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Evaluation of the Potential of Recuperator on a 300-kW Turboshaft Helicopter Engine

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Zusammenfassung

Die ständig zunehmenden Anforderungen im 21. Jhd. an die Entwicklung hocheffizienter, umweltfreundlicher Flugzeug-Triebwerke fordert den Einsatz von Rekuperatoren mit reduziertem Kraftstoffeinsatz, geringeren Emissionen und gedämpften Motorengeräuschen. Dies ist vor allem für Drehflügler-Triebwerke von Interesse, da diese im Einsatz mehr als 60% in Teillast betrieben werden. Dabei liegen ineffiziente spezifische Kraftstoffverbrauchseigenschaften vor. Die vorliegende Arbeit betreibt zuerst eine Aufarbeitung von vorherigen Entwicklungsarbeiten rekuperierender Helikopter-Turbowellenmotoren, gefolgt von der aktuellen Bedeutung der gesammelten Erfahrung und der aktuellen Forschung an drei Haupttypen von Wärmetauschern, nämlich rohrförmig, primäre Oberfläche und Platten-Rippen. Auf dieser Basis sollen Wärmetauscher für den potenziellen Einsatz als Drehflüglertriebwerksrekuperatoren mit aktuellen oder zukünftigen Technologien gefunden werden.

In der nächsten Phase dieser Arbeit wurde ein Prozess für die integrierte multidisziplinäre Simulation von Drehflüglern entwickelt, um umfassende Aussagen zur Systemleistung bei Verwendung von rohrförmigen Rekuperatoren oder Rekuperatoren mit primärer Oberfläche während des Einsatzes treffen zu können. Ein allgemeines Drehflügler-Modell wurde bezogen auf einen Mehrzweckhelikopter Bo105 betrieben mit zwei Allison 250-C20B Turbowellen-Motoren analysiert. Durch den Einsatz eines Rekuperators konnte eine wesentliche Reduktion des Kraftstoffverbrauchs erzielt werden. Die vorgeschlagene Methodik ist anschließend erweitert worden, um das Potenzial von Drehflüglern mit Rekuperator unter dem Hauptgesichtspunkt von hocheffizienten Rekuperatoren mit primärer Oberfläche bei Flugbedingungen von 0 – 250 km/h und 0 – 3000 m zu analysieren. Die gewonnenen Ergebnisse deuten darauf hin, dass eine hohe Effektivität unter bestimmten Einsatzbedingungen (besonders bei Einsätzen auf kurzen Distanzen) bei Berücksichtigung des gegebenen dramatischen Gewichtsanstiegs für den weiteren Rekuperatorentwurf nicht geeignet sein könnte.

Nach Optimierung mit mehreren Zielfunktionen mittels der Implementierung eines Genetischen Algorithmus (GA) wurde das Pareto Front Modell abgeleitet, um die verbundenen Zwischenabhängigkeiten und den Zielkonflikt zwischen dem Potenzial zur Kraftstoffeinsparung und der Gewichtsbelastung durch den Rekuperator zu erfassen. Vier optimale Entwurfslösungen wurden ausgewählt und für drei repräsentative

Helikoptereinsätze simuliert. Ein optimaler Kompromiss stellte sich für eine Rekuperator-Effizienz von 76,1% und einem Gewicht von 27,48 kg ein. Die vorgeschlagene Methodik kann also ein zeiteffizientes Werkzeug für die umfassende Betrachtung von Drehflüglerantriebssystemen in Verbindung mit potenziell geeigneten hocheffizienten Rekuperatoren hinsichtlich multidisziplinärem Entwurf und Optimierung darstellen.

Abstract

The increasingly demanding requirements for developing highly efficient, environmentally friendly aero-engines in the 21st century highlights the utilization of recuperators with reduced fuel burn, lower emissions and attenuated engine noise. This is particularly attractive for rotorcraft powerplants, as more than 60% of the mission time is spent at part load, which shows non-optimum specific fuel consumption (SFC) characteristics. The present work first conducts an elaborated investigation on previous development work of recuperated helicopter turboshaft engines, and followed by the relevance of accumulated experience, as well as recent research on three main kinds of heat exchanger candidates, i.e. tubular, primary surface and plate fin, it seeks to find heat exchangers potentially applicable to rotorcraft recuperators with technologies prevailing to date or in the near future.

In the next phase of this work, an integrated rotorcraft multidisciplinary simulation framework has been developed to comprehensively assess the system performance of the rotorcraft adopting tubular or primary surface recuperator at mission levels. A generic rotorcraft model is analyzed based on a typical multi-purpose utility helicopter Bo105 powered by two Allison 250-C20B turboshaft engines. A substantial amount of fuel burn reduction is realized with the adoption of recuperator. The proposed methodology is then further extended to evaluate the potential of recuperated rotorcraft with prime focus on highly effective primary surface recuperator under the flight condition of 0-250 km/h and 0-3000 m. The obtained results suggest that the selection of high value of effectiveness may not be suitable in certain cases (especially short range missions) for further recuperator design considering the inherited dramatic growth in weight penalty.

