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An Integrated Methodology to Assess the Operational and Environmental Performance of a Conceptual Regenerative Helicopter

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ABSTRACT

This paper aims to present an integrated multidisciplinary simulation framework, deployed for the comprehensive assessment of combined helicopter–powerplant systems at mission level. Analytical evaluations of existing and conceptual regenerative 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 reference simple cycle and conceptual regenerative twin-engine light helicopter, modeled after the Airbus Helicopters Bo105 configuration, simulated under the representative mission scenarios. 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 regenerative 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 regenerative 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

Roman symbols

T_{out}	Heat exchanger outlet temperature, K
T_{Comp}	Compressor delivery temperature, K
$T_{Exhaust}$	Exhaust air temperature, K
Vb_e	Airspeed for maximum endurance, m/sec
Vb_r	Airspeed for maximum range, m/sec
V_{max}	Maximum cruise speed, m/sec

Greek Symbols

ΔAUM	Delta all-up-mass, kg
ΔCO_2	Delta carbon dioxide, kg
$\Delta Fuel\ burn$	Delta mission fuel burn, kg
ΔNO_x	Delta nitrogen oxides, kg
$\Delta Weight$	Delta weight, kg

Acronyms

ACARE	Advisory Council for Aeronautics Research in Europe
AGL	Above Ground Level
AUM	All-Up-Mass, kg
CATIA	Computer Aided Three-dimensional Interactive Application
CAE	Chemical Equilibrium with Applications
DP	Design Point
EHOC	European Helicopter Operators' committee
EW	Engine Weight. kg
FOCA	Federal Office of Civil Aviation
FPT	Free Power Turbine
HE	Heat Exchanger
HPC	High Pressure Compressor
HPT	High Pressure Turbine
LPC	Low Pressure Compressor
MFB	Mission Fuel Burn, kg
MTOW	Maximum Takeoff Weight, kg
NASA	National Aeronautics and Space Administration
OD	Off-Design
OW	Operational Weight, kg
OEW	Operational Empty Weight, kg
PSR	Perfectly Stirred Reactor
REG	Regenerated
SC	Simple Cycle
SAR	Search And Rescue
SFC	Specific Fuel Consumption, µg/J
TEL	Twin Engine Light
TW	Total Weight, kg
TO	Take-off
UAVs	Unmanned Ariel Vehicles
WSG84	World Geodetic System dated in 1984

1.0 INTRODUCTION

1.1 Background

Early helicopters employed reciprocating engines which offered low Specific Fuel Consumption (SFC) and therefore were very economical. However, they were heavy, bulky and were complex to maintain. The introduction of turboshaft engines provided a significant break-through in size and weight of engines, thereby over the years they have played a dominant role in enabling substantial improvements in the payload and range capabilities of the helicopters.

The transition from reciprocating engines to turboshaft engines was accompanied with a trade-off for engine SFC. The reduction in engine weight to about 0.512kg/kw-hr was realized by an increase in SFC to about 0.6083kg/kw-hr(1). Since then, the gas turbine engine manufacturers have ensured significant development efforts to progressively improve the SFC by capitalizing on turbomachinery component efficiencies, expanding the metallurgical boundaries and by employing advanced manufacturing techniques. These developments enabled higher Pressure Ratios (PR), higher Turbine Entry Temperatures (TETs), compact size and lighter engines. It is however now generally accepted that any further development in the helicopter gas turbine technology, without the consideration to exploit innovative and novel 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 heat exchanged engines, or semi-closed cycle engine architectures. Furthermore, currently the prominent increase in the environmental concerns has demanded 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.

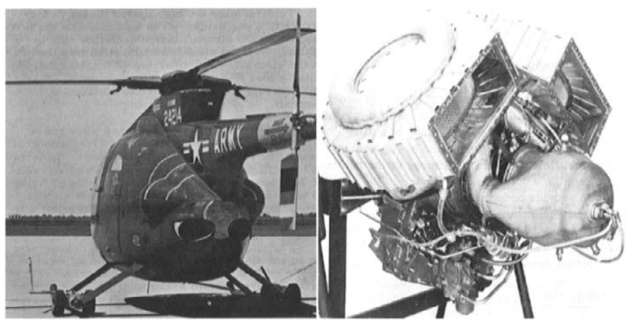
In response to the demand and to extend and maintain effective rapid transition towards a sustainable and greener aviation industry (specifically in Europe) the ACARE (Advisory Council for Aviation Research and Innovation in Europe) has set some ambitious and complex targets for "Vision 2020", under the Strategic Research and Innovation Agenda(2). Vigorous programs of aeronautics and air transport research are already underway, delivering important initiatives and benefits for the aviation industry(2). This has led to a renewed interest in heat exchanged engine concepts as an effective alternative to make future air transportation sustainable and more environmental friendly.

When targeting drastic improvements in engine fuel efficiency for helicopters, one of the most promising candidate is the advanced regenerative turboshaft concept. Rosen elaborated in(3), "the (Unmanned Aerial Vehicles) UAVs or helicopters that are intended for extremely long duration missions may require powerplants that are much more efficient than Brayton cycle gas turbine engines". Also Saravanamoutto in(4), when discussing regenerative technology, suggests "it is not impossible that regenerative units will appear in the future, perhaps in the form of turboshaft engines for long endurance helicopters".

The level of benefits offered by a helicopter regenerative powerplant engine is predominantly influenced by the type of operation, the required mission range the helicopter is designed to serve and the overall evaluation criteria(5). One of the major challenge of today's rotorcraft powerplant is the increased specific fuel consumption during part power. A typical helicopter cruises between 55% to 65% of installed power and more importantly this particular flight regime represents around 80% to 90% of the helicopter's mission(6). One of the most promising solution to overcome this challenge is by adopting the regenerative powerplant, as this offers a prominent benefit during part-power operation.

The deployment of regenerative technology has always been of great interest to enhance the operational capabilities of helicopters, specifically of those that are utilized for military operations. The employment of the regenerative technology in helicopters dates back to the early 1960's. Various programs have been conducted by both government and private industry to demonstrate the performance and operational capabilities of regenerative technology against the conventional technology. The "T63 Regenerative Engine Program"[7] conducted by US Army in 1965 is a remarkable achievement in showcasing the unprecedented capabilities of regenerative technology. The program successfully completed a 50hr flight worthiness test in a Light Observation YOH-6A helicopter (AUM=998kg) employing a sub-optimum "Bolted-on-Type" regenerative engine (shown in Fig.1). The employed regenerative engine substantially improved the helicopter fuel requirements and increased its maximum specific range by 25.7%[7]. Following the "T63 Regenerative Engine Program" various other programs are reported in the literature. For example a comprehensive evaluation of regenerative powerplants is reported by Colin F. McDonald in Recuperated Gas Turbine Aero-engines, Part I[8] Part II[9] and Part III[10].

It is evident from the literature that the assessment and evaluation of the conceptual regenerative cycle is conducted with prime focus on the enhancement of helicopter engine performance and operational benefits, paying little attention towards the assessment of environmental impact resulting from the change in engine technology. One of the reasons for not accounting for helicopter emissions in the past might have been driven by lack of concern for "environmental degradation" by government and associated authorities. However, as the aviation industry has developed over time, the concerns over its impact on the environment have also grown significantly.



a) b)

Figure 1: (a). Modified YOH-6A helicopter (AUM=998 kg); (b). T63 helicopter turboshaft engine with twin tubular "bolt-on" recuperator modules, reproduced from[7].

