A PRELIMINARY PARAMETRIC STUDY FOR AN ADVANCED PROPULSION TECHNOLOGY HELICOPTER

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Abstract

This paper aims to present a preliminary trade-off study through the deployment of an integrated helicopter multidisciplinary simulation framework. Analytical evaluations of existing and conceptual intercooled recuperated engine designs are carried out in terms of operational performance and environmental impact. The proposed methodology comprises a wide-range of individual modeling theories applicable to helicopter flight dynamics, gas turbine engine performance as well as a novel, physics-based, stirred reactor model for the rapid estimation of various helicopter emissions species. The overall methodology has been deployed to conduct a preliminary trade-off study for a conventional simple cycle and conceptual intercooled recuperated twin-engine-medium helicopter, modelled after the Aérospatiale SA330 helicopter configuration. Extensive comparisons are carried out and presented for the aforementioned helicopters at both engine and mission level, along with general flight performance charts including the payload-range diagram. The acquired results from the design trade-off study suggest that the conceptual intercooled recuperated helicopter can offer significant improvement in the payload-range capability, while simultaneously maintaining the required airworthiness requirements. Furthermore, it has been quantified through the implementation of a representative case study that, while the intercooled recuperated configuration can enhance the mission range and payload capabilities of the helicopter, it may have a detrimental effect on the mission emissions inventory, specifically for NO_x (Nitrogen Oxides). This may impose a trade-off between the fuel economy and environmental performance of the helicopter. The proposed methodology can effectively be regarded as an enabling technology for the comprehensive assessment of conventional and conceptual helicopter–powerplant systems, in terms of operational performance and environmental impact as well as towards the quantification of their associated trade-offs at mission level.

Nomenclature

Symbols

T_{out}	Heat exchanger outlet temperature, k
T_{Comp}	Compressor delivery air temperature, k
$T_{Exhaust}$	Exhaust gas temperature, k
$T_{Int\ Out}$	Intercooler outlet temperature, k
$T_{LPC\ out}$	Outlet temperature of low pressure compressor, k
T_{Inlet}	Inlet Temperature (288.15K)
V_{be}	Cruise speed for maximum endurance, m/sec
V_{br}	Cruise speed for maximum range, m/sec
ε	Effectiveness
ΔAUM	Delta all-up-mass, kg
ΔCO2	Delta carbon dioxide, kg
ΔFB	Delta mission fuel burn, kg
ΔNOx	Delta nitrogen oxides, kg
ΔWeight	Delta weight, kg
Φ	Equivalence Ratio

Acronyms

ACARE	Advisory Council for Aeronautics Research in Europe
AGL	Above Ground Level
AUM	All-Up-Mass
CAE	Chemical Equilibrium with Applications
FOCA	Federal Office of Civil Aviation
FPT	Free Power Turbine
HE	Heat Exchanger
HPC	High Pressure Compressor
HPT	High Pressure Turbine
INT	Intercooler
ICR	Intercooled Recuperated
LPC	Low Pressure Compressor
OW	Operational Weight, kg
OEW	Operational Empty Weight, kg
OPR	Overall Pressure Ratio
PSR	Perfectly Stirred Reactor
REC	Recuperator
SC	Simple Cycle
SFC	Specific Fuel Consumption, μg/J
TEM	Twin Engine Medium
TET	Turbine Entry Temperature
TW	Total Weight
TO	Take-off
UAVs	Unmanned Ariel Vehicles

1. INTRODUCTION

Early helicopters employed reciprocating engines that offered low Specific Fuel Consumption (SFC) and thereby were very economical. However, they were bulky and were difficult to maintain. The introduction of gas turbine power-plants revolutionized the rotorcraft performance capability, and played an important role in enhancing the payload-range capabilities of the helicopters[1]. They efficiently provided necessary power at significantly reduced weights compared to early piston engines.

The specific power and SFC of the gas turbine engines has significantly improved over the second half of the 20th century, driven mainly by the advances achieved in the areas of materials, aerodynamics, combustion, cooling and control systems[1]. These developments have enabled manufacturers to achieve higher Overall Pressure Ratios (OPR), higher Turbine Entry Temperatures (TETs), and advanced cooling techniques. The advancements in the aforementioned technology domains have enabled the engines to withstand higher temperatures, become more compact and lighter as well as achieve consistent improvements in engine SFC. It is however now generally accepted that any further development in the helicopter gas turbine technology, without the consideration to exploit innovative designs, may offer limited improvements in SFC. Therefore, the engine design philosophy to achieve drastic improvements in engine SFC can be redirected towards the introduction of intercooled and heat exchanged engines, or semi-closed cycle engine architectures. Furthermore, currently the prominent increase in the environmental concerns has prompted the aviation industry to enhance the operational life of powerplants and has strongly positioned the aviation industry to innovate and produce more sustainable and “low carbon” environmental friendly solutions.

In response to the demand and to extend and maintain effective rapid transition towards a sustainable and greener aviation industry (specifically in Europe) the ACARE (Advisory Council for Aviation Research and Innovation in Europe) has set some ambitious and complex targets for “Vision 2020”, under the Strategic Research and Innovation Agenda[2]. Vigorous research is being carried out to deliver important initiatives and a huge amount of capital is being invested to manufacture more sustainable and environmental friendly engines.

When targeting drastic improvements in engine fuel efficiency for helicopters, the most promising candidates are the advanced regenerative turboshaft, and the intercooled recuperative concept. According to Rosen[1], “the (Unmanned Aerial Vehicles) UAVs or helicopters that are intended for extremely long duration missions may require power plants that are much more efficient than Brayton cycle gas turbine engines”.

The InterCooled Recuperative (ICR) engines are recognized to be one of the most promising alternative options for powerplant configurations in terms of reductions in fuel burn and emissions. These advantages in the current era are imminent considering the high fuel prices[3] and the increasing government legislation around environmental degradation[4]. Moreover the availability of the technology can now enable the development of light weight and efficient heat exchangers[4] that can fulfill the purpose without penalizing the performance and operation of existing rotorcraft.

2. SIMULATION METHODOLOGY

This study requires the deployment of a multidisciplinary helicopter simulation framework. The modelling methodology deployed for the simulation of complete helicopter operations within this paper comprises a series of dedicated numerical formulations, each addressing a specific aspect of helicopter flight dynamics, engine performance and computation of mission emissions inventory. The proposed simulation methodology herein comprises the Lagrangian rotor blade modal analysis presented in[5&6], a flight path profile analysis based on the World Geodetic System dated in 1984 (WGS 84)[7], a non-linear trim procedure solving for the aeroelastic behaviour of the main rotor blades as described in[8&9], and an engine performance analysis model and gas turbine emissions model as detailed in[10&11]. Each of the aforementioned modelling methods is integrated together within a standalone framework under the name “HECTOR”, Cranfield university in-house helicopter simulation framework. HECTOR is capable of simulating complete, three-dimensional helicopter missions using a fully unsteady aeroelastic rotor model. HECTOR has been extensively described in[5], therefore only a brief description of the associated models is provided in this paper.