Through the execution of multi-objective genetic algorithm (GA) optimization, the Pareto front model is derived qualifying the associated interdependency and trade-off between the fuel saving potential and recuperator weight penalty. Four optimal design solutions are selected, and simulated for three representative helicopter missions. The optimum trade-off is attained for the employed recuperator effectiveness of 76.1% with the weight of 27.48 kg. The proposed methodology could be a cost-effective and computationally efficient tool for the comprehensive assessment of the rotorcraft powerplant system incorporating a potentially suitable, high performance recuperator, with regards to multidisciplinary design and optimization.

Contents

Nomenclature

Acronyms

CC	cross-corrugated
GA	Genetic Algorithm
HPT	high pressure turbine
NTU	number of transfer units
ISA	international standard atmosphere
LPT	low pressure turbine
MSL	mean sea level
MTOW	maximum takeoff weight
OTS	offshore transportation
PAT	passenger air taxi
PSR	primary surface recuperator
PSV	police surveillance
PR	pressure ratio
RC	recuperated cycle
SAR	search and rescue
SC	simple cycle
SFC	specific fuel consumption
SP	specific power
TIT	turbine inlet temperature

Symbols

A	rotor disc area or heat transfer area	[m^2]
A_c	flow cross section area	[m^2]
C^*	heat capacity ratio	[-]
C_{d0}	profile drag coefficient	[-]
$C_D S$	equivalent flat-plate area	[m^2]
c_p	specific heat	[J/(kg· K)]
D_h	hydraulic diameter	[m]
f	Fanning friction factor	[-]
G	gross mass	[kg]
G_{area}	area goodness factor	[-]
G_{vol}	volume goodness factor	[-]
H_i	internal height	[m]
j	Colburn factor	[-]
$L1$	width	[m]
$L2$	length	[m]
$L3$	height	[m]
m	mass flow rate	[kg/s]
ΔM	weight difference	[kg]
Nu	Nusselt number	[-]
p	pressure	[Pa]
P	power or corrugation pitch	[W] or [m]
Pr	Prandtl number	[-]
S	wetted surface	[m]
St	Stanton number	[-]
T	temperature	[K]
U	overall heat transfer coefficient	[-]
V	internal volume of the unitary cell	[m^3]

Greek Symbols

δ	wall thickness	[m]
θ	corrugation inclination angle	[°]
k	empirical correction factor	[-]
ρ	air density	[kg/m^3]

ρ_m	material density	[kg/m^3]
g	gravitational acceleration	[m/s^2]
σ	rotor solidity	[-]
μ	advance ratio or viscosity	[-] or [Pa· s]
ν	velocity	[m/s]
η	efficiency	[-]
λ	thermal conductivity	[W/(m· K)]
ε	effectiveness	[-]
β	surface compactness	[-]

Subscripts

avi	available
Aux	auxiliary system
ds	design
f	flight
h	flight altitude
i	induced
mec	mechanical
MR	main rotor
o	profile
p	parasitic
req	required
sys	system
t	total
tip	blade tip
TR	tail rotor

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1. Introduction

1.1 Background

During these years, considerable progress has been made in the fields of combustion, mechanical design, materials science and turbine components aerothermal improvement, etc. which provides appealing performance for propulsion gas turbines including turboshaft, turboprop, turbojet and turbofan [1-3]. However, after several decades of development, it proves to be increasingly difficult to exploit the improvement potential in the gas turbine systems merely on the basis of the simple thermodynamic cycle. Besides that, the aero-industry has faced significant challenges from the beginning of the 21st century, among which the most salient being the reduced emissions, improved SFC, less noise and lower life cycle cost [4]. Advisory Council for Aerospace Research in Europe (ACARE) suggested environmental targets for aero-engines, and based on the Clean Sky program, a helicopter is expected to achieve a 26% reduction in CO_2, a 65% cut in NO_x, a 15% decline in specific fuel consumption (SFC), and halve the perceived aircraft noise by 2020 compared to the year 2000 [5]. In addition to environmental concerns, fuel economy would also be of great importance for future aero engines development, taking the MD 500E helicopter as an example, fuel and lubricants account for 28.6% (109.29$) of the total direct operating cost, according to the estimated direct cost per hour in 2014 from MD Helicopters, Inc.[6]. As one of the most effective techniques to overcome these challenges, adopting high performance heat exchangers are of great significance to meet the growing demand for highly efficient, environmentally friendly aero-engines [7].

Turboshaft engines play a dominant role in helicopter propulsion, and they are adopted to drive the main transmission and rotor systems. Figure 1.1 shows the schematic illustration of a typical turboshaft engine and its common configuration. It presents a conventional Brayton cycle which includes compression, combustion and turbine expansion. Currently, turboshaft engines are normally of free power turbine configuration with a single spool or in some cases two spool gas generators. Pressure ratio is usually in the range 7 to 10, and turbine inlet temperature varies from about 1250 to 1450 K requiring turbine blade cooling [9]. Larger turbine inlet temperature and higher pressure ratio are expected for some medium and large turboshaft engines.