Regenerated engines are one of the most promising alternative (aero-engine) powerplant configurations when targeting significant reductions in fuel burn and lower gaseous emissions e.g. Carbon dioxide (CO_2), as elaborated in[8]. The most fundamental advantage offered by the regenerative engine due to its distinct thermodynamic cycle is the reduction in fuel burn, achieved through recuperation of exhaust heat. The particular advantage of recuperation is rather significant in the current era, considering the forecasts for high fuel prices[11] and the strongly imposed government legislations for maintaining adequate emissions levels[2]. In addition the readiness of advanced materials and manufacturing technologies can now enable the availability of customized, compact, light weight and efficient heat exchangers that can be implemented without penalizing the operational capabilities of the helicopter[10].

1.2 Scope of the present work

The literature currently available on regeneration technology with regards to its application to helicopters reveals a gap in knowledge. A complete assessment of the technology in terms of its implications on engine design parameters, associated effects on fuel burn and gaseous emissions inventory has not been addressed in an integrated multi-disciplinary environment, with implicit consideration of the individuality of a complete three-dimensional helicopter operation.

This study proposes an integrated helicopter multidisciplinary design framework, targeting the preliminary design of a sub-optimum regenerative engine as well as the identification of its design trade-offs in terms of fuel consumption and gaseous emissions inventories at mission level. 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 rotorcraft emissions species.

The overall methodology has been applied to conduct a preliminary design trade-off study for a reference and conceptual twin-engine light helicopter, modeled after the Eurocopter Bo105 configuration, simulated under the representative mission scenarios. Extensive comparisons are made between the aforementioned helicopters at both engine and mission level, along with general flight performance charts including the payload-range diagram.

It has been established through the design trade-off study that the effectiveness of the on board heat exchanger is a critical parameter in determining the level of acquired benefits from the deployment of regeneration. It has also been shown that, for a regenerative helicopter to be economically viable, it must meet its corresponding break-even range, where the fuel savings fully compensates for the added weight.

Finally, it has been emphasized through the implementation of a representative case study that, while the regenerative configuration can improve the mission range and payload capabilities, it can 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 helicopter–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.

2.0 SIMULATION METHODOLOGY

2.1 Helicopter multidisciplinary design framework

This study requires the deployment of an integrated multidisciplinary helicopter simulation framework. The modeling 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 model analysis presented in[12&13], a flight path profile analysis based on the World Geodetic System dated in 1984 (WGS 84)[14], a non-linear trim procedure solving for the aeroelastic behaviour of the main rotor blades as described in [15-16], an engine performance analysis model and gas turbine emissions model as detailed in[17&18].

Each of the aforementioned modeling methods is integrated together within a standalone framework under the name "HECTOR" (HEliCopTer Omni-disciplinary Research Platform). HECTOR is capable of simulating complete, three-dimensional helicopter missions using a fully unsteady aeroelastic rotor model. HECTOR has been extensively described in[12&20], therefore only a brief description of the associated models is provided in this paper.

2.2 Turbomatch

The engine modelling and performance simulation code (Turbomatch) employed for the simulations carried out in this study is a Cranfield University in-house code, developed over a number of decades[17]. Turbomatch has previously been utilised in several studies available in the literature for the prediction of Design Point (DP) and Off-Design (OD) performance of gas turbine engines[21-22]. In order to comply with the scope of work presented in this paper, the engine is assumed to be operating at steady-state OD conditions throughout the mission.

2.3 Gas turbine emissions model

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[18]. Since the scope of this study is to assess the advancement in the engine technology and its associated trade-offs, only a brief description of the emissions modelling methodology has been included herein. However, the details of numerical formulation and methodology employed for the purpose of emissions prediction has been extensively reported by the authors in the following reference[23]. Thus, further elaboration shall be omitted.

2.4 Description of integrated HECTOR framework

The schematic representation of the integrated tool adopted for the purpose of this study is illustrated in Figure 2. Each defined mission profile is translated into discrete segments based on user defined input values in terms of operational procedures (velocity, altitude, climb and decent rate) and geographical latitude and longitude. The initial All Up Mass (AUM) is equal to the sum of the Operational Empty Weight (OEW), the useful payload, and the on-board fuel supplies. The required amount of fuel for a given mission has to be initially assumed; therefore an initial guess is made for the weight of the on-board fuel supply which is then refined through an iterative process.

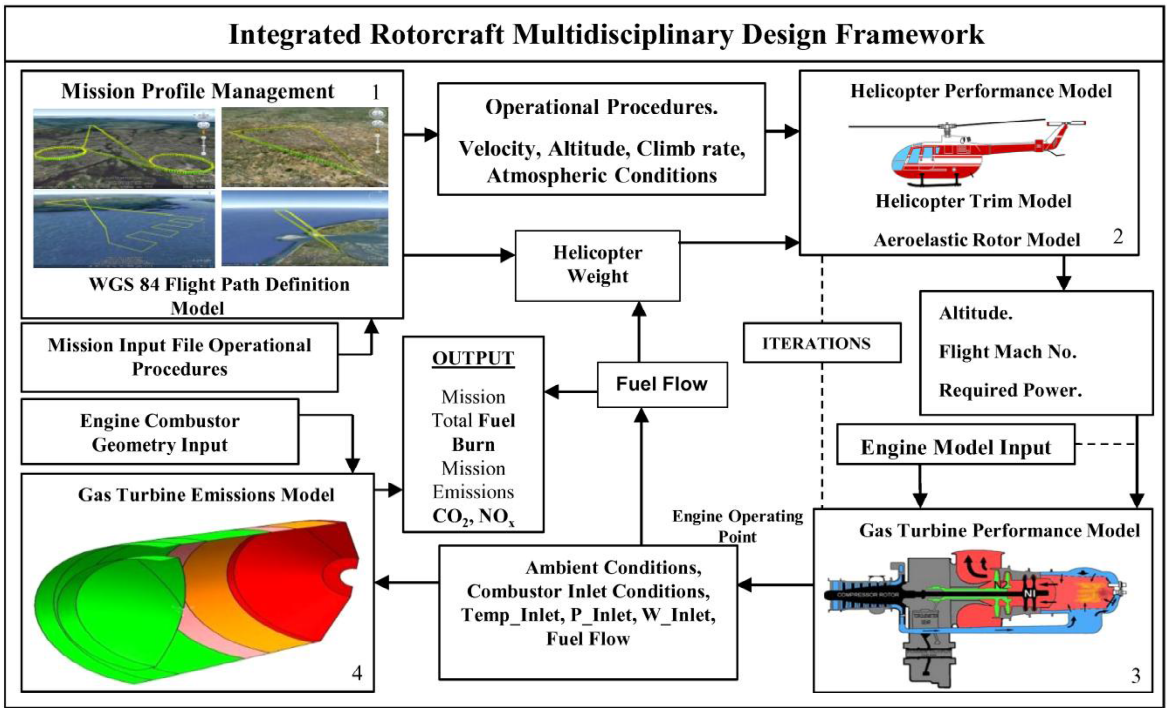


Figure 2: HECTOR, HElicopTer Omni-disciplinary Research-platform.

