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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
HEX	Heat Exchanger
LH2	Liquid hydrogen
m	Mass
MGT	Micro gas turbine
MTOW	Maximum Takeoff Weight
NTU	Number of Transfer Units
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, thanks to improvements in turbomachinery and material capabilities [1]–[5]. Nevertheless, aviation currently contributes 2% to 3% of the world's manmade emissions of carbon dioxide [6]. 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) [7].

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 [8]) 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 [9].

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 [10]. 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 [5]. The intermittent research of the following decades culminated in the design of 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 was tested without cracks or leakage. However, it never moved past the prototype phase [11].

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 powerplant, 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 breakeven point, at which the recuperator added weight is compensated by reduction in fuel burn was highlighted by Ali in [12] as an indicator in the quantification of this compromise. Alternatively, the economic viability of a regenerative helicopter seems to be 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). Tacconi as well invites to be careful about the balance involved to ensure that engine weight and parasitic drag do not offset improvements in SFC, when heat exchangers and/or intercoolers are added to the cycle [13].

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. 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 [14].

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 [15]. 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 [3], 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 [16].

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 [17], 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 built on the results and methods described by Zhang in [10], [14], [18], [19]. The latter represent the main inspiration and the starting point of the present work, which finally aims to highlight the opportunity offered by liquid hydrogen to offset parasitic weight of heat exchangers in recuperated micro gas turbines for aeronautical applications.

2. METHODOLOGY

Building on the work done by Zhang in [18], a numerical model capable of simulating turboshaft engine steady state design and off-design operations is reproduced. 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.

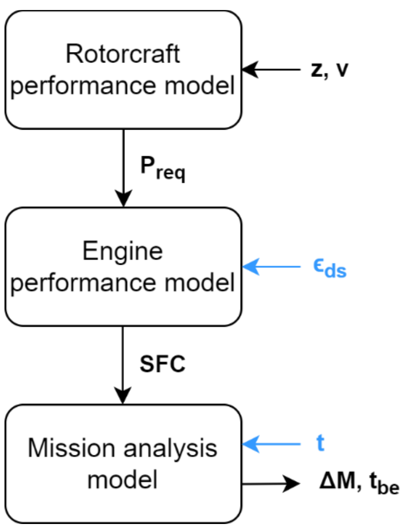

FIGURE 1: THE INTERACTIONS AMONG THE MODELS INCLUDED IN THE SIMULATION FRAMEWORK (INDEPENDENT VARIABLES IN BLUE).

2.1 Rotorcraft performance model

The rotorcraft performance model developed by Zhang [14] 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 Eq. (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.

$$P_{req} = P_{t,MR} + P_{t,TR} + P_p + P_{aux} \tag{1}$$

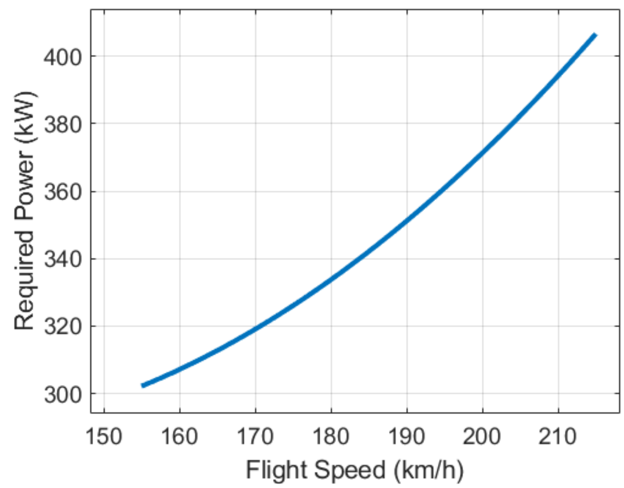

FIGURE 2: POWER REQUIRED FOR LEVEL FLIGHT AT 500 M ALTITUDE.

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 300 kW 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 [18].

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 (one for each engine) 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. This manual provides a correlation to compute off-design effectiveness and pressure losses, given the mass flow [20], 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:

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

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 counterflow 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 (Fig. 3) according to Eq. (5) (valid for $0.60 < \epsilon_{ds} < 0.75$) and Eq. (6) (valid for $0.80 < \epsilon_{ds} < 0.90$) in [14].