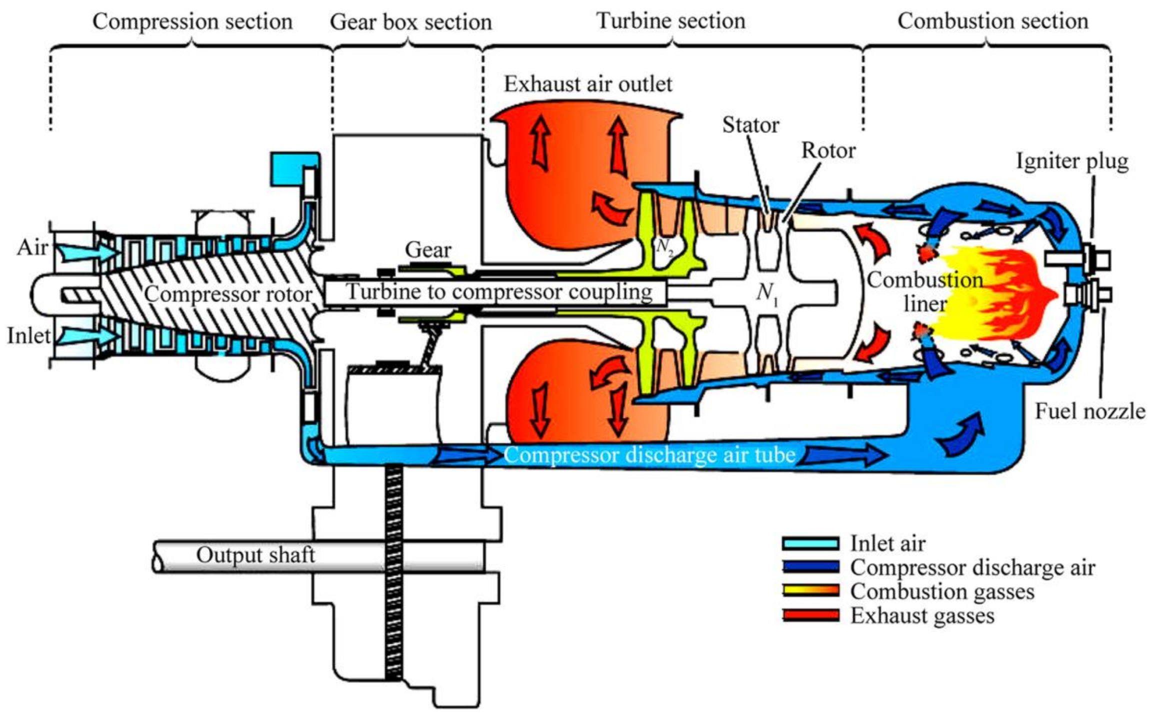


Figure 1.1: A schematic illustration of the turboshaft engine [8]

Out of safety considerations and certification issues, current helicopters are usually equipped with two or more engines. In case that accident happens and one engine fails, the others could still provide excess power to maintain the flight and perform a controlled landing. However as a matter of factor, during the majority of mission time (typically more than 60%) these engines are operating at partial load which shows non-optimum SFC characteristics.

Recuperator could significantly increase system efficiency, and the working principle is to utilize turbine exit exhaust gas to preheat compressor discharge air before it enters the combustion chamber, as a result, thus cutting fuel consumption and thereby reducing emissions (as given in Figure 1.2). Obviously, the temperature difference between the exhaust gas and compressed air plays a vital role in the theoretically achievable benefit of the recuperation process. The recuperator could only work effectively under the condition that the exhaust gas temperature exceeds the corresponding compressor outlet temperature. Small temperature difference, caused by too large pressure ratio, low turbine inlet temperature etc. would have a negative effective on it.

Recuperator has found good acceptance for many commercial gas turbine applications like stationary power generation, microturbines, etc. [11]. However, at present it is still primarily limited to land-based applications, and has not been widely deployed to gas turbines for rotorcraft powerplants. According to the early researches on the recuperated gas turbine aero-engines summarized by McDonald et al. [1,12], although there were numerous studies on what performance gains for aircrafts and helicopters could be realized by incorporating a recuperator, and some engines were even modified and tested to include a recuperator in 1960s and 1970s, which demonstrated the feasibility of recuperated operation, recuperators were not deemed attractive enough because of the significant performance promotion of simple-cycle gas turbines, low fuel cost and concerns about recuperator structural integrity at that era.

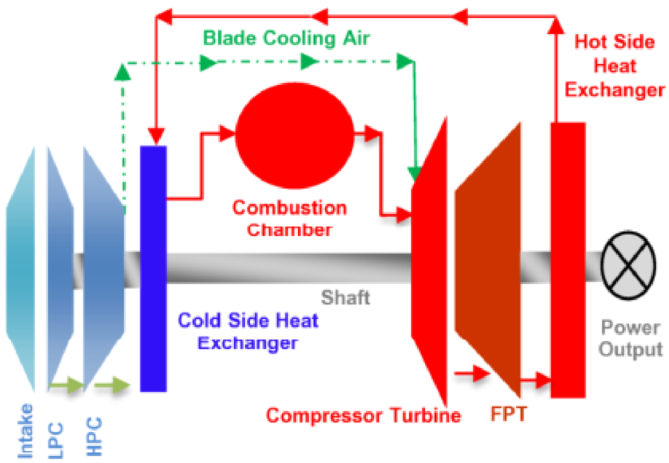


Figure 1.2: Schematic layout of a single-spool recuperated turboshaft engine [10]

The urgent socio-economic considerations, including strict emissions legislation, reduced fuel consumption requirement, etc., together with the unique needs for military application (increased range, lower noise, reduced infrared signature), will definitely have a profound influence on the design of next generation helicopter propulsion, and suggest more complex engine configurations. In the current years, advancements in high temperature heat exchangers with light weight, high effectiveness and improved reliability has started to emerge with the development of advanced materials and manufacturing technologies, highlighting its application in improving aero-engines performance without penalizing the operational capabilities of the rotorcraft powerplant [7,13,14].