For each flight segment HECTOR calculates the engine power requirement, intake inlet conditions, and updates the new space-wise position of the helicopter. TURBOMATCH subsequently establishes the engine's operating point to meet the power demand required and establishes the fuel flow and corresponding combustor inlet pressure, temperature and mass flow. This information is then utilised by the emissions model HEPHAEUSTUS to compute the corresponding emissions inventory of CO_2 and NO_x for the imposed flight segment.

The time-dependent fuel consumption at time *t* along with the respective emissions inventory, is then updated by applying a numerical time integration scheme on the time-variations of engine fuel flow and emission indices from zero up to the current mission flight segment. The calculated value of fuel burn is then subtracted from the initial AUM in order to account for the gradual weight reduction during the course of the mission. The overall process is re-iterated in a fixed-point manner until convergence is obtained for the total mission fuel burn. A detailed description of the numerical integration of engine performance model (TURBOMATCH) and emissions model (HEPHAESTUS) with HECTOR has been separately reported by the authors in the following reference[23]. Thus, further elaboration shall be omitted.

2.5 Regenerated turboshaft

For the purpose of this study a TEL helicopter configuration is investigated. The currently installed simple cycle turboshaft engine is notionally modified by adding a HE, demonstrating a regenerated turboshaft engine. The regenerated turboshaft incorporates a HE (presented in Fig. 3); the hot side is placed downstream of the Free Power Turbine (FPT) and the cold side upstream of the combustion chamber. This arrangement enables heat transfer between the exhaust gas and the compressor delivery air prior to combustion chamber.

Depending on the Heat Exchanger Effectiveness (HEE), the ability of the heat exchanger to transfer heat (derived by using equation 1), an increase in (working fluid) compressor delivery air temperature is achieved. This process of preheating upstream of the combustion chamber leads to lower fuel input requirements and essentially results in reduced overall mission fuel burn compared to the baseline simple cycle engine. However, the penalties resulting from the employment of the HE include; i) the additional pressure losses introduced by the heat transfer process and by the installation arrangement of the HE, ii) the added weight of the heat exchanger and finally, iii) the increase in inlet temperature of the combustion chamber which increases the combustor tendency to emit higher concentration of nitrogen oxides (thermal NO_x).

The schematic presented in Fig. 3 is simply the reflection of how the engine is modeled in TURBOMATCH and is purely drawn for demonstration purposes. The schematic may vary depending on the choice and the installation arrangement of the heat exchanger.

$$HE\ effectiveness = \frac{T_{out} - T_{Comp}}{T_{Exhaust} - T_{Comp}}\ \%$$ **Equation [1]**

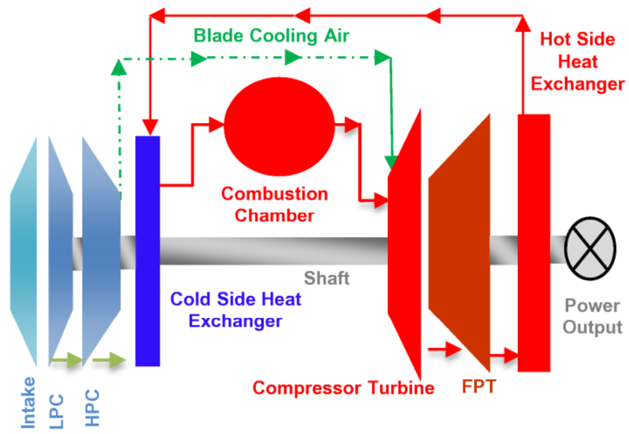


Figure 3: Schematic layout of a single-spool regenerated turboshaft

2.6 Compilation of reference helicopter and engine model

A Twin Engine Light helicopter model based on the configuration of the MBB Bo105 (now under Airbus Helicopters) was implemented in HECTOR Table 1. The specific helicopter is equipped with two Rolls-Royce Allison 250-C20B turboshaft engines. Thus, the corresponding, Reference Allison 250-C20B (Engine A1) and a “Regenerated” Allison 250-C20B (Engine B1) engine models were introduced and implemented in TURBOMATCH. The design point comparison for various engine parameters for Engine A1 and the sub-optimum regenerated Engine B1 are presented in Table 2.

2.7 Reference combustor modeling

As an input requirement to the emission model (HEPHAESTUS) the combustor geometry of a reference Rolls-Royce Allison 250-C20B engine was investigated in detail. A “reverse engineering” approach was adopted by means of publicly available data. The complete, full-scale, three-dimensional combustion chamber was modeled using CATIA Part Modeling to derive the best possible approximations for the inlet area, outlet area, volume, and length of the various "zones" (e.g.: flame front, primary, intermediate, and dilution zones) within the combustor.

Table 1. Twin Engine Light helicopter model similar to MBB BO105 helicopter.

Characteristic	Imperial Units	Metric
Engines	2 x RR[a] Allison25C_20B turboshaft	
Engine Power	2 x 420 shp	2 x 313 kW
Length	28.08 ft	8.56 m
Height	9.84 ft	3.0 m
Max Gross Weight	5511.5 lb	2500 kg
Max Standard Fuel	992.08 lb	450 kg
Range	310 nm	575 km
Service Ceiling	17,001 ft	5182 m
Vmax (at cruise)	131 kt	242 km/h
Payload	1322.8lb	600

Table 2: Design point, engine parameters for reference Engine A1 and regenerated Engine B1turboshaft

Engine Design Parameters	Reference Engine A1	Regenerated Engine B1
Pressure Ratio	7:1	7:1
Mass Flow (Kg)	1.56	1.56
TET (K)	1470	1470
TO Power (KW)	313	313
SFC @ TO (μg/J)	119.8	95.55
Dry Weight (Kg)	75	75
HE Weight (kg)	-	9.75
HE ε %	-	40
Total Weight (Kg)	75	84.75

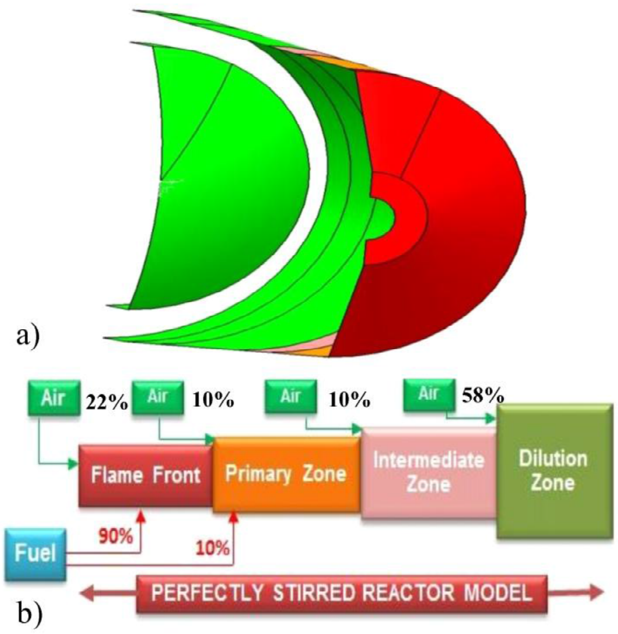


Figure 4: a). Combustion chamber of reference Rolls-Royce Allison 250-C20B engine; b) Combustor zones and reactor models assumed for NO_x modelling of rotorcraft combustor.

The Rolls-Royce Allison 250-C20B engine is equipped with a straight through single can combustor module[24]. The coordinates of the combustor module were obtained from two-dimensional engine cutaway drawings available in the public domain. The obtained coordinates were subsequently exported to CATIA Part Modeling in order to obtain a digital three-dimensional representation for the reference combustor module, as shown in Fig. 4a. The obtained digital combustor design was then used to approximate the dimensions of the different zones (lengths and volumes) within the corresponding model in HEPHAESTUS.