2.1. Turbomatch

TURBOMATCH is a Cranfield Univeristy code that has been developed over number of decades to perform engine design point (DP), off-design and transient performance simulaitons for predefined flight conditions[11]. The simulations are purely based on zero-dimensional modeling of various thermodynamic proccesses of discrete engine components. For the purpose of this study the engine is assumed to be operating at steady-state design and off-deisgn conditons.

2.2. Hephaestus

In order to predict the gaseous emissions arising from the fossil fuel combustion in the combustion chamber, the deployment of a robust prediction methodology is necessary. To satisfy this need, a generic emission indices calculation software has been adopted with the integration of Hephaestus, developed by Cranfield University. Hephaestus provides a general prediction methodology based on the stirred reactor concept along with a set of simplified chemical reactions. Hephaestus is capable of accounting for differences in the combustion system. Thus the user can specify a combustor geometry in terms of primary, intermediate and dilution zone volumes as well as the mass flow distribution of a given combustor design. Hephaestus has previously been adopted in several aircraft trajectory optimization studies for example in[11]. Since the scope of this study is to assess the advancement in the engine technology and its associated trade-offs, details on the emissions modelling methodology have not been included herein, however, the numerical formulation and methodology employed for the purpose of emissions prediction has been separately reported by the authors in the following references[12&13]. Thus, further elaboration shall be omitted.

2.3. Integrated HECTOR framework

The architectural schematic of the integrated tool adopted for this study is presented in Figure 1. Initially a mission is defined and each defined mission profile is broken down into discrete flight segments with pre-defined time steps which are based on user defined input values in terms of operational procedures and geographic latitude and longitude. The sum of Operational Empty Weight (OEW), the useful payload, and the onboard fuel is equal to the initial All Up Mass (AUM). The amount of fuel required for the mission is assumed at first, so an initial guess is made for the weight of the on-board fuel supply which is refined through an iterative process. For each flight segment the engine power requirement and the inlet conditions are calculated, while the new space-wise position of the rotorcraft is subsequently updated by HECTOR. The engine performance model TURBOMATCH then establishes the engines operating point to meet the required power demand and determines the engine fuel flow along with the corresponding combustor inlet temperature, pressure and mass flow. The data from TURBOMATCH is subsequently utilized by HEPHAESTUS which is then used as an input to generate the corresponding emissions inventory for carbon dioxide (CO_2) and Oxides of Nitrogen (NO_x) for a given flight segment. During this process, the aggregate fuel flow and the emission inventory is calculated implicitly from zero up to the current mission flight segment with respect to time. The calculated value of fuel burn is then subtracted from the initial AUM to account for the continuous weight reduction that takes place during the course of the mission. The overall process is repeated using a fixed-point approach until convergence is obtained for the total mission fuel burn.

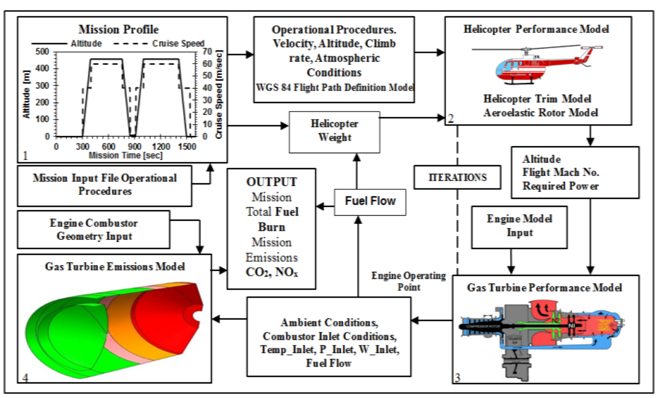


Figure 1: HECTOR, HElicopTer Omni-disciplinary Research-platform.

A detailed description of numerical integration of HECTOR with the engine performance model (TURBOMATCH) and emissions model (HEPHAESTUS) has been reported by the authors in reference [12].

2.4. Intercooled Recuperative Turboshaft (ICR)

For the purpose of this study a twin-engine-medium helicopter configuration is investigated. The corresponding baseline simple cycle engine is notionally modified by introducing an InterCooler (INT) and a Heat Exchanger (HE), demonstrating an ICR turboshaft engine. The modified sub-optimum ICR turboshaft engine incorporates; an intercooler placed between the Low Pressure Compressor (LPC) and High Pressure Compressor (HPC) and a HE, whose hot side is placed downstream of the Free Power Turbine (FPT) and cold side is placed upstream of the combustion chamber. This process of initially intercooling and then preheting upstream of the combustion chamber leads to lower fuel requirements and hence results in reduction of overall mission fuel burn comapred to the baseline simple cycle engine. However, the incorporation of these additional components has some side effects, such as additionl pressure losses and also the added weights of the INT and HE. Furthermore, the increase in the temperature at the inlet of the combustion chamber also elevates the level of thermal NO_x formed within the combustor and hence, influences the overall NO_x production. The schematic of the notionally modified sub-optimum ICR engine is presented in Figure 2. The schematic presented in Figure 2 is simply the reflection of how the engine is modeled in TURBOMATCH (gas turbine performance model) and is purely drawn for demonstration purposes. The schematic may vary depending on the choice and the installation arrangement of the heat exchanger. The effectiveness of the INT and HE can be defined as given in equations 1 and 2.

$$HE\ Effectiveness = \frac{T_{out} - T_{Comp}}{T_{Exhaust} - T_{Comp}} \quad \textbf{(Equation 1)}$$

Where:

HE = Heat Exchanger

T_{out} = HE outlet temperature

T_{Comp} = Compressor delivery air temperature

$T_{Exhaust}$ = Exhaust gas temperature

$$INT\ Effectiveness = \frac{T_{Int\,Out} - T_{LPC\,out}}{T_{Inlet} - T_{LPC\,out}} \quad \textbf{(Equation 2)}$$

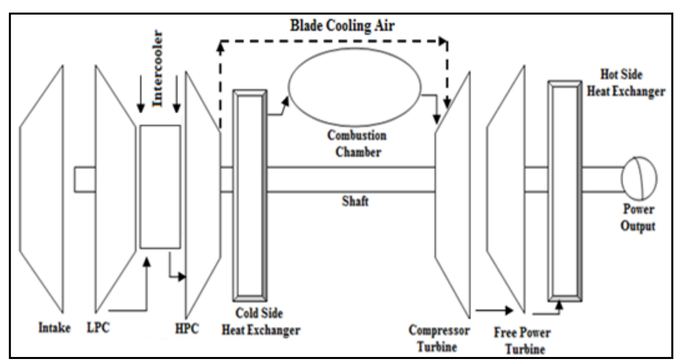


Figure 2: Schematic layout of a single-spool Intercooled Recuperated Turboshaft.

Where:

INT = Intercooler

$T_{Int\ Out}$ = Intercooler Outlet Temperature

$T_{LPC\ out}$ = Outlet temperature of low pressure compressor
T_{Inlet} = Inlet Temperature (288.15K)

2.5. Reference Helicopter Configuration and Engine Model

A twin-engine-medium helicopter based on the configuration of Aérospatiale SA330 Puma was implimented in HECTOR. Table 1 presents the design parameters of the helicopter. The specific rotorcraft is equipped with two Turbomeca TURMO IV-C turboshaft engines. Thus, the corresponding, baseline Turmo IV-C (Engine A1) and the "Intercooled Recuperated" Turmo IV-C (Engine B1) were implemented in TURBOMATCH. The engine design parameters for the Engine A1 and Engine B1 are presented in Table 2.