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

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

Where m_{HEX} is the recuperator weight for unit of mass flow rate, while ϵ_{ds} is the heat exchanger design effectiveness, which is an independent variable of the problem.

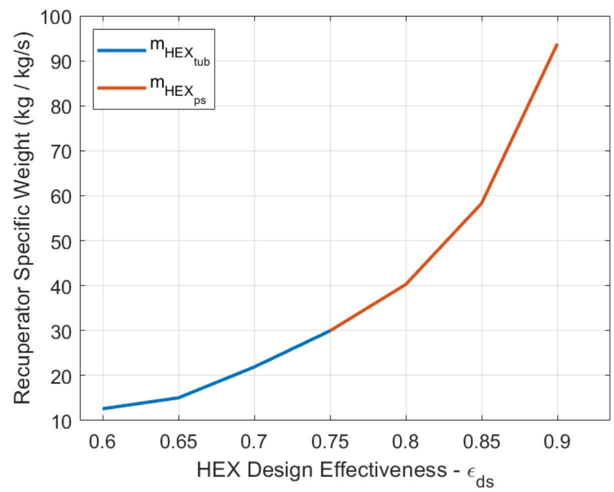

FIGURE 3: THE SPECIFIC WEIGHT OF RECUPERATOR FOR TUBULAR AND PRIMARY SURFACE GEOMETRIES.

The same correlation between heat exchanger mass and design effectiveness (Fig. 3) is considered for both the kerosene and the hydrogen case since the design should not go through disruptive geometric modifications, which would affect the recuperator mass. This is supported by the limited variation of the heat capacity ratio referred to the exhaust gases from the KR to the HR engine case. Consequently, the calculated variation of NTU between the kerosene and hydrogen cases is limited (3-8%) as well throughout the whole design effectiveness spectrum of the problem, as depicted in Fig. 4. As a result, the HEX geometry is only partially impacted, and its mass either.

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 a 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 typical ones considered here is well known. Nevertheless, 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.

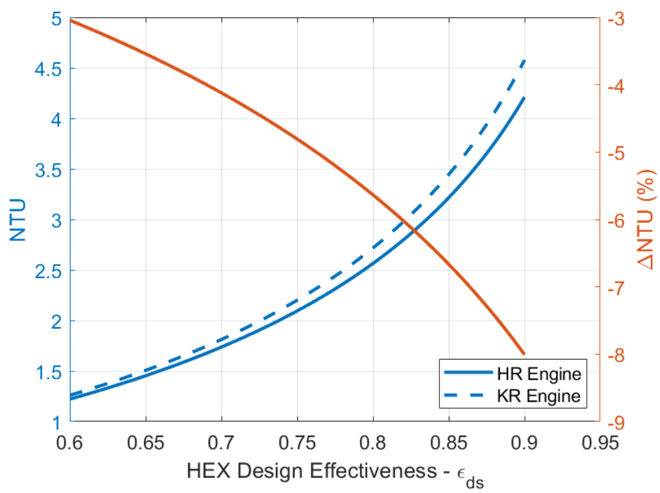

FIGURE 4: COMPARISON BETWEEN THE NTU VALUES FOR THE TWO RECUPERATED ENGINE CASES.

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 total mass of fuel injected in the combustion chamber during the cruise mission is obtained by multiplying the SFC, derived from the engine performance model, by the power required, derived from the aircraft performance model, and the duration of the mission, which is an independent variable of the problem, as described by Eq. (7).

$$m_{fuel} = SFC \times P_{req} \times t \tag{7}$$

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 [21]. 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. 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 [22] 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. (8) easily. This equation is used for the mass estimation of the tank, being accepted the constraint on the length for this specific rotorcraft application.

$$m_t = 0.2498 \times m_{LH2} + 16.89 \tag{8}$$

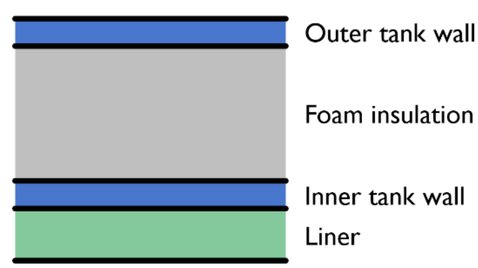

FIGURE 5: STRUCTURE OF THE LH2 TANK WALL.