The combustion chamber is represented by combining four distinctive zones, all simulated using a series of Perfectly Stirred Reactor (PSR) models, as shown in Fig. 4b. The theory behind PSR focuses predominantly on the influence of the different levels of turbulent mixing on the chemical reactions within prescribed volumes, rather than on the details of spatially-varying velocities and turbulence fields within a combustor. It is also assumed that, the flame front is well mixed and can also be approximated with a PSR model.

Each reactor assumes a chemical equilibrium state for calculating the reactor temperature, pressure, and density. The model includes 18 species for the equilibrium calculations using the NASA CEA program[25]. The NO_x mass fraction variation is calculated using the extended Zeldovich mechanism (includes N2O mechanism) and Prompt NO_x methodology reported in Refs.[26–29]. The analysis assumes that, 90% of the fuel is burned at the flame front zone at a fixed equivalent ratio of 0.9. The remaining fuel fraction is assumed to be burned within the region of the combustor primary zone. The distribution of air mass flow fractions within each of the combustor zones, is in accordance with sensible engineering estimations and it is assumed to remain constant at off-design operating conditions. The volume of each reactor is estimated based on the combustor geometry information obtained from the developed CATIA model.

2.8 Heat exchanger weight estimation

The HE weight correlation utilized for the purposes of this study is adopted from[6], the particular correlation is presented in Figure 5a. It needs to be emphasized that the HE weight correlation adopted for the purpose of this study is for the fixed surface HE concepts. The helicopter configuration investigated in this study represents a TEL configuration; therefore the gross heat exchanger weight for the helicopter was extended to “two engines” during the simulations to establish weight deltas between the baseline and the regenerated engines. With regards to the additional pressure losses introduced by the heat exchanger similar values are utilized as reported previously, e.g. by the “Allison T63 Regenerative Program”[7].

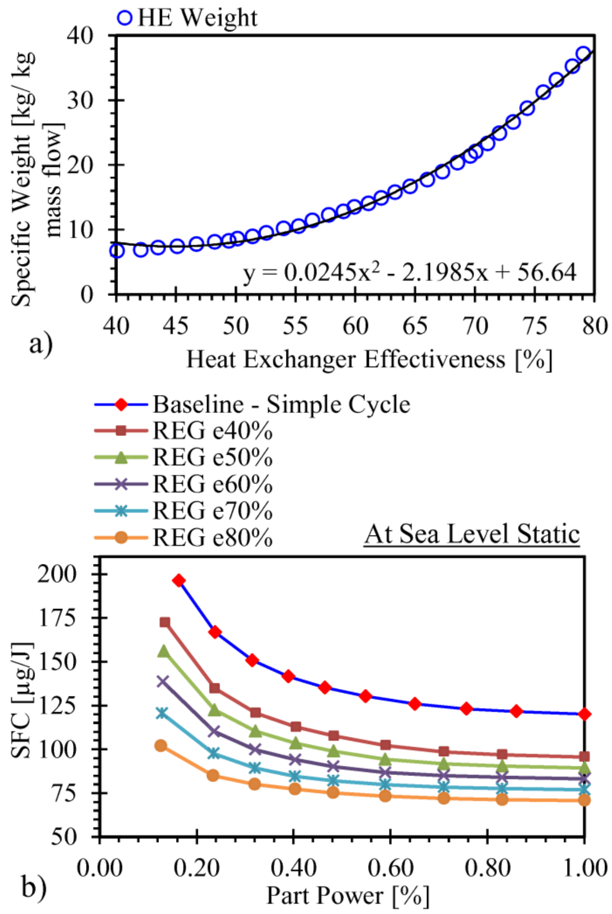


Figure 5: (a). Fixed geometry tubular type heat exchanger specific weight; (b): SFC vs (P/P.Design) for reference engine A1 and regenerated engine B1 turboshaft.

3.0 RESULTS AND DISCUSSION

3.1 Comparison of engine part-power performance at engine level

Due to the exchanged heat between the compressor delivery air and exhaust gas, a prominent increase in the compressor delivery air temperature, prior to the combustion chamber is experienced by the regenerated Engine B1. The level of rise in the combustion inlet temperature is a function of the heat exchanger effectiveness, and tends to increase linearly as the heat exchanger effectiveness increases. This particular engine characteristic imposed by the heat transfer process serves as the fundamental advantage offered by the regenerative engine, resulting in significantly lower fuel requirements compared to simple cycle engine.

Figure 5b presents the variation in SFC at design point and at part-load (P/P_{Design}) for reference Engine A1 and regenerated Engine B1 turboshaft. The heat exchanger effectiveness was varied between 40% and 80%. A significant improvement in SFC for Engine B1 relative to Engine A1 at part power is prominent. For a range of HE effectiveness e.g. 40% to 80% the SFC improvement at medium power varies from approximately, 19% at 40% HE effectiveness and increases up to 43% at 80% HE effectiveness. The Overall Pressure Ratio (OPR) for both Engines A1 and B1, at design point is 7:1, TET is 1470K and mass flow is 1.56 kg, as shown in Table 2 respectively.

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 3.3 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 Bo105 helicopter along with its validation with the flight test data has been separately reported by the authors in[(23)].

3.3 Comparison of integrated helicopter-engine flight performance

To replace an existing simple cycle helicopter engine with a conceptual regenerated engine, several helicopter design requirements must be satisfied. These requirements are mainly attributed towards maintaining the helicopter payload-range capability and airworthiness requirements e.g. One Engine Inoperative. The latter requirement is mainly concerned with maintaining the required Take-off (TO) power or the maximum contingency power of the installed engine. With regards to the payload range capability, this is ensured by maintaining the required power for Maximum Takeoff Weight (MTOW) of the helicopter as well as its fuel consumption rate.

Figure 6a presents helicopter flight dynamics and trims analysis results in terms of main rotor power requirements for the reference and conceptual regenerative helicopter, results presented are based on the straight and level flight and are simulated for a range of HE effectivenesses. It is noted that the added weight of the on-board heat exchanger results in increasing the helicopter AUM, coupled with this are the increased pressure losses introduced by the HE. Both aforementioned penalties associated with the on-board 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 6c presents the variation in the specific air range for both representative helicopters and their associated engine fuel flow as a function of cruise speed. It is worthy to note that the underlying operational capability of the helicopter in terms of its (cruise speed) speed for maximum endurance (Vb_e) and speed for maximum range (Vb_r) is not influenced by the installation of the HE. The acquired results presented in Fig. 6c suggest a substantial improvement in the specific air range of the helicopter; this is mainly attributed to the significant improvement in fuel flow requirements associated with the regenerated helicopter.