Table 1: Aérospatiale SA330 Super Puma Design Parameters

Design Parameters	Units
Engines	2 xTurbomeca Turmo IV-C
Engine Power	2 x 1163 kW
Operational Empty Weight	3536 kg
All-Up-Mass	6000 kg
Service Ceiling	4800 m
Number of blades	4

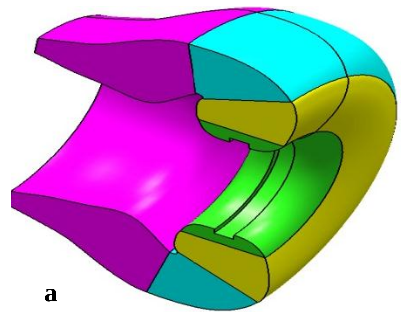
Table 2: Design point, engine parameters for Baseline Engine A1 and notionally modified sub-optimum ICR Engine B1turboshaft

Engine Design Parameters	Reference Engine A1	ICR Engine B1
Pressure Ratio	5.9:1	6:1
Mass Flow (kg)	5.9	5.9
TET (K)	1330	1330
TO Power (kW)	1163	1389.1
SFC @ TO (μg/J)	106.8	76.30
Dry Weight (kg)	225	225
Recuperator Weight (kg)	-	39.65
Intercooler Weight (kg)	-	12.85
Recuperator ε^* %	-	40
Intercooler ε^* %	-	40
Total weight (kg)	-	277.5

$^*\varepsilon$= Effectiveness

2.6. Reference Combustor Model

As an input requirement to the emission model, HEPHAESTUS, the combustor geometry of Reference Engine A1 was investigated in detail. A "reverse engineering" approach was adopted by means of publicly available data. A 3D combustion chamber was modelled using CATIA Part Modelling to derive the best possible approximations for the inlet area, outlet area, volume and length of the various 'zones' (i.e. flame front primary, intermediate and dilution) within the combustor. Due to the limited availability of the engine technical drawings of the Reference Turbo IV-C engine in the public domain, a generic combustor representative of a similar engine family class was assumed to represent the combustor geometry for both, Engine A1 and Engine B1configurations. A Java based "plotdigitiser" program[14] was used to obtain the coordinates of the combustor module by using a two dimensional engine cutaway drawing available in the public domain of the assumed representative engine. The obtained coordinates were exported to CATIA *Part Modelling* to design and represent a reference Turmo IV-C combustor module (isometric view shown in Figure 3a). The specific combustor was then used to approximate the different zones (lengths and volumes).



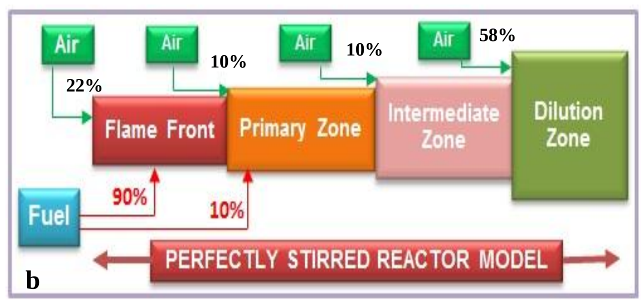


Figure 3: (a) Generic TURMO IV-C Combustor Model isometric view; (b) Combustor Zones and Reactor Models assumed for NO_x modeling of rotorcraft.

Figure 3a shows the profile of the baseline combustor model. The combustion chamber is divided into four distinctive zones, the flame front, primary zone, intermediate zone and the dilution zone, all have been simulated using a series of Perfectly Stirred Reactor (PSR) models (as shown in Figure 3b). It is assumed that the flame front is well mixed and can be approximated to a PSR for this particular application. The PSR model includes 18 species for equilibrium calculations using the NASA CEA program[15].The NO_x mass fraction variation is calculated using the extended Zeldovich mechanism and the prompt NO_x methodology is modelled as reported in[16-18]. With regards to the fuel split, it is assumed that the fuel is burned in the flame front zone at a fixed equivalent ratio Φ=0.9 and that the remaining fuel is burned in the primary zone. The percentage distribution of air mass flow within each zone were defined based on best engineering judgments and were kept constant throughout the power range of the engine. Another important assumption to note is that the combustion chamber of the ICR Engine B1 is modeled as such to enable same equivalence ratio as the baseline engine (Φ=0.9) at the flame front. The volume of each reactor is estimated based on the combustor geometry information obtained from the CATIA model and has been kept constant throughout the power range of the engine. These assumptions are made in order to ensure that a fair comparison of the emissions, specifically NO_x is carried out at a preliminary level. A detailed description of the emission model adopted within this study has been separately reported by the authors in the following references[12&13], therefore further elaboration shall be omitted.

2.7. Heat exchanger weight estimation

The HE weight correlation for this study is adopted from the previously reported study by Nicolas Kalios in[19] and is presented in Figure 4a. The HE correlation for the purpose of this study is for the fixed surface tubular type HE concepts. The helicopter configuration investigated in this study represents a twin-engine-medium configuration, therefore the gross HE weight was considered for two engines.

2.8. Intercooler weight estimation

The intercooler unlike the recuperator is not exposed to high temperatures and they have to withstand relatively lower temperatures ranging from 200°-350°C[4]. The correlation for the intercooler has been developed by scaling down the representative correlation of HE adopted from[19] and is represented in Figure 4b. Details of the methodology employed for the purpose of intercooler weight estimation have been extensively reported by the authors in reference [20].

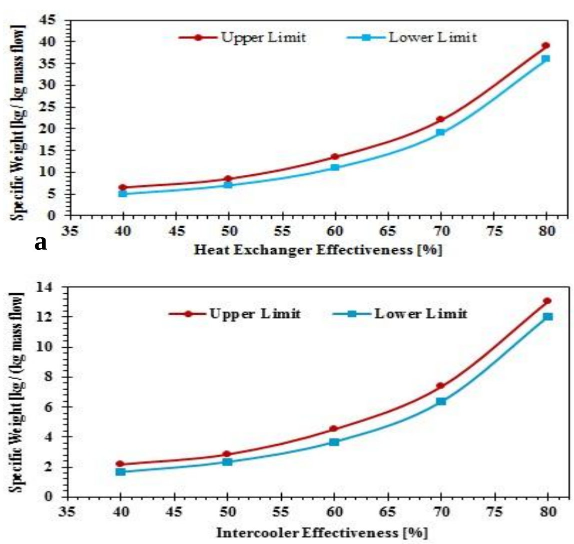


Figure 4: (a) Fixed geometry tubular type heat exchanger specific weight correlation adopted from[14]; (b) Intercooler specific weight correlation.