1.2 Research objectives

The main objective of the present study is to develop a computationally efficient and cost-effective tool for the comprehensive assessment of recuperated rotorcraft powerplant systems in terms of operational performance under various flight condition as well as at mission levels. The methodology deployed within this work could essentially be regarded as an enabling technology to address the multidisciplinary design complexity and interdependencies arising from the incorporation of high performance recuperator.

1.3 Thesis outline

The strategy of this work is given as follows:

Chapter 1 presents general information about the research background, objectives and outline of this thesis.

In Chapter 2, it conducts an elaborated investigation on previous development work of recuperated helicopter turboshaft engines, and followed by the relevance of accumulated experience, as well as recent research on three main kinds of heat exchanger candidates, i.e. tubular, primary surface and plate fin, it seeks to find heat exchangers potentially applicable to rotorcraft recuperators with technologies prevailing to date or in the near future.

In Chapter 3, an integrated rotorcraft multidisciplinary simulation framework, which involves helicopter flight dynamics, engine performance, mission management and recuperator weight estimation etc., is proposed and developed for the comprehensive assessment of rotorcraft powerplant systems adopting tubular or primary surface recuperators at helicopter mission levels.

For the next phase of this study, in Chapter 4, the potential of helicopter turboshaft engines incorporating highly effective primary surface recuperators are evaluated under various flight conditions (0-250 km/h and 0-3000 m). The improved part-load performance against the reference non-recuperated cycle is also discussed, as well as the recuperator size and installation considerations.

In Chapter 5, the established multidisciplinary simulation framework is further extended through the employment of multi-objective genetic algorithm (GA) optimization for recuperator design. Obtained optimal recuperator design solutions are evaluated under typical mission scenarios. The overall approach and simulation methodology can be effectively extended and applied to conduct multidisciplinary design and optimization for recuperated rotorcraft powerplants.

2. High temperature heat exchangers for recuperated rotorcraft powerplants

With emphasis on recuperated helicopter turboshaft engines, in this work previous recuperator development activities are summarized. For completeness on this topic, focuses are mainly given on representative works that have at least led to engine design layout concepts, thus providing a comprehensive understanding in terms of fundamental principles (matrix design, flow arrangement and material selection) and operating characteristics (weight, volume, heat transfer and pressure loss). On the basis of the relevance of accumulated experience, recent development of three types of heat exchanger candidates, i.e. tubular, primary surface and plate fin are evaluated which could be potentially used in rotorcraft applications. Eventually, the material selection and manufacturing technology are also discussed in detail.

2.1 Development of recuperated turboshaft engine concepts

2.1.1 Previous development activities

Ever since 1960s, government and industrial vendors have investigated the performance improvement of aircrafts and helicopters by utilizing recuperators [15-21]. During that time, several modified recuperated engines were built and tested with emphasis on fuel consumption reduction and flight range promotion, demonstrating the feasibility of this technology strategy [16-18]. An engineering program was undertaken in 1965 to design and incorporate a recuperator for the Lycoming T53 engine, and according to the technical report [16], compared with the original simple cycle, the recuperated turboshaft engine was fabricated to provide a fuel savings of approximately 24% at an engine power rating of 75%. For the T53 engine, primary surface geometry has also been taken into consideration, however because of core leakage, it was decided to manufacture the recuperator with the more conventional tubular heat transfer surface for a two-pass cross-counterflow arrangement. The annular recuperator was installed at the turbine exhaust end as shown in Figure 2.1, depicting the engine design layout concepts and recuperator development experience from 1960 to 2000.

