these configurations is unavoidably higher than the baseline engine. In a specific mission, the point at which the mass of saved fuel equals the mass of the additional equipment for recuperation and/or hydrogen is here defined as the “breakeven point”. The breakeven point is an essential indicator to assess whether the adoption of recuperator and hydrogen tanks is beneficial for the given mission. If the breakeven point was not met during this mission, then the lower SFC would not compensate the added weight due to the added complexity of the engine considered. ΔM is the parameter used to mathematically identify when the breakeven point is reached, i.e. for a null ΔM. Positive values of ΔM justify KR and HR engine configurations. ΔM is defined as the ratio of the difference between the saved amount of fuel and the additional equipment for recuperation and/or hydrogen and the MTOW, as shown in Eqn. (8). The choice of a dimensionless parameter, such as ΔM, is preferable with a view to future work that may deal with comparing different aircraft across various missions.

$$\Delta M = \frac{\left(m_{fuel_{KS}} - m_{fuel}\right) - \left(m_{HEX} + m_{tank_{H2}}\right)}{MTOW} \tag{8}$$

3.1 Cruise mission investigation

Helicopter missions typically include takeoff, climb, cruise, descent, hover and landing. With prime focus on the steady state behavior of the components, the recuperator is considered to operate only during cruise condition. As a consequence, the reference mission that is considered by the present study entails just the cruise phase, therefore horizontal flight condition at fixed speed and altitude: 180 km/h at 500 m, respectively.

Considering the KR engine, ΔM is negative at the beginning of the cruise, since no fuel has been saved yet at that point, so the recuperator represents just a weight penalty Fig. 5. As the cruise flight time increases, ΔM shows a linear trend up to reaching the breakeven point ($\Delta M = 0$), after which it keeps growing at the same rate. A positive ΔM denotes the chance to extend the mission range or increase the payload for the helicopter. For high-effectiveness primary surface recuperators, a longer flight time, which can exceed the 2 hours, is needed to save enough fuel to compensate their bulky weight and reach $\Delta M = 0$. The effectiveness of the recuperator is a critical parameter to reach the breakeven point. For instance, a primary surface heat exchanger for a design effectiveness of 75% maybe considered suitable for a mission that includes 1.5 hours of cruise, while unsuitable for another one with a shorter cruise flight time.

Considering the HR engine, the overall trend of ΔM resembles the KR case. In fact, in Fig. 5 show that dependence of ΔM from the cruise flight time remains linear. However, the time needed to reach $\Delta M = 0$ is shorter for all the heat exchanger effectiveness values taken into account, when compared to the KR case. Additionally, this reduction is achieved despite the additional weight penalty due to the hydrogen tank, which is specific for the hydrogen engine configuration.

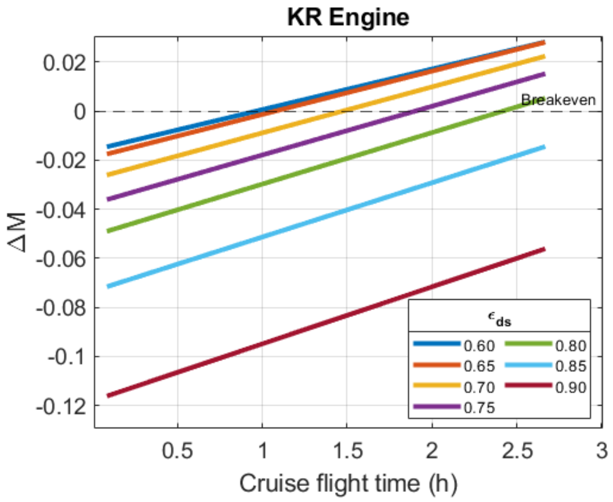

FIGURE 5: THE VARIATION OF ΔM VERSUS CRUISE FLIGHT TIME FOR THE KEROSENE RECUPERATED ENGINE.

4. CONCLUSION

The integration of recuperators leads to conflicting design requirements, namely parasitic weight of the recuperator against fuel saving. The need for quantifying the correlation between these two aspects has been addressed in the present study and extended to the case of a liquid hydrogen fueled powerplant. This means assessing the trade-off between the improved efficiency and the increased weight due to both recuperator and the necessary storage tank for LH2.