3. RESULTS AND DISCUSSIONS

3.1. Reference and conceptual sub-optimum ICR engine part-power performance

The variation in SFC at design point at part-load (P/P_{Design}) for the baseline engine A1 and the ICR Engine B1 is presented in Figure 5. The effectiveness of the intercooler and HE was varied between 40% and 80%, and a significant improvement in SFC is apparent for Engine B1 relative to Engine A1. For the assumed intercooler and HE effectiveness ranged between 40% and 80% the SFC improvement at medium part power lies between approximately 25% at 40% effectiveness and increases up to 55% at 80% effectiveness. The overall pressure ratio for both engines at design point is 5.9:1 but the LPC and HPC pressure ratios were varied for the intercooler to be feasible based on their effectiveness. The TET was 1330K and the mass flow was 5.9 kg for both Engines A1 and B1.

The compressor delivery temperature of the Engine B1 is lower than the baseline Engine A1 due to the addition of intercooler between the LPC and HPC. The intercooler acts as an independent identity and as such the recuperator does not have any bearing on it. The recuperator preheats the air upstream of the combustion chamber and mixes with the compressor delivery air so as to increase the combustion chamber inlet temperature of the ICR Engine B1. The decrease in intercooler outlet temperature is a function of the intercooler effectiveness and tends to decrease with increase in effectiveness. Also the amount of increase in combustion chamber inlet temperature is a function of the recuperator effectiveness which tends to increase linearly with increase in effectiveness. This process serves as the fundamental benefit offered by the intercooled/recuperative engine, resulting in lower fuel requirements.

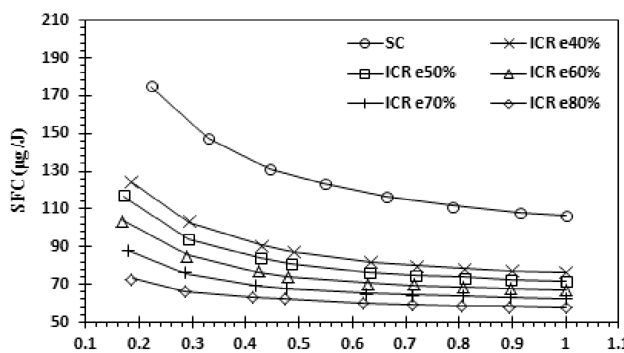


Figure 5: SFC vs (P/P.Design) for Baseline Engine A1 and ICR Engine B1.

3.2. Reference helicopter flight dynamic and trim analysis validation

With regards to the helicopter flight dynamics and trim analysis in terms of main rotor power requirements, an extensive comparison is presented in section 3.2 between both the reference and conceptual regenerated configuration. However, the flight dynamics and trim analysis in terms of main rotor power required, collective pitch, lateral cyclic pitch and longitudinal cyclic pitch for reference SA330 PUMA helicopter along with its validation with the flight test data has been separately reported by the authors in[21].

3.3. Comparison of integrated helicopter-engine flight performance

Several design requirements must be first met to replace the existing baseline simple cycle helicopter engine with the ICR engine. Firstly, the gross weight of the baseline engine must be maintained and finally the size, volume and fuselage aerodynamic profile of the existing helicopter must also be maintained. In this study it is assumed that the installation of intercooler and HE will have a minimal effect on the helicopter size, volume and fuselage aerodynamic profile and therefore their aerodynamic performance effects are not included within the scope of this study.

Figure 6a presents helicopter flight dynamics and trims analysis results in terms of main rotor power requirements for the reference and conceptual ICR helicopters. Results presented are based on the straight and level flight and are simulated for a range of INT and HE effectivenesses. It is noted that the added weight of the on-board INT and HE results in increasing the helicopter AUM. Coupled with this are the increased pressure losses introduced by the INT and HE. Both aforementioned penalties associated with the on-board INT and HE, essentially add a roughly constant amount of power e.g. an additional power that is predominantly influenced by the on-board HE effectiveness and is independent of the flight speed. The most prominent effect of these penalties is in the low to medium speed segments of flight. Fig. 6b presents these effects when simulated for different flight altitudes. To avoid repetition the flight altitude effect results are only included for regenerated helicopter with 60% on-board HE effectiveness.

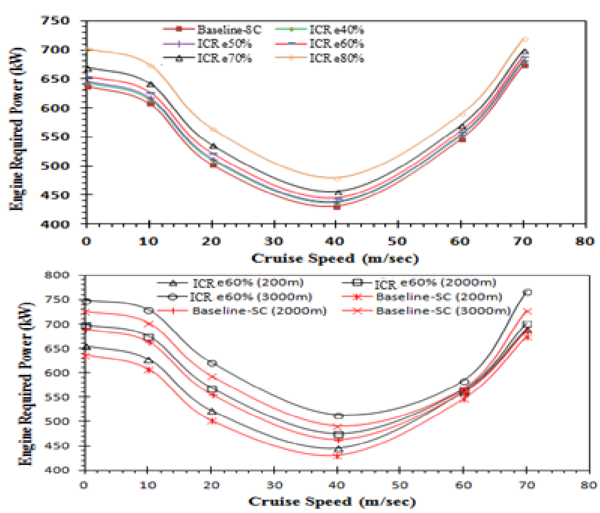


Figure 6: Reference SA330 PUMA and conceptual ICR helicopter, power vs cruise speed sea leval and various altitudes

Figure 7 presents the variation in specific air range for both the baseline and the ICR rotorcrafts and their corresponding engine fuel flow as a function of cruise speed. The results presented in Figure 6b suggest a considerable improvement in the specific air range of the rotorcraft which is mainly attributed to the noted improvement in the fuel flow requirements associated with the ICR rotorcraft.

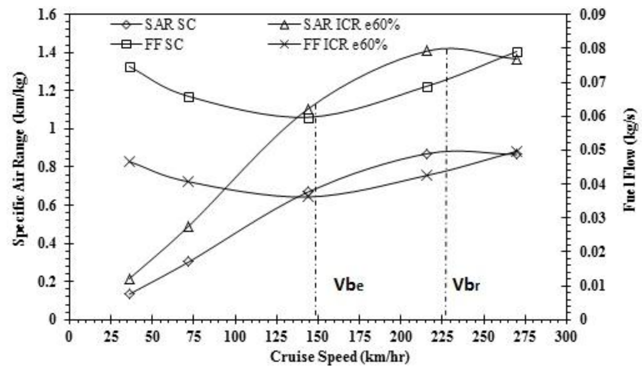


Figure 7: Specific Air Range for Baseline Engine A1 and ICR Engine B1 helicopter with 60% HE effectiveness.

3.4. NO_x Formation

Gaseous emissions from helicopter engines are not easily assessed, as there is very limited data available on the estimation of helicopter emissions. According to Federal Office of Civil Aviation[22] (FOCA), the EI NO_x emission for helicopter engines can be approximated within a relative error of 10-15% by the equation 1.

$$EI\ NO_x \left(\frac{grams\ of\ NO_x}{kg\ of\ fuel}\right) \approx 0.2133 * (SHP)^{0.5677} \quad \textbf{(Equation 3)}$$

Where,
SHP = shaft horse power is the power delivered by the free-power turbine.