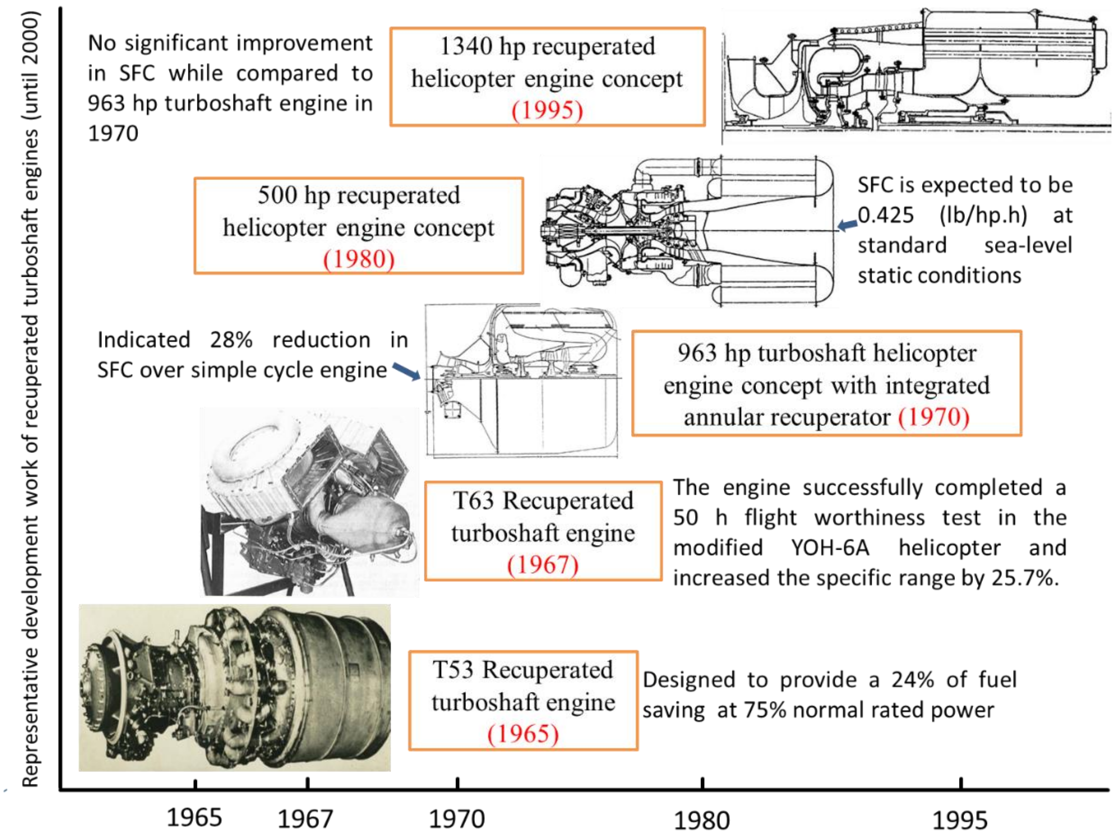


Figure 2.1: Previous exploration of recuperated helicopter turboshaft engines

An important accomplishment was realized in 1967 when a 50h flight test for a Light Observation YOH-6A helicopter, with the recuperated Allison T63 turboshaft engine as its sole source of propulsion was successfully performed. The recuperators were firmly attached to the engine exhaust duct using Marman clamps, and it also exhibited a two-pass cross-counterflow configuration with exhaust gas flowing outside the tubes and compressed air flowing single pass inside the tubes (see Figure 2.2 [17]). To the authors' knowledge, this would be the only manned flight test for the recuperated aircraft based on open literature sources in the 20th century. It was recognized from the program that the addition of a recuperator would reduce fuel burned significantly and has contributed to a remarkable 25.7% growth in the maximum range of the helicopter [18]. However, although the benefits of recuperated rotorcraft have been well identified, it was not deemed as appealing enough to deploy in large scale, primarily due to concerns on long-term structural integrity and reliability, together with the market forces (e.g. abundance of low-price fuel). In 1975 Young [22] presented an aero-engine paper entitled "The Heat Exchanger Cycle: Has its Time Come?", and obviously based on the state-of-the-art technology advancements at that time, the answer was clearly negative.

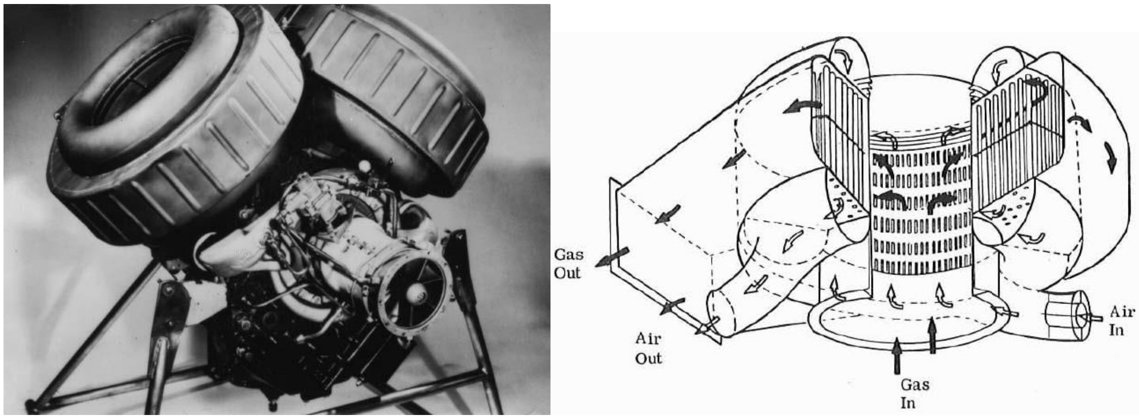


Figure 2.2: a). T63 engine with twin tubular "bolt-on" recuperator modules, b). Recuperator flow configuration [17]