3. RESULTS AND DISCUSSION

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. Specifically designed components related to the fuel system for hydrogen, including pumps and ducts, would be required to replace the existing ones for a full conversion of the helicopter from jet fuel, 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 KS, 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 storage 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, either KR or HR. ΔM is the parameter used to mathematically identify when the breakeven point is reached. 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. (9). The choice of a dimensionless parameter, is preferable with a view to future work that may deal with comparing different aircraft across various missions.

$$\Delta M = \frac{(m_{fuel_{KS}} - m_{fuel}) - (m_{HEX} + m_{tank\,H2})}{MTOW} \tag{9}$$

Breakeven is reached for a null ΔM. Positive values of ΔM justify KR and HR engine configurations. In the case presented in Fig. 6, the breakeven time is about one hour. In fact, the orange line, which is related to ΔM assumes positive values from that mission time onwards (green area). Again, in correspondence of the breakeven time the “Fuel Saved” and the “Recuperator+Tank” lines assume the same values, setting ΔM to zero.

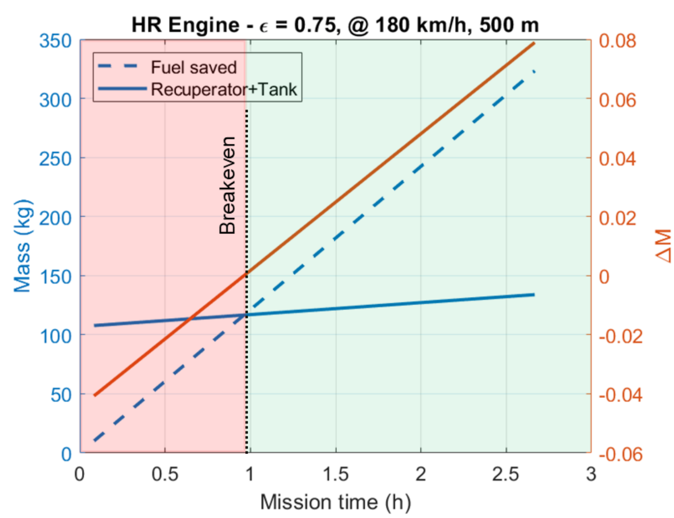

FIGURE 6: GRAPHICAL REPRESENTATION OF THE BREAKEVEN POINT FOR A SPECIFIC ENGINE CONFIGURATION.

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 involved 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.

Considering the KR engine, the results about the behavior of ΔM in the cruise mission confirm the ones already obtained and presented by Zhang in [14], without remarkable deviations. 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. 7). 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 two hours, is needed to save enough fuel to compensate their bulky weight and reach $\Delta M = 0$. The design effectiveness of the recuperator seems a critical parameter for the time needed 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 now the HR engine, the overall trend of ΔM resembles the KR case. In fact, Fig. 8 shows that the dependence of ΔM on 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.

Finally, adopting a more effective recuperator leads to longer breakeven times. Whilst this last consideration is valid for both KR and HR engines, Fig. 9 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 ($0.6 < \epsilon_{ds} < 0.75$).

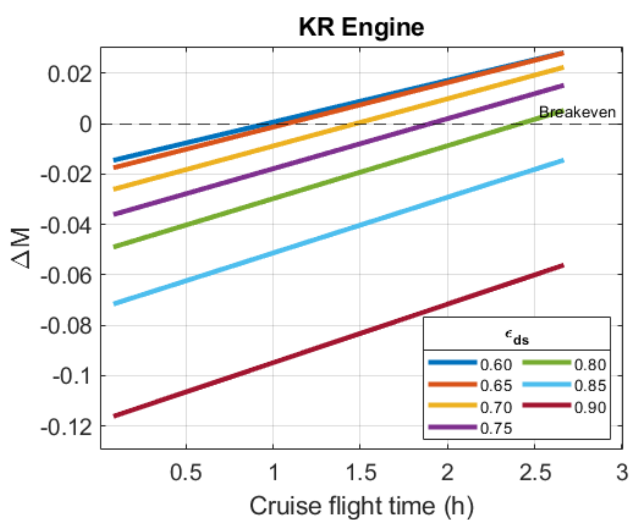

FIGURE 7: THE VARIATION OF ΔM VERSUS CRUISE FLIGHT TIME FOR THE KEROSENE RECUPERATED ENGINE.