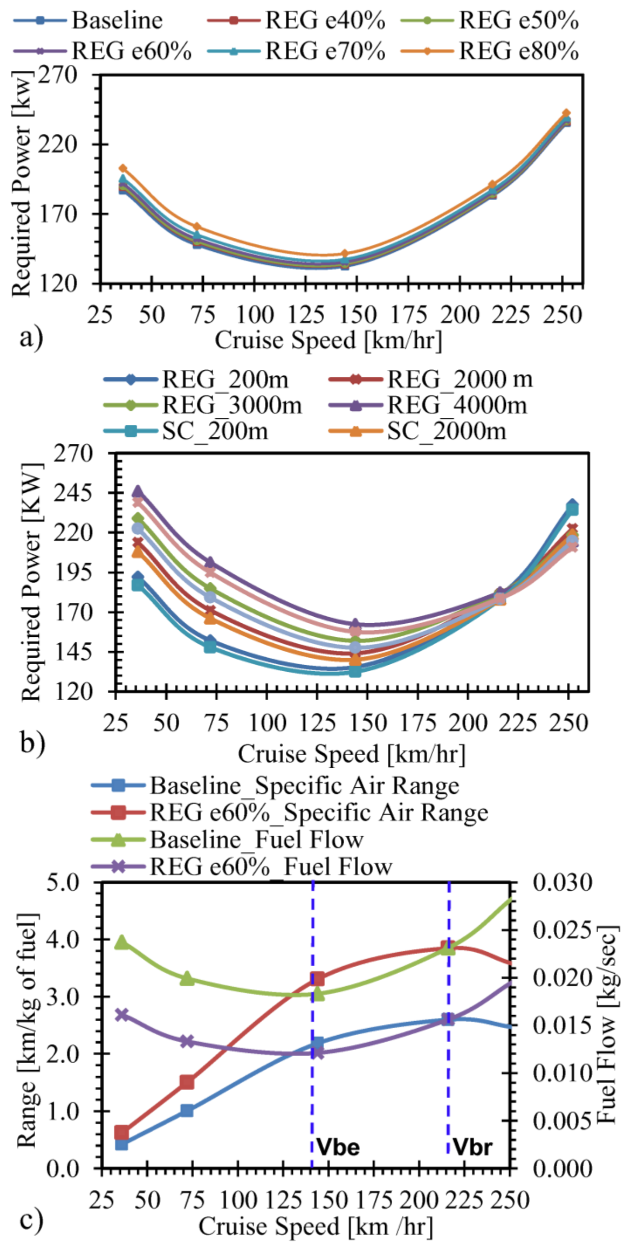


Figure 6: (a). Reference BO105 and regenerative helicopter, power vs cruise speed; (C).Specific air range for reference B0105 and regenerative helicopter with 60% HE effectiveness.

3.4 NO_x formation

In terms of the gaseous emissions computation, the prime focus of this study is to capture the possible variations of those emissions species that are primarily affected by the regeneration process. This mainly concerns with the reduction of CO_2 and tentative increase in NO_x, the remaining effects are not within the scope of this study.

The fundamental "fuel efficient characteristic" of regeneration hugely favors reduction in CO_2 emissions. However, demands conditions within the combustion chamber that inevitably support elevated levels of thermal NO_x[30]. 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 regeneration clearly influences the combustion entry temperature shown in Fig. 7b. 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 generating elevated levels of thermal NO_x. Fig. 7a 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.

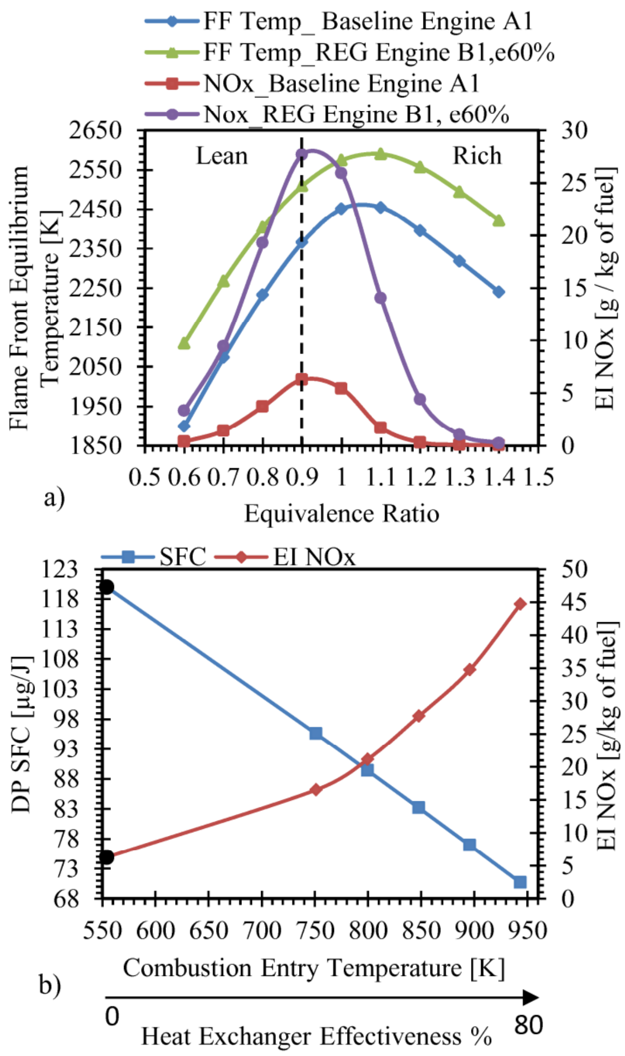


Figure 7: (a). EI NO_x and combustor equilibrium temperature Vs equivalence ratio, reference engine A1 and regenerated engine B1; (b). SFC & EI NO_x vs inlet temperature for equivalence ratio of 0.9, reference engine A1 and regenerated engine B1, at design point, black circles imply simple cycle engine.

With regards to the regeneration, 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 Fig. 7a. An important assumption to emphasize here is that the combustion chamber of the regenerated engine B1 is redefined as such to achieve same equivalence ratio as reference engine A1 (0.9), this is purely to ensure a fair basis of comparison for analyzing the combustion performance e.g. in terms of emitted emissions, specifically NO_x.

3.5 Reference engine A1 NO_X prediction

Figure 8 compares HEPHAESTUS predictions for the variation of NO_x emission index against engine shaft power, with experimental data as well as with the empirical approximate function derived and reported by FOCA in[31]. Experimental data are included considering two families of engines for which FOCA conducted NO_x measurements. These effectively represent the lower and upper bounds of the overall deviation observed in the measured data. The behavior of the approximate FOCA expression is also included in Fig. 8 for completeness. HEPHAESTUS has been matched at DP conditions considering both the lower and upper bounds of the measured data, as well as with the approximate function proposed by FOCA. However, only the engine model corresponding to the FOCA approximated function has been implemented in HECTOR for the computation of emissions inventories at mission level.

Reasonable agreement can be observed throughout the power range for which results are presented, considering all three cases. Specifically, the trend of the NO_x emission index with engine power has been captured adequately by the proposed approach. It is emphasized that, the combustor zone sizing process was essentially carried out with the objective to align the predicted values of NO_x against the data corresponding to each case, at DP conditions (417shp) only. Once the predicted value of NO_x emission index was well matched, the combustor details were kept fixed throughout the OD power range. The deviation observed in Fig. 8 between HEPHAESTUS predictions and the FOCA data considering lower engine power settings, are attributed predominantly to OD engine performance modeling [deficiencies associated with the use of generic and scalable component maps in TURBOMATCH[22].