A simulation framework capable to reproduce a turboshaft engine steady state design and off design operation has been built to assess the performance of a reference helicopter flying in fixed cruise conditions. The baseline KS engine has been compared against KR and HR engines over the same mission to highlight the opportunities offered by both recuperation and the use of a high specific energy content fuel, such as hydrogen. The mission analysis shows that the selection of a certain recuperator effectiveness may be suitable in some cases depending on the cruise flight duration. For instance, a recuperated configuration with high-effectiveness primary surface recuperator requires longer cruise times to reach the breakeven point than a low-effectiveness tubular recuperator. Whilst this last consideration is valid both for KR and HR engines, Fig. 7 clearly shows a remarkable reduction of the cruise flight time to reach breakeven point for the HR engine case. In fact, the breakeven point is reached in nearly half of the cruise flight time for any selected effectiveness in the 60-90% range considered, namely less than one hour for lightweight, low effectiveness recuperators, as shown in Fig. 6.

The obtained results show sensitive reduction of the breakeven time and suggest that the adoption of a recuperated hydrogen cycle may make recuperation more attractive for aeronautical applications of micro gas turbines. Moreover, the reduction of the breakeven time to less than one hour of cruise flight may raise interest on low-effectiveness recuperated LH2-fueled micro gas turbines for potentially zero-emission short endurance flight, including light rotorcraft and Urban Air Mobility applications.

Suggested future work could focus on two main themes: powerplant configuration and type of mission. On the one hand, the investigation of hybrid thermoelectric configurations could further support the use of micro gas turbines in the transition to decarbonized flight. On the other hand, the extension of this type of tradeoff study to more specific flight missions (e.g., search and rescue, firefighting, etc.) may increase the interest on these innovative powerplant arrangements for real life operational scenarios, which feature complex flight profiles.

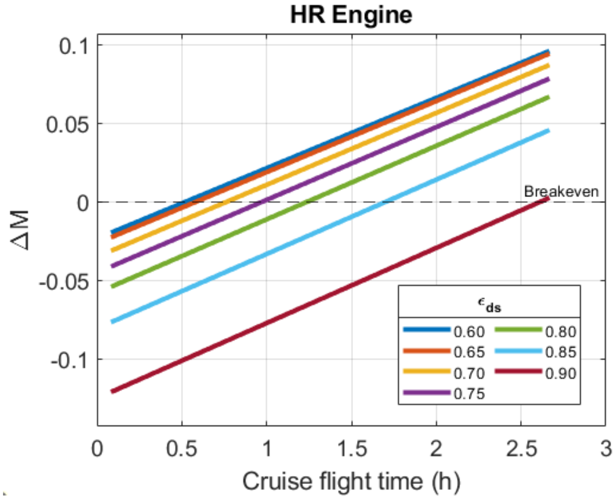

FIGURE 6: THE VARIATION OF ΔM VERSUS CRUISE FLIGHT TIME FOR HYDROGEN RECUPERATED ENGINE.

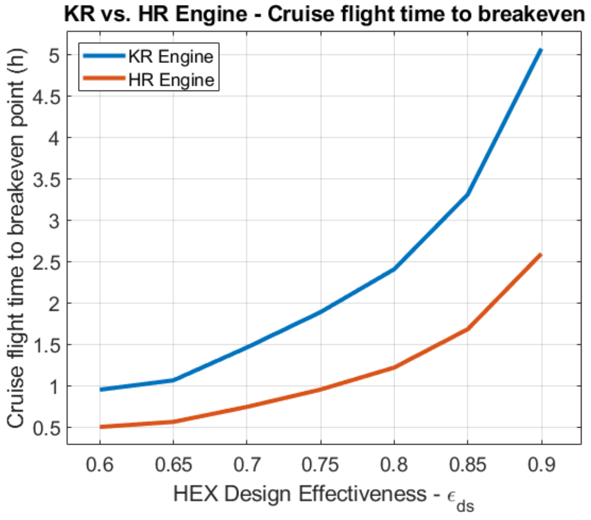

FIGURE 7: CRUISE FLIGHT TIME TO REACH BREAKEVEN POINT FOR DIFFERENT ENGINE CONFIGURATIONS.

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