For the computation of gaseous emissions, the focus of this study is limited to examine the change of emission species associated with the incorporation of intercooling and recuperation within the turboshaft engine. This mainly deals with the reduction of CO_2 and a tentative increase in NO_x emissions, the rest of the emission species are not included within the scope of this study.

The fundamental “fuel efficient characteristic” of ICR Engine B1 hugely favors reduction in CO_2 emissions. However, demands conditions within the combustion chamber that inevitably support elevated levels of thermal NO_x. The increase in thermal NO_x concentration is predominantly influenced by the increase in the equilibrium temperatures at early stage(s) of the combustion process. The incorporation of intercooling and regeneration clearly influences the combustion entry temperature shown in Fig. 8b. A linear drop in the SFC is supported by the increase in inlet temperature, leading to lower fuel flow requirements for given shaft power, hence improving engine thermal efficiency and therefore SFC. However, this advantage is attained by rising equilibrium temperature within the flame front which results in producing elevated levels of thermal NO_x. Figure 8a demonstrates the predicted variation of NO_x emission index with equivalence ratio. The concentration of NO_x reaches the highest level near the stoichiometric mixture. The total NO_x formed in the combustor is the summation of the concentration arising from each reactor. As such, the NO_x formation rate is largely dependent on the corresponding conditions within each reactor. Increasing equivalence ratio essentially raises gas temperature, which inevitably increases the concentration of thermal NO_x and therefore increases the total production of NO_x.

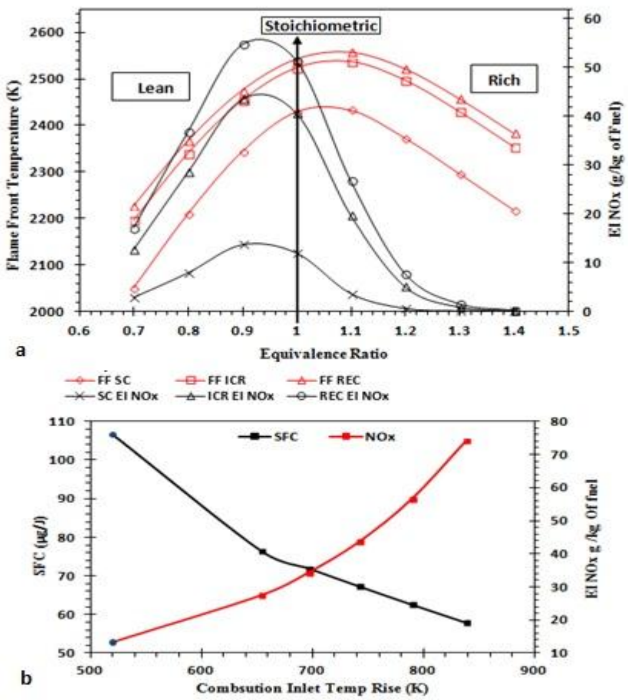


Figure 8: (a) EI NO*x* and combustor equilibrium temperature Vs Equivalence Ratio, Engine A1 and ICR Engine B1; (b) SFC & EI NO*x* vs inlet temperature Engine A1 and ICR Engine B1, at design point, points denoted by circles imply Engine A1.

With regards to the ICR Engine B1, a significant increase in the equilibrium temperature is supported through the rise in combustor inlet temperature; as a result the concentration of NO_x (thermal NO_x) increases drastically, as illustrated in Figure 7a. It is interesting to note that the incorporation of regeneration alone results in higher flame temperature and NO_x production. This is mainly attributed to the fact that, in the ICR engine the intercooling causes a drop in compressor delivery temperature and therefore has a lower combustion entry temperature (T3) compared to the regeneration engine.

3.5. Compilation of representative mission scenarios

The performance evaluation of the conceptual ICR helicopter against the baseline simple cycle helicopter is carried out by constructing representative mission scenarios. Various generic reference missions were designed, representing mission range of 10 nautical miles up to 280 nautical miles. Each mission scenario and flight segment throughout the mission profile was defined as to reflect the realistic capability of the helicopter configuration investigated. The power requirements and mission time and range were kept constant between the reference and conceptual regenerated helicopter configurations. To maintain simplicity and consistency each reference mission was simply designed to fly a straight line trajectory and comprised the following flight segments; 1). Idle Before Take-off, 2.) Hover, 3).Climb, 4.) Cruise, 5.) Descent, 6.) Idle After Land. To avoid repetition, only two example mission profiles are presented in Figure 9(a) and (b).

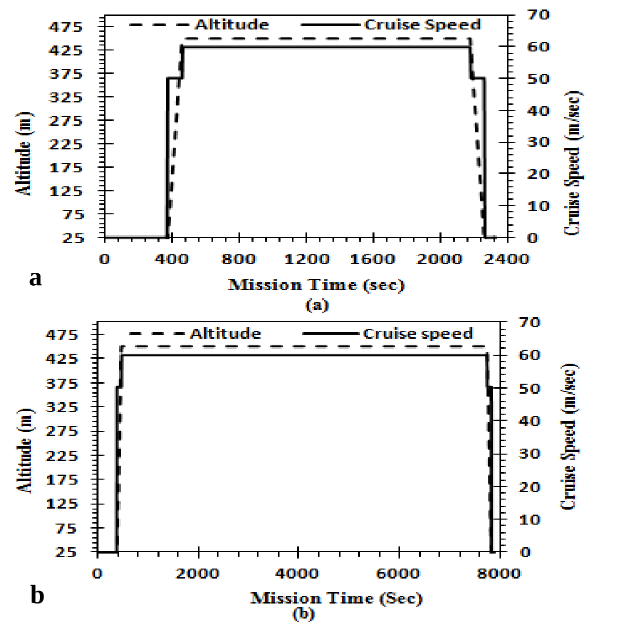


Figure 9: (a) Time variations of deployed operational airspeed and AGL altitude for mission range of 60 nautical mile; (b) Time variations of deployed operational airspeed and AGL altitude for mission range of 240 nautical miles.

3.6. Break-even point

The point at which the HE "added weight" is exactly compensated by reduction in mission fuel burn, represents a break-even point. In other words, in order for a sub-optimum regenerated helicopter to be economically viable, the fuel carrying capacity of the regenerative helicopter must be reduced by an amount equal to the weight added by the installed heat exchanger(s). Once the break-even point is satisfied for a given on-board heat exchanger, any additional fuel reduction can be regarded as reduction in All-UP-Mass (AUM) represented as DELTA AUM (ΔAUM).

3.7. All up mass

For the purpose of this study a positive ΔAUM demonstrates reduction in AUM of the ICR rotorcraft in comparison to the baseline rotorcraft, while a negative ΔAUM denotes an increase in the AUM which can also be termed as "weight penalty". The misison that justifies the need for ICR demostrates a positive ΔAUM while the one with a negative ΔAUM would not justify the need of ICR engine. A positive ΔAUM can either be used as mission fuel saving, enabling the rotorcraft to increase its mission range, or it can be used to increase the payload capability of the rotorcraft.

3.8. Mission analysis results

A substantial amount of reduction in fuel burn is seen for all the simulated missions. The reduction in mission fuel burn depends greatly on the INT and HE effectiveness. The average misison fuel burn reduction achieved at 40% effectiveness is 26.5% which goes up to 50% at 80% effectiveness, as presented in Table 3.