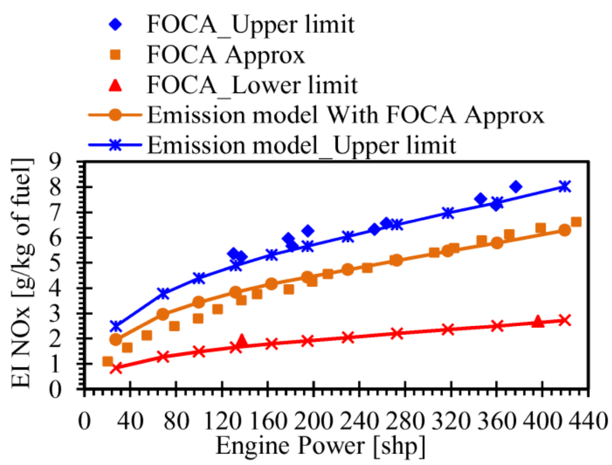


Figure 8: NO_x emission index prediction for the reference Rolls Royce Allison 250-C20B engine – comparison of estimates of HEPHAESTUS emissions model and experimental measurements derived by FOCA[31], including representative lower and upper bounds.

3.6 Compilation of representative mission scenarios

The performance evaluation of the regenerated helicopter against the reference 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 Fig. 9.

3.7 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).

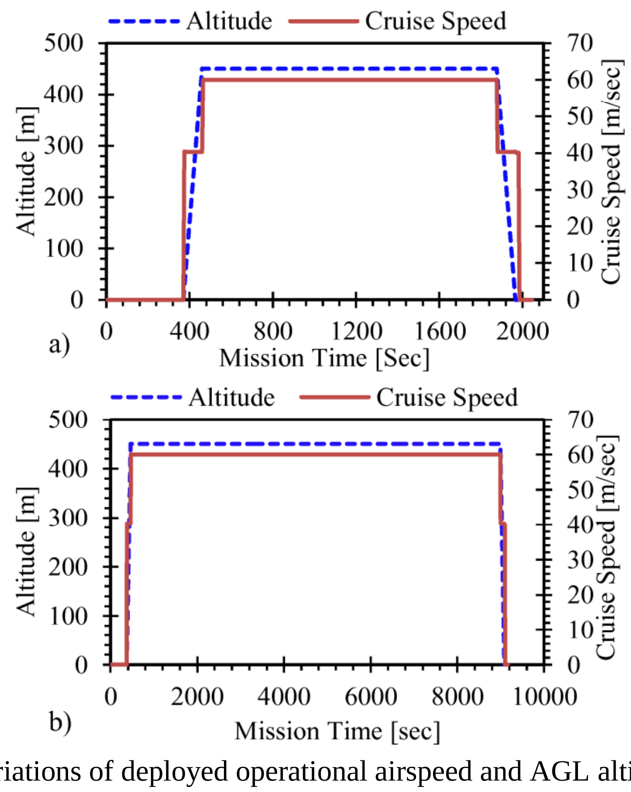


Figure 9: (a). Time variations of deployed operational airspeed and AGL altitude for mission range of 50 nautical mile; (b) Time variations of deployed operational airspeed and AGL altitude for mission range of 50 nautical mile.

3.8 All-up-mass

For the purpose of this study a positive ΔAUM demonstrates reduction in AUM of the regenerated helicopter compared to its corresponding reference simple cycle helicopter and a negative ΔAUM demonstrates increase in AUM (a negative ΔAUM can be classed as "weight penalty"). Similarly the positive delta for emissions (CO_2 and NO_x) implies reduction in overall mission emission inventory and a negative delta implies the penalty in mission overall emission inventory. The missions that justify the need for regeneration demonstrate positive ΔAUM and missions with negative ΔAUM are not considered feasible engine designs.

Depending on the evaluation criteria, an obtained positive ΔAUM can either be utilized as mission fuel saving, enabling the helicopter to increase its mission range, or it can be utilized as increase in useful payload. It is however also possible to utilize the obtained positive "ΔAUM" to offer benefits in both aforementioned areas.

3.9 Mission analysis results

A substantial amount of mission fuel burn reduction is realized for all simulated missions. The percentage reduction in mission fuel burn is found greatly sensitive to the heat exchanger effectiveness. For all the missions simulated, a percentage fuel burn reduction is of the order of 22% for 40% on-board HE effectiveness, and a reduction of the order of 41% is achieved with an on-board HE effectiveness of 80%. Fig. 10a presents variation in mission fuel burn as a function of mission range for all simulated mission with respect to both helicopter configurations.

Figure 10b presents the ΔFuel Burn against the heat exchanger effectiveness for all simulated missions corresponding to conceptual regenerated 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 HE in terms of fuel bun, the corresponding added gross weight of the HE must be subtracted from the derived ΔFuel Burn for a given mission. Once the 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 heat exchanger weight increases exponentially as a function of HE effectiveness, for all simulated values of HE effectiveness there is a representative break-even range, where the amount of fuel reduction compensates exactly for the respective weight added by the on-board HE. This can be noticed from Fig. 11a, each HE effectiveness trend initiates with a weight penalty (negative ΔAUM) and essentially meets the break-even line. From Fig. 11b, it is interesting to note that the 50% HE effectiveness compared to 40% HE effectiveness requires less range to meet break-even, this is due to the fact that, the increase in added weight when advancing from 40% to 50% HE effectiveness is relatively low. However, the reduction in SFC is high, resulting in greater overall fuel burn reduction at 50% HE effectiveness.

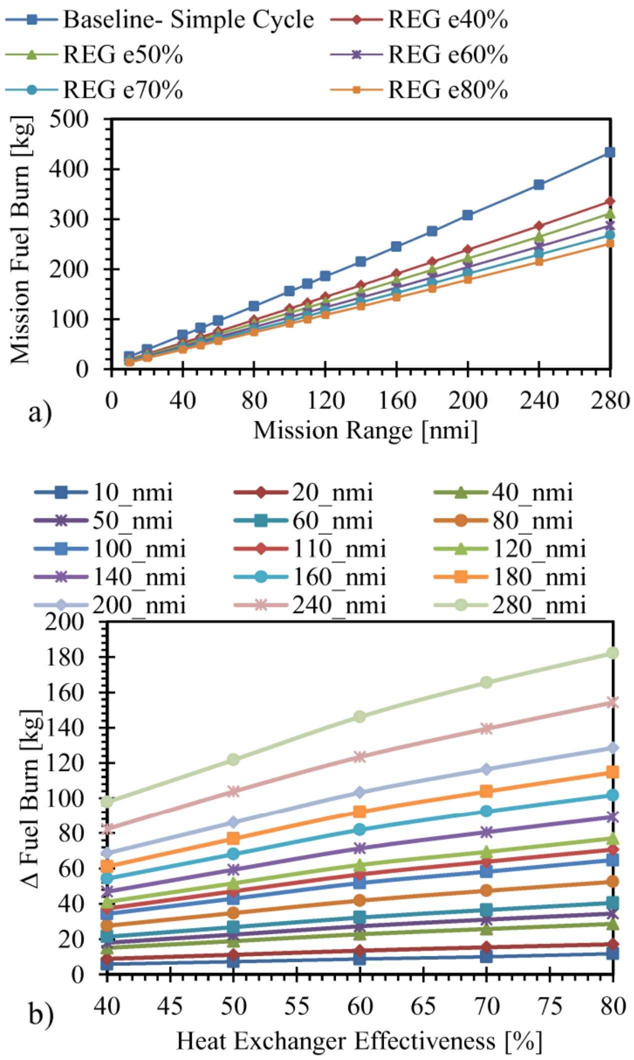


Figure 10: (a). Mission fuel burn Vs mission range for simple cycle and regenerative helicopter; (b). Delta fuel burn Vs HE effectiveness for TEL regenerated for simulated missions

A favorable reduction in CO_2 is evident from Figure 12a. Since the CO_2 is interdependent on the mission ΔFuel Burn, therefore a proportional positive reduction in ΔCO_2 is realized as in the case of ΔFuel Burn. Due to the reasons highlighted earlier under the section 3.4. A significant increase in mission NO_x is attained, presented as negative ΔNO_x in Fig. 12b.