Between about 1970 and 2000, along with the flight demonstration, there was desultory interest in recuperated helicopter investigation. Emphasis in this area includes system analysis and evaluation [23-32], component investigation (mainly heat exchanger) [33-39] and technical prospects [40-44]. Several recuperated turboshaft engine concepts were analyzed, and some of them even indicated specific engine design layout, but they were never built and tested, let alone deployed for helicopter service. It was revealed by these periodical analyses and performance evaluations of recuperated turboshaft engines that there was still no systematic incentive for major modifications of engine architecture considering the significant performance improvement of simple-cycle conventional engines. A reference engine design in the 1000 hp (745.7 kW) power class was established in 1970 for both recuperated and simple cycle variants, with the air flow rate of 5 lb/s (2.27 kg/s), pressure ratio of 9 and a turbine inlet temperature of 2300 F (1533 K). It provides a SFC of 0.365 lb/(hp.h) (namely, 0.222 kg/(kW.h)), and a bare engine specific weight of 4.75 hp/lb (i.e. 7.81 kW/kg, here accessories like gearbox, fuel pump, etc. are not included) respectively, at the selected recuperator effectiveness of 65% [23]. The annular recuperator of tubular construction acted as the structural backbone of the engine assembly by wrapping around the turbomachinery so as to provide compact lightweight engine packages, as given in Figure 2.1.

In 1980 a research program was undertaken to conduct a preliminary design and analysis of a 500 hp (372.3 kW) recuperated turboshaft engine [28]. Both plate-fin and tubular heat exchanger types were considered, and even though the cost would be higher, tubular type was selected from the viewpoint of configuration, installation and weight. The tubular recuperator mounted aft of the engine to receive the turbine exhaust gas directly. It was indicated that an engine configuration with a cycle pressure ratio of 10, a turbine inlet temperature of 2300 F (1533 K), and a recuperator effectiveness of 70% was most suitable for the 1980 environment. In 1987, projections were also made in Ref.[33] that recuperated turboshaft propulsion engines would become a reality before the end of this century considering the then current heat exchanger technology advancements. The development and deployment of such aero-engines, initially for defence systems, seems to be more likely a question to be resolved.

A reference reported in 1992 provided limited information about the AL-34-1 recuperated turboshaft engine in Russia, and the SFC of 0.348 lb/(hp.h) (i.e. 0.212 kg/(kW.h)) was achieved with a recuperator weight of 88 lb (40 kg) at altitude conditions [31]. A study conducted in 1995 investigated the recuperated cycle applied for a 1000 kW class turboshaft engine whose pressure ratio and maximum turbine inlet temperature were 8 and 1600 K [35]. The geometry in the recuperator was designed for cross flow type with exhaust gas crossing three times the tube bundle while compressed air makes a double pass inside the tubes, and Figure 2.3 shows the cross section of the recuperator.

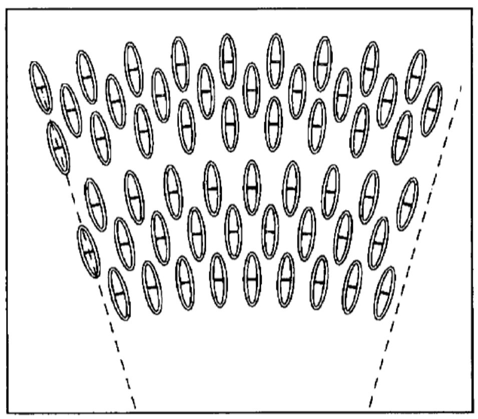


Figure 2.3: Recuperator tube matrix layout [35]

Based on the information gleaned by McDonald [1,12] as well as various program reports [16-18,23,28,35], Table 2.1 summaries primary features of representative recuperated helicopter turboshaft engines studied in the past. Rather than recuperated industrial gas turbines which could normally have satisfying effectiveness values of 90%, by the very nature of helicopter application, these researches generally focused on heat exchangers with a relatively low value of effectiveness at approximately 70% as a result of strict weight limitation and spatial constraint. Since light weight is a major requirement for propulsion gas turbines, tubular type is selected in the previous work which represents the best solution, and this would be discussed in detail in a later section. For recuperator applications, normally compressed air and exhaust gas share the similar values of mass flow rate and specific heat, and therefore the heat capacity rate ratio ${}^{C_{min}}/_{C_{max}}$ between them is approximately equal to 1. There are a variety of possible flow arrangements for heat exchanger, among which counter flow scheme offers the best heat transfer approach with the superior temperature gradient in the matrix as shown in Figure 2.4. However, considering practical integration and layout requirements, in most cases the cross-counterflow arrangement is recognized as a better candidate. Apparently, as can be observed in Figure 2.4, it is difficult to achieve a high effectiveness of 75% or more for the two-pass cross counterflow configuration with one fluid mixed and the other unmixed. Increasing the number of cross-flow passes could approach the flow configuration to the pure counterflow, thus obtaining a higher effectiveness, however, it would inevitably lead to significantly larger recuperator volume penalty as well. From this viewpoint, two-pass arrangement is accepted as a good choice with compatible aero-engine gas flow paths.