Table 3: ICR engine reduction in fuel burn relative to baseline

ICR effectiveness %	Average Reduction in Fuel burn (%)
40	26.5
50	32.4
60	37.9
70	43.6
80	50.6

Figure 10a presents varaition in mission fuel burn as a fucntion of mission range with respect to both rotorcraft configurations.

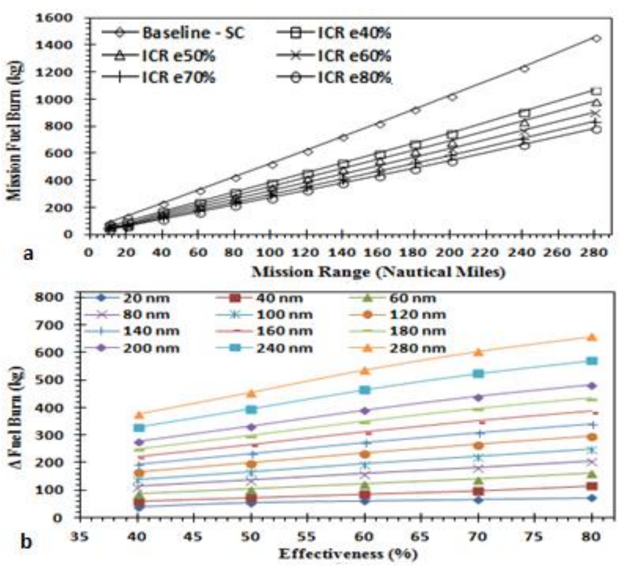


Figure 10: (a). Mission fuel burn Vs mission range for simple cycle and ICR helicopter; (b) Delta Fuel burn Vs HE Effectiveness for TEM ICR for simulated missions.

Figure 10b presents the ΔFuel Burn against the heat exchanger effectiveness for all simulated missions corresponding to conceptual ICR helicopter. It is evident that the reduction in fuel burn follows a linear trend and shifts upwards, indicating a proportional increase as the mission range increases. However, to derive actual earnings resulting from employment of the onboard intercooler and recuperator in terms of fuel bun, the corresponding added gross weight of the combined onboard INT and REC must be subtracted from the derived ΔFuel Burn for a given mission. Once the INT and HE added weight is accounted for, the remaining delta (positive or negative) can then be regarded as either an increase or decrease in the All-Up-Mass of the helicopter.

Due to the fact that the INT and REC weight increases exponentially as a function of INT and REC effectiveness, for all simulated values of INT and REC effectivenesses there is a representative break-even range, where the amount of fuel reduction compensates exactly for the respective weight added by the on-board INT and REC. This can be noticed from Figure 11a, each INT and REC effectiveness trend initiates with a weight penalty (negative ΔAUM) and essentially meets the break-even line. From Figure 11b. It is interesting to note that the 40% and 50% ICR effectiveness require almost the same range to meet the break-even, this is due to the fact that the increase in added weight is relatively low. However, the reduction in SFC is high, which results in higher overall fuel burn reduction at 50% effectiveness.

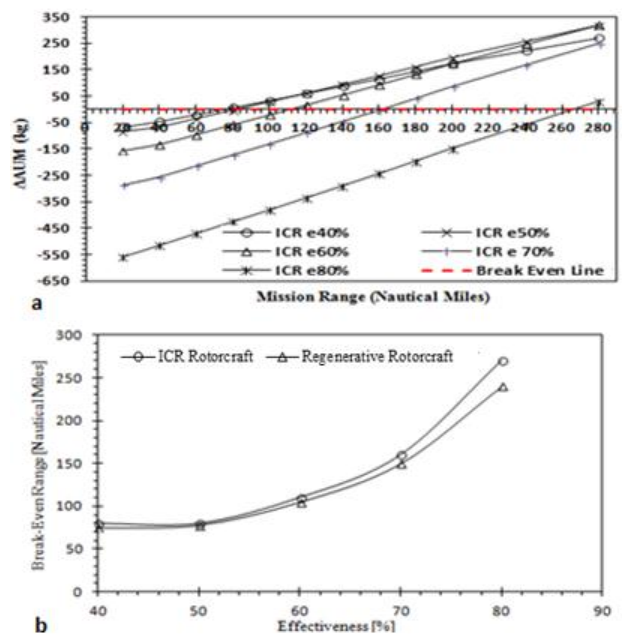


Figure 11: (a). Delta All-Up-Mass Vs Mission Range for TEL regenerated helicopter. (b). Break-even Range for TEM ICR and Recuperated helicopter

The break-even range data for the regenerative helicopter configuration has been adopted from [13] and is compared with the acquired data for ICR helicopter in Figure11 (b). It is evident that the break-even range for the regenerative rotorcraft is lower than the ICR. This is mainly attributed to the fact that the regeneration alone results in higher fuel savings and has lower weight penalty compared with the ICR helicopter.

With regards to the CO_2 emissions a favourable reduction can be seen from Figure 12a. Since the CO_2 is interdependent on ΔFB, therefore, a proportional positive reduction in ΔCO_2 is evident similar to that of ΔFB. A significant increase in mission NO_x is evident from Figure 12b , due to the reasons highlited in section 3.3.

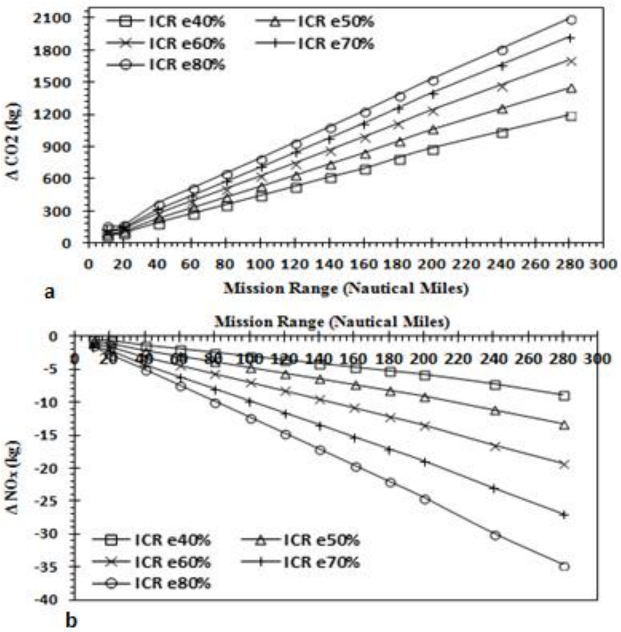


Figure 12: (a) Delta CO2 Vs Mission Range for TEM ICR helicopter; (b) Delta NO*x* Vs Mission Range for TEM ICR helicopter.

3.9. Derivation of payload-range diagram

In order to construct the required payload-range diagrams with regards to the helicopters deployed for the purpose of this study, the relationship between specific range and Operational Weight (OW) needs to be established. Thus, HECTOR was employed in order to obtain the corresponding fuel flow curves for different values of OW. A number of nonlinear trim performance simulations was carried out starting with zero payload (OW=OEW), and subsequently increasing the rotorcraft's OW gradually up to the Maximum Take-Off Weight (MTOW). The operational empty weight simply dictates zero useful payload, while maximum payload essentially corresponds to AUM=MTOW.