3.10 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 regenerative helicopter with respect to reference configuration. Under the simulated conditions the regenerative helicopter demonstrated the potential to improve the maximum attainable range by 51.3%, 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 6.43% in maximum payload capability is realized, the corresponding weight penalty is attributed to the added weight of the on-board heat exchanger.

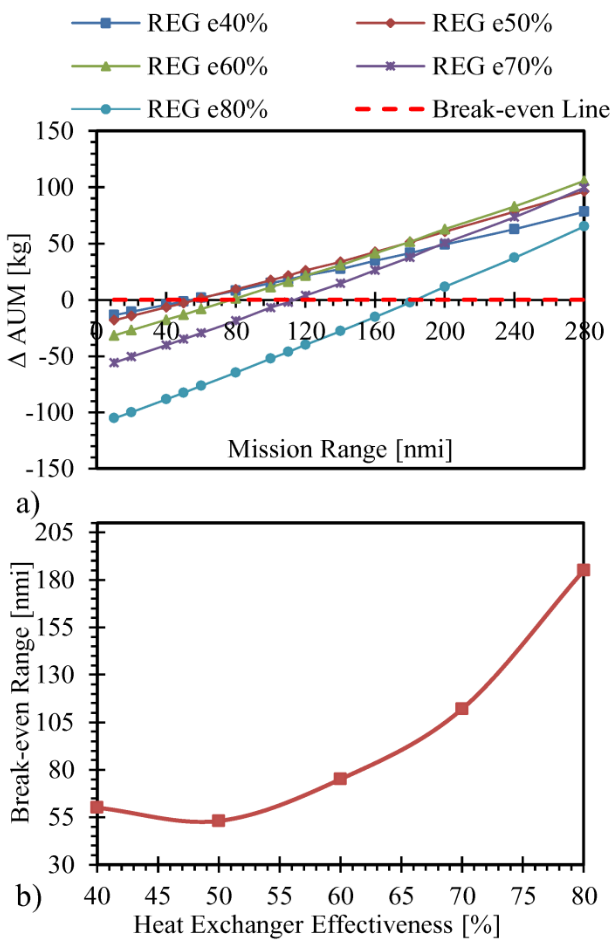


Figure 11: (a). Delta All-Up-Mass Vs Mission Range for TEL regenerated helicopter; (b). Break-even range vs HE effectiveness for TEL regenerated helicopter

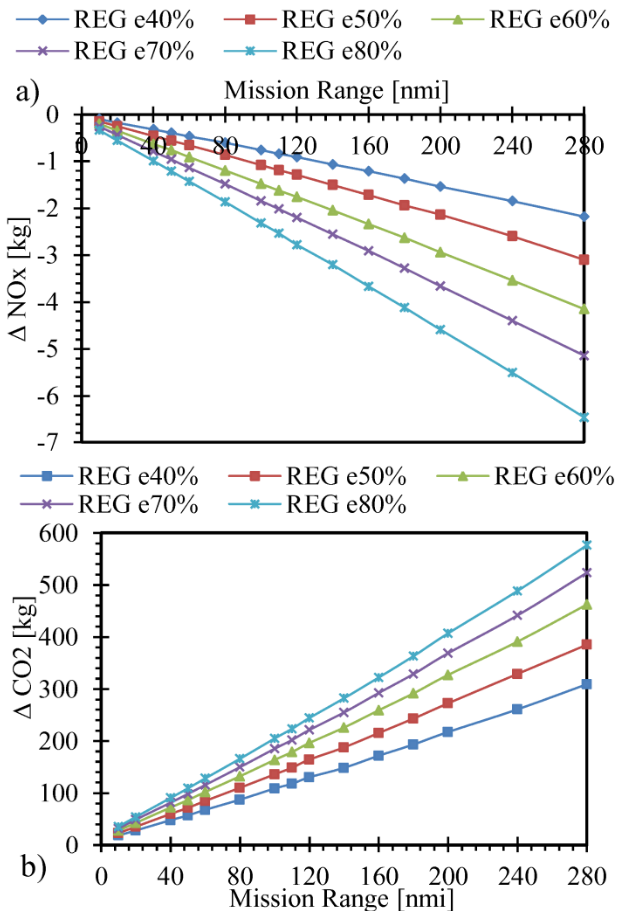


Figure 12: (a). Delta CO_2 Vs Mission Range for TEL regenerated helicopter; (b) Delta NO_x Vs mission range for TEL regenerated helicopter

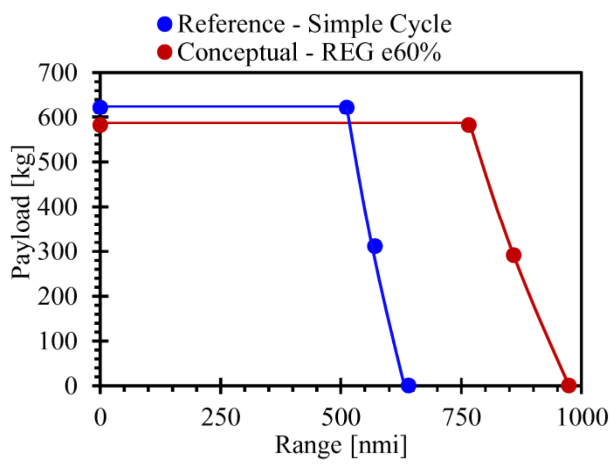


Figure 13: Payload-range diagram for reference BO105 and regenerated helicopter

3.11 Case study

In order to assess the potential of the conceptual regenerated helicopter within a realistic helicopter operation, a case study was designed based on a typical Search And Rescue (SAR) mission. The acquired operational procedures in terms of geographical location selection, deployed airspeed, altitude, climb/descent rates and idle times have been defined in collaboration with the European Helicopter Operator's Committee (EHOC).

The corresponding flight profiles in terms of global coordinates along with deployed operational altitudes and airspeeds are illustrated in Fig. 14.