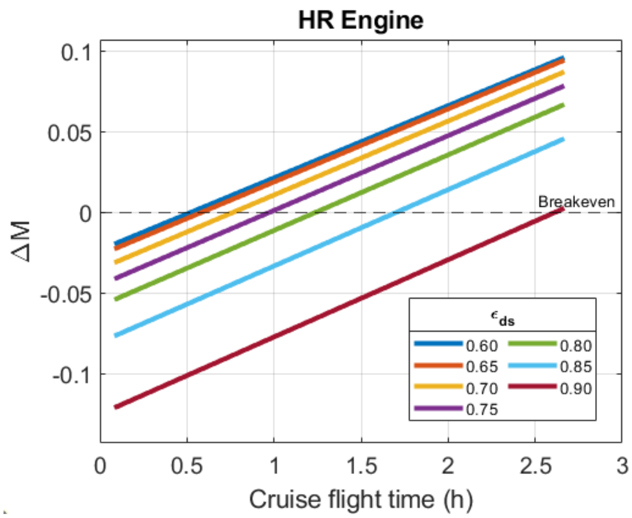

FIGURE 8: THE VARIATION OF ΔM VERSUS CRUISE FLIGHT TIME FOR HYDROGEN RECUPERATED ENGINE.

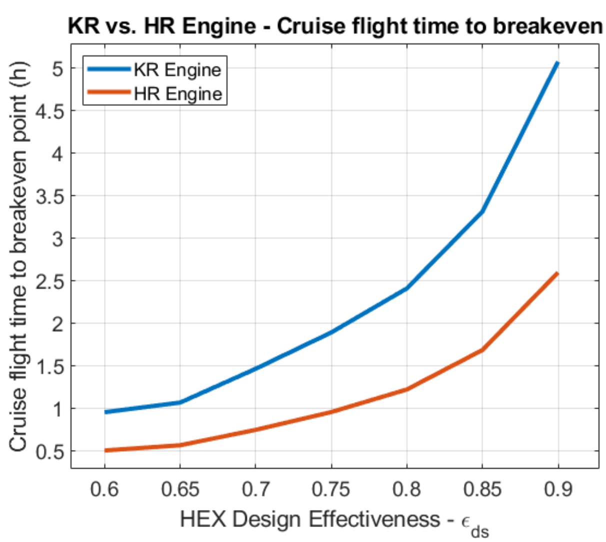

FIGURE 9: CRUISE FLIGHT TIME TO REACH BREAKEVEN POINT FOR DIFFERENT ENGINE CONFIGURATIONS.

4. CONCLUSION

The integration of recuperators in an MGT-based propulsion system 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 existing studies and is here 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 the heat exchanger(s) and the necessary storage tank for LH2.

Building on the existing work by Zhang, a numerical model capable of simulating turboshaft engine steady state design and off-design operations is reproduced and extended 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 liquid hydrogen.

The mission analysis shows that the selection of a certain recuperator design 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 a longer cruise time to reach the breakeven point than a low-effectiveness tubular recuperator. Consequently, adopting high-effectiveness recuperators for short-endurance missions seems to affect negatively the load capacity of the aircraft. The SFC might be reduced, but the amount of fuel saved during the mission would be lower than the weight of the recuperators installed. In the end, the payload and/or the fuel loading, thus the range, would be reduced, MTOW being equal.

The obtained results for the HR engine show sensitive reduction of the breakeven time and suggest that the adoption of a recuperated hydrogen cycle may represent a real opportunity by making recuperation more attractive for aeronautical applications of micro gas turbines. In fact, the potential reduction of the breakeven time to less than one hour of cruise time 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 three main themes: new technology and materials, powerplant configuration and type of mission. Firstly, additive manufacturing technologies have recently allowed to achieve attractive values of recuperator compactness, hence, less bulky HEX for the same design effectiveness. This could further support the case for implementation of regenerative micro gas turbine cycles for aeronautical applications. Secondly, the investigation of hybrid thermoelectric configurations could promote the use of micro gas turbines in the transition to decarbonized flight. And thirdly, 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.

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