Figure 13 presents the presents the characteristics of the acquired payload-range diagram for reference and conceptual helicopters. A considerable amount of improvement in maximum attainable range is obtained for the conceptual ICR helicopter with respect to reference configuration. Under the simulated conditions the regenerative helicopter demonstrated the potential to improve the maximum attainable range by 60%, when cruising at Vb_r. However, these improvements in the range are achieved at a cost to the maximum payload capability of the helicopter. A reduction of around 20% in maximum payload capability is realized, the corresponding weight penalty is attributed to the added weight of the on-board INT and REC.

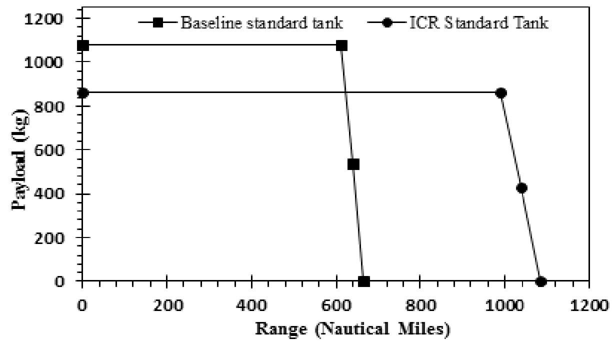


Figure 13: Payload-range diagram for Reference SA330 and regenerated helicopter

3.10. Case Study

A case study for a typical Oil and Gas mission is carried out in order to assess the potential of the ICR helicopter. The geographical location in terms of global coordinates along with the set operational procedures and mission profiles are given in Figure 14a and 14b. The 111.6 nautical mile (nm) Oil and gas mission proves to be favourable for the employment of intercooler and recuperator.

A positive ΔAUM is achieved for 40, 50 and 60% effectiveness, while the ΔAUM for effectiveness of 70% and 80% is negative. From Figure 16a it can be seen that, the total weight (TW) dotted red line for the ICR rotorcraft lies below the line of the baseline rotorcraft (TW) which is denoted by the solid red line upto 60% effectiveness. The region between both the lines (red solid and red dotted) denotes the reduction in AUM, which starts to diminish above 50% effectiveness. The optimum effectiveness for this particular mission is 50% in terms of fuels savings with a weight saving of 68kg as shown in Figure 16b. Due to the added weight of the INT and HE above the effectiveness of 60%, the weight gain diminshes resulting in weight penaty.

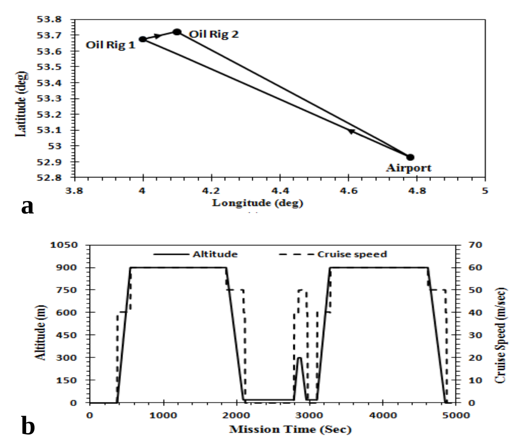


Figure 14: Oil and Gas mission: (a) geographical global coordinates; (b) time variations of operational airspeed and AGL altitude.

In terms of eissions inventories, a significant reduction in CO_2 is realized (Approx. 34%), supported by improved thermal efficiency of the ICR engine, shown in Figure15a.

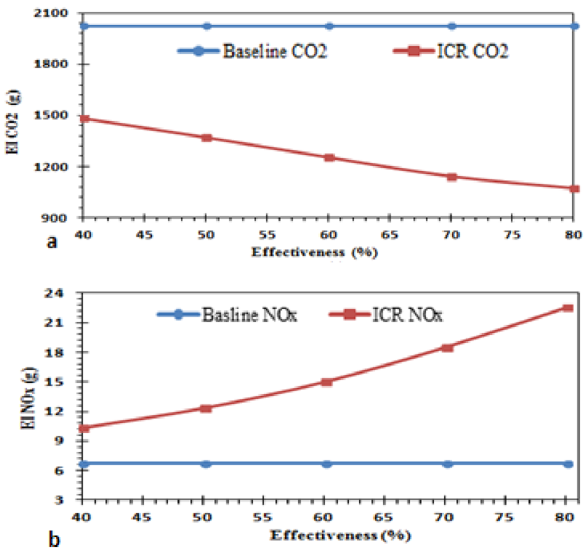


Figure 15: (a) Emitted CO2, (b) Emitted NO*x* for TEM, Baseline Simple Cycle and ICR rotorcraft, SAR Mission

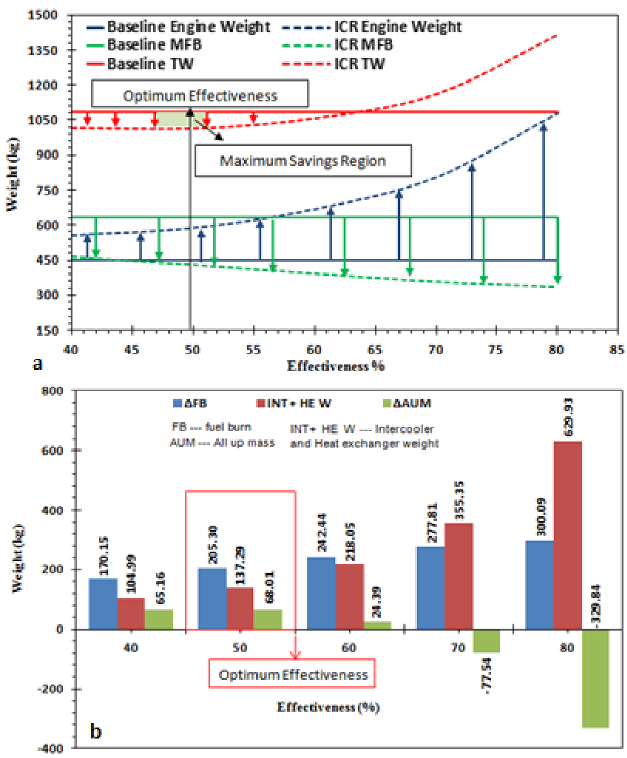


Figure 16: (a) ICR tradeoff study, Oil and gas mission; (b) ΔAUM for conceptual ICR rotorcraft.

The ΔCO_2 is a function of amount of fuel reduced by the ICR engine. Although there is a significant reduction in CO_2, there is around 84% increase in misson NO_x inventory, presented in Figure 15b.

4. Conclusions

A well-known and effective approach of intercooling and recuperation is deployed to enhance the integrated performance of an existing simple cycle turboshaft helicopter. The methodology is based on incorporating an intercooler between the low pressure compressor and the high pressure compressor and a recuperator, which enables the heat transfer between the exhaust gas and the compressor delivery air to the combustor chamber. The deployed methodology is implemented by adopting an integrated helicopter multidisciplinary simulation framework capable of computing the flight mechanics, engine performance and gaseous emissions of any defined helicopter configuration within any designated mission.