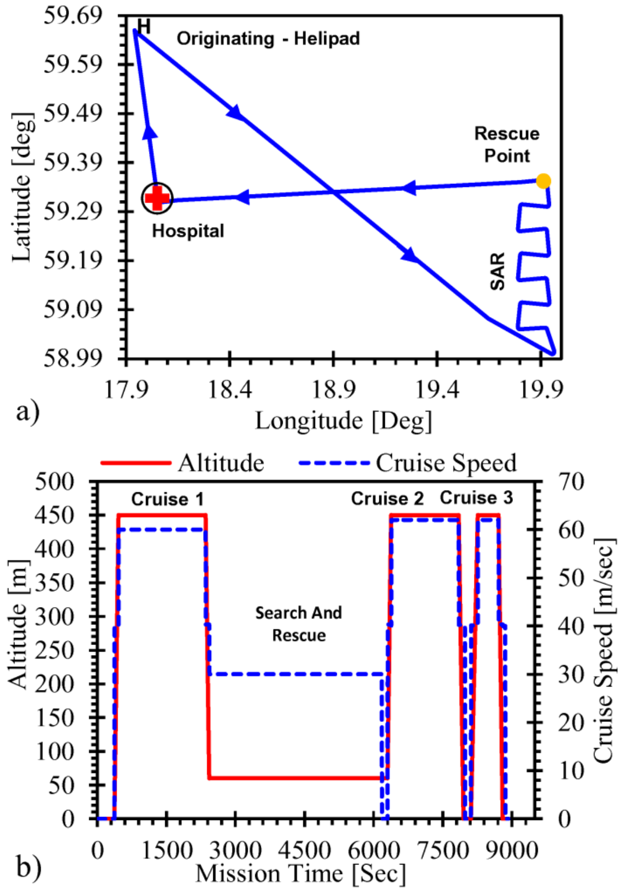


Figure 14: Search and rescue mission: (a) geographical global coordinates; (b) time variations of operational airspeed and AGL altitude

The implemented SAR mission proves to be a positive and favorable operation for regeneration employment. A positive ΔAUM is achieved for all simulated HE effectiveness (40% - 80%), presented in Fig. 15a. The total weight (Engine + Mission fuel) dotted line for the conceptual regenerated helicopter lies below the reference engine total weight. The region between both the aforementioned lines represents the reduction in "AUM", which diminishes above 60% HE effectiveness; this is due to the fact that gross weight added by the heat exchanger significantly increases above 60%. Also, the fixed range of the mission, 200 nautical miles limits maximum attainable fuel savings. Therefore, under the simulated conditions and assumptions, the optimum HE effectiveness for the respective mission is achieved as 60% in terms of fuel savings, corresponding to fuel savings of the order of 34% and with the potential to reduce the helicopter AUM by 94kg (3.76%), as highlighted in Fig. 15b.

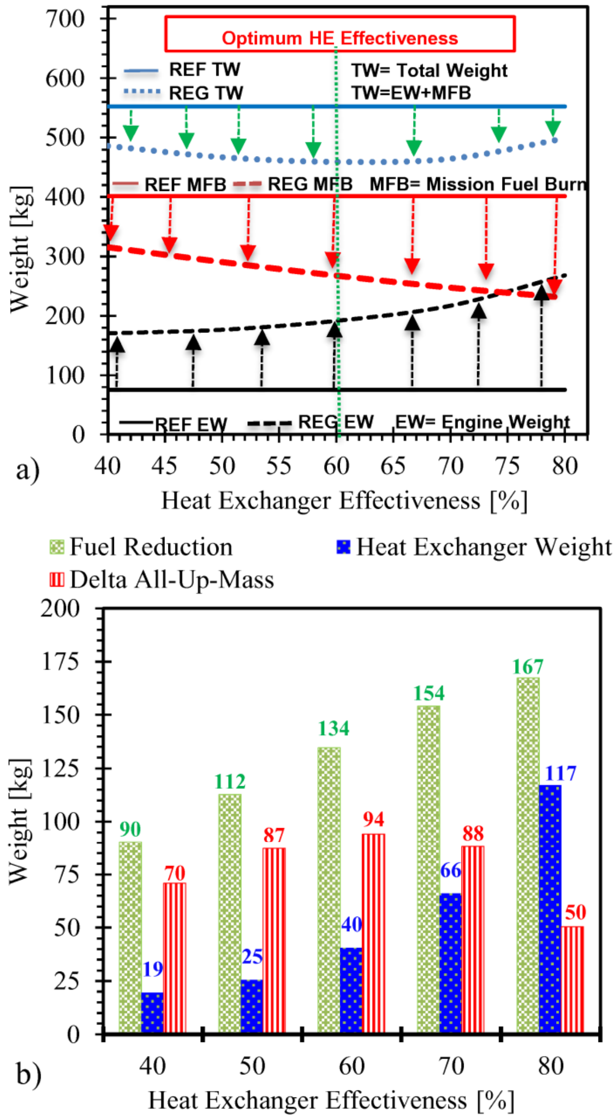


Figure 15: Heat exchanger ooptimization for conceptual regenerated helicopter, SAR Mission; (b) ΔAUM for conceptual regenerative helicopter

With regards to the associated emissions, a reduction of approx. 34% in mission CO_2 inventory is realized, supported by the improved thermal efficiency of the regenerated engine, shown in Fig. 16b. As elaborated in the earlier section of this paper, the inevitable increase in NO_x resulting from the regeneration process, results in around 181% increase in mission NO_x inventory, presented in Fig. 16a respectively.

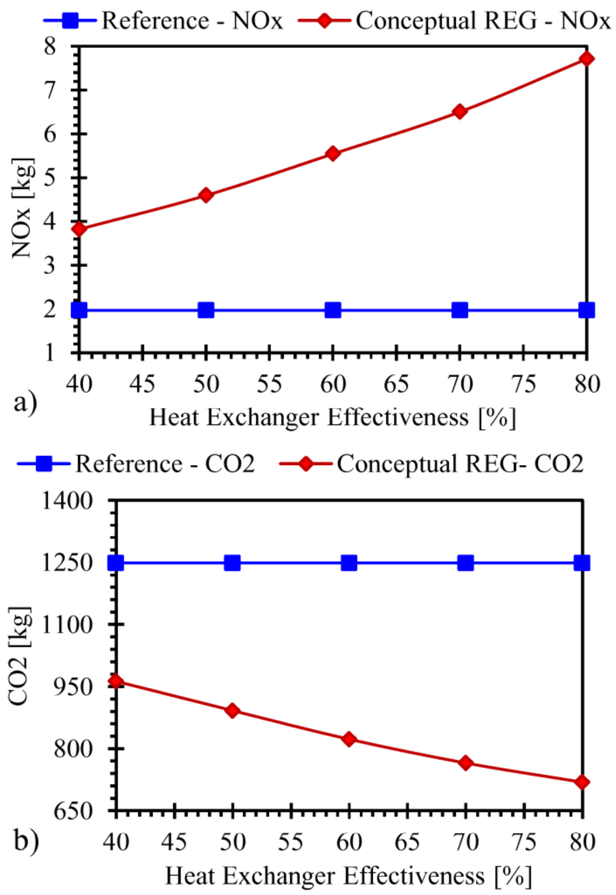


Figure 16: (a) Emitted CO_2, (b) Emitted NO_x for TEL, reference - simple cycle and regenerated helicopter, SAR Mission

4. CONCLUSIONS

A well-known and effective approach of regeneration is deployed to enhance the integrated performance of an existing simple cycle turboshaft helicopter. The methodology is based on incorporating a heat exchanger, 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 multidisciplinary simulation framework capable of computing the flight mechanics engine performance and gaseous emissions of any defined rotorcraft 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 light helicopter, modeled after the Eurocopter Bo105 configuration, simulated on representative mission scenarios.

It has been demonstrated through the design trade-off study that the effectiveness of the on board heat exchanger is a critical parameter in determining the level of acquired benefit from the employment of regeneration. It has also been established that, for a regenerative 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 heat exchanger. It has been demonstrated that the conceptual regenerative 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 case study that, the acquired sub-optimum regenerative engine design with a HE effectiveness of 60%, offers a 34% reduction in mission fuel burn, a 34% reduction in mission CO_2 inventory and results in almost two times higher mission NO_x inventory compared to reference simple cycle engine.

Finally, it has been emphasised that, while the regenerative 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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