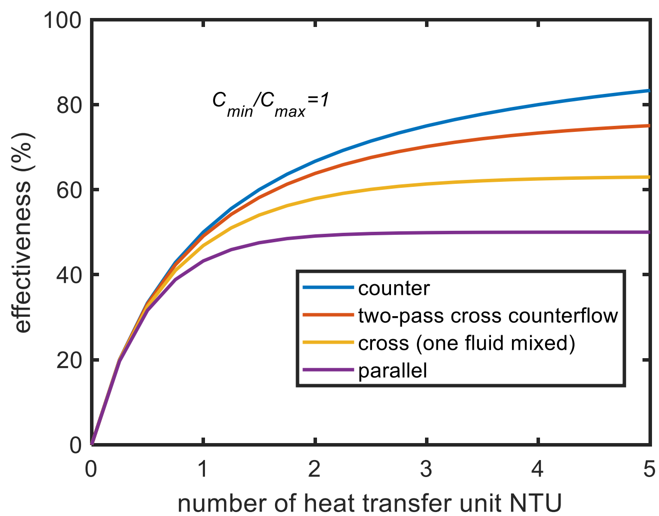


Figure 2.4: Comparison of various flow arrangements

From the 21st century, it is well concluded that meeting increasingly stricter future economic and environmental requirements will for certain have a significant impact on aero-engines design and operation, which has also contributed to the enormous interest in developing intercooled recuperated aero-engines (IRA). While incorporating an intercooler into the recuperated helicopter, the advantages of intercooling would be offset under static conditions due to the lack of ram air cooling flow, which may necessitate a more complicated or even impractical engine layout. European proposed leading-edge engine technologies within specific framework program (FP) for the vision of 2020. The EEFEA (Efficient and Environmentally Friendly Aero-Engines, 5th European FP) [45, 46], and the subsequent NEWAC (New Aero Engine Core Concepts, 6th European FP)

[47] have been aimed at developing a future environmentally friendly IRA aero-engine. Even though the investigated subject is a turbofan engine, rather than a turboshaft, the adopted recuperator is still worth mentioning. The recuperator is designed and constructed by MTU Aero engines GmbH in Germany, and presented in Ref.[48-52]. Both recuperator wind-tunnel experiment and finite element analysis were conducted for this two-pass cross-counterflow profile tube recuperator as displayed in Figure 2.5 [49], and the results showed good structural integrity, high reliability and long life potential. However, a very extensive development and testing effort, including overall engine performance experiment, flight worthiness test, must be undertaken before its eventual deployment.

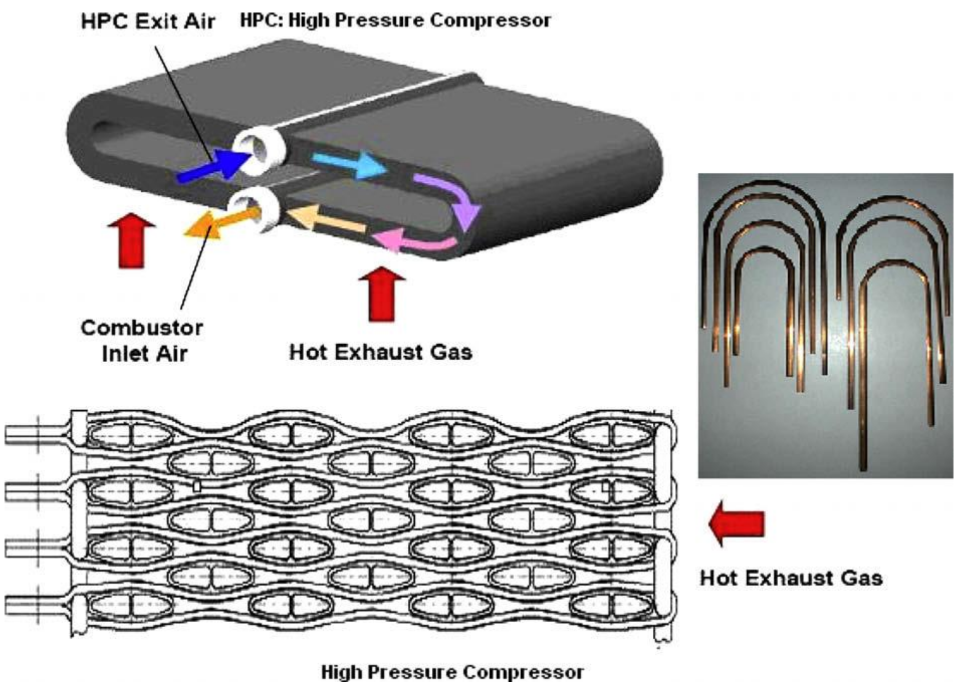


Figure 2.5: MTU recuperator and the U-shaped elliptic profiled tubes [49]

Even though the benefits of recuperation are well recognized, it would also have some disadvantages under specified conditions. One may be the reduction of output power of such recuperated engines, partly caused by the additional pressure drop of the compressed air during passing through the recuperator, in comparison to non-recuperated engines. Such power reduction needs great care in aircraft and helicopter applications where maximum power is often desired and/or necessary during take-off and climb to altitude. This may involve the retrofit of turboshaft engine (such as the modification of the engine compression system), or a bypass valve may be controlled to selectively switch between recuperated and non-recuperated mode based on engine operating conditions [20, 28, 53].

Another potential disadvantage is the additional bulk and weight of recuperator. In most cases, turbine engines provide high power to weight ratio over reciprocating engines of the same power rating, therefore they have found widely acceptance in aircraft applications. The incorporation of a recuperator would to some extend weaken this strength. The beneficial fuel saving may not compensate the additional recuperator weight. The detailed trade-off evaluation were conducted at mission level in Ref.[54-56], and it was suggested that the application of recuperator possesses great potential, especially for long duration and large range mission, but it may not be necessarily suitable for all types of helicopter missions.

It is interesting to note that Frontline Aerospace, Inc. applied a US patent for the MicroFire™ gas turbine recuperator suitable for light aircraft and helicopters in 2009 [53], and this cross flow design utilizes a plurality of stacked foils to form microchannels, aimed at having an effectiveness in excess of 60% or even 80% while maintaining a small pressure drop of around 3-5%. Accordingly, Figure 2.6 shows the layout of the recuperated helicopter, and an exploded view of the recuperator. By creating turbulent flow, pin fins are utilized within the flow paths to further enhance heat transfer between exhaust gas micro-channels and the compressed air micro-channels.

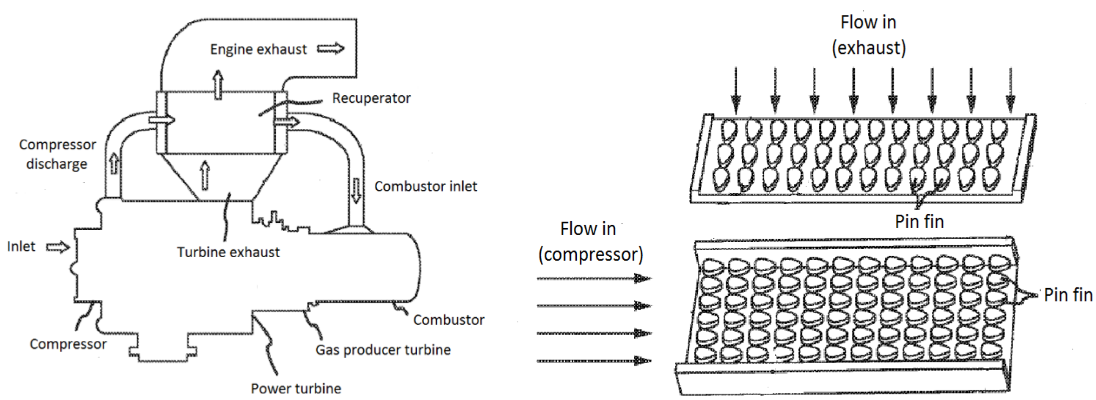


Figure 2.6: a). Layout of the recuperated helicopter, b). An exploded view of the recuperator [53]

Besides the most commonly investigated recuperator with stationary, fixed-boundary matrix, alternatively, as another form of heat exchanger, a regenerator uses some type of thermal storage material that moves between the cold and hot streams periodically to transfer heat. A series of valuable development and testing efforts have been undertaken by Lombardo et al. in the early 1960s using liquid mental as heat transport fluid for applications to aircraft turboshaft engines incorporating regenerators, which demonstrates the feasibility and performance of such a system in aircraft powerplants [57-60]. A number of regenerative cycles for high efficiency gas turbines have been reported in Ref.[61]. However, the negative characteristics of the regenerator in terms of durability and seal leakage have continuously impeded its widespread application. The reduction of seal leakage below about 7% has been achieved through the ongoing technological development for rotary ceramic disk regenerators, but factors including complex integration with the rotating machinery, along with the seal system and drive mechanism, aggravate the cost concerns [13]. With magnesium alloy being selected as material, a regenerator was designed and assessed by the CFD tool CFX in 2008 for a turboshaft helicopter engine, and the obtained results indicated that the thermal efficiency could be improved by 5% with 23% reduction in terms of SFC [62].

Reference engine	Lycoming T53	Allison T63	conceptual design	conceptual design	conceptual design
Year	1965	1967	1970	1980	1995
Engine power (hp)	1100	280	963	500	1340
Air flow rate (lb/s)	10.7	2.8	5	3.26	4.68
Pressure ratiao	6.3	6.2	9	10	8
Turbine inlet temp. (F)	1720	1770	2300	2300	2420
SFC (lb/hp.h)	0.52	0.587	0.365	0.425	0.39
Sp. weight (hp/lb)	1.36	1.51	4.75 (for a bare engine)	1.67	-
Effectiveness	66%	60%	65%	70%	70%
Total pressure loss (%)	7	9.86	6	10	10
Flow arrangement	air makes two passes through the recuperator tubes, while gas make a single pass outside tubes	air flows single pass inside the tubes, and gas flows two-pass outside the tubes	air flows single pass inside tubes, and gas flows two-pass across tube bundle	air makes two transverse passes inside the tubes, while gas flows radially outward, making a single pass through the recuperator core	air flows two-pass inside the tubes, while gas flows three-pass across the tube bundle