The overall methodology has been deployed to conduct a preliminary design trade-off study for a reference and conceptual twin-engine-medium helicopter, modeled after the Aérospatiale SA330 simulated on representative mission scenarios.

It has been demonstrated through the design trade-off study that the effectiveness of the on-board intercooler and heat exchanger are critical parameters in determining the level of acquired benefit from the employment of intercooling and recuperation. It has also been established that, for a conceptual intercooled recuperated helicopter to be economically viable, it must meet its corresponding break-even range, where the fuel savings fully compensate for the added weight of the on-board intercooler and heat exchanger. It has been demonstrated that the conceptual intercooled recuperated helicopter has the potential to significantly improve the maximum attainable range capability, while simultaneously maintaining the required airworthiness requirements of the helicopter. Furthermore, it has been established through the implementation of a representative Oil & Gas case study that, the acquired sub-optimum intercooled recuperated engine design with an on-board intercooler and recuperator effectiveness of 50% has the potential to reduce mission fuel burn of the order of 34%, while it increases the mission NO_x inventory of the order of 84% compared to the reference simple cycle engine.

Finally, it has been emphasised that, while the conceptual intercooled recuperated helicopter configuration can improve the mission range and payload capability, it may have a detrimental effect on the mission emissions inventory level, specifically for NO_x (Nitrogen Oxides), imposing a trade-off between the fuel economy and environmental performance of the helicopter. The proposed methodology can effectively be regarded as an enabling technology for the comprehensive assessment of conventional and conceptual rotorcraft–powerplant systems, in terms of operational performance and environmental impact as well as towards the identification of their associated design trade-offs at mission level.

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6. References

[1]. KENNETH M. ROSEN, A Prospective: The Importance of Propulsion Technology to the Development of Helicopter Systems with a Vision for the Future The 27th Alexander A. Nikolsky Lecture, Journal of the American Helicopter Society.

[2]. Advisory Council for Aeronautics Research in Europe home page http//www.acare4europe.com.

[3]. ROBERT C. HENDRICKS, N. LOWERY, DAVID L. DAGGET, PETER ANAST, “Future fuel scenarios and their potential impact to aviation” NASA Glenn research Center, Cleveland, Ohio, 44135.

[4]. COLIN F. MCDONALD, "Gas turbine recuperator renaissance" Journal of Heat Recovery Systems, volume 10, Issue 1, 1990, Pages 1–30.

[5]. GOULOS, I., 2012, “Simulation Framework Development for the Multidisciplinary Optimization of Rotorcraft,” Ph.D. thesis, Cranfield University, Cranfield, Bedfordshire, UK.

[6]. GOULOS, I., PACHIDIS, V., AND PILIDIS, P., “Lagrangian Formulation for the Rapid Estimation of Helicopter Rotor Blade Vibration Characteristics,” Article accepted for publication in the Aeronautical Journal (to appear), 2014.

[7]. European Organization for the Safety of Air Navigation (EUROCONTROL) and Institute of Geodesy and Navigation (IfEN), 1998, WGS 84 *IMPLEMENTATION MANUAL*, EUROCONTROL, Brussels, Belgium.

[8]. GOULOS, I., PACHIDIS, V., AND PILIDIS, P., “Flexible Rotor Blade Dynamics for Helicopter Aeromechanics Including Comparisons with Experimental Data,” Article accepted for publication in the Aeronautical Journal (to appear), 2014.

[9]. GOULOS, I., PACHIDIS, V., AND PILIDIS, P., “Helicopter Rotor Blade Flexibility Simulation for Aeroelasticity and Flight Dynamics Applications,” Article accepted for publication in the Journal of the American Helicopter Society (to appear), 2014.

[10]. Macmillan, W. L., 1974, “Development of a Module Type Computer Program for the Calculation of Gas Turbine Off Design Performance,” Ph.D. thesis, Cranfield University, Cranfield, Bedfordshire, UK.

[11]. CELIS, C., LONG, R., SETHI, V., AND ZAMMIT MANGION, D., 2009, “On Trajectory Optimization for Reducing the Impact of Commercial Aircraft Operations on the Environment”, ISABE-2009 1118, 19th Conference of the International Society for Air Breathing Engines, Montréal, Canada

[12]. F. ALI, I. GOULOS, K. TZANIDAKIS,V. PACHIDIS, R. D’IPPOLITO, “A multidisciplinary approach for the comprehensive assessment of integrated rotorcraft–powerplant systems at mission level”. Proceedings of ASME Turbo Expo 2014: Power for Land, Sea and Air, June 16 - 20, 2014, Dusseldorf, Germany.

[13]. F. ALI, I. GOULOS, V. PACHIDIS. “An integrated methodology to assess the operational and environmental performance of a conceptual regenerative helicopter” The Aeronautical Journal, manuscript number: AeroJ-D-13-04065. (to appear), 2014.

[14]. GORDON, S., AND MCBRIDE, B. J., 1994, “Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications. I. Analysis”, References 240 NASA Reference Publication 1311, National Aeronautics and Space Administration, Lewis Research Center, Ohio, US.

[15]. Web-Based software, http://plotdigitizer.sourceforge.net/

[16]. CELIS, C., LONG, R., SETHI, V., AND ZAMMIT MANGION, D., 2009, “On Trajectory Optimization for Reducing the Impact of Commercial Aircraft Operations on the Environment”, ISABE-2009 1118, 19th Conference of the International Society for Air Breathing Engines, Montréal, Canada

[17]. MILLER, J. A., AND BOWMAN, C. T., 1989, "Mechanism and Modelling of Nitrogen Chemistry in Combustion", *Progress in Energy and Combustion Science,* Vol. 15, pp. 287-338

[18]. FLETCHER, R. S., AND HEYWOOD, J. B., 1971, “A Model for Nitric Oxide Emissions, from Aircraft Gas Turbine Engines”, AIAA Paper 71-123, AIAA 9th Aerospace Sciences Meeting, New York, US.

[19]. NICOLAS C. KAILOS, Increased helicopter capability through advanced power plant technology Journal of the American Helicopter Society, Volume 12, Number 3, 1 July ,pp. 1-15(15).

[20]. MOHTASIM SYED, 2012, "Assessment of Conceptual, more efficient and low emissions Helicopter powerplant cycles," Unpublished M.Sc thesis, Cranfield University, Bedfordshire, UK.

[21]. GOULOS, I., GIANNAKAKIS, P., PACHIDIS, V., AND PILIDIS, P., 2013. “Mission Performance Simulation of Integrated Helicopter–Engine Systems Using an Aeroelastic Rotor Model,” ASME J.Eng. Gas Turbines Power,135(9), 091201-1.

[22]. THEO RINDLISBACHER. “Guidence on the Determination of Helicopter Emissions”. Federal Office of Civil Aviation FOCA ,Division Aviation Policy and Strategy. Document Reference: 0/ 3/33/33-05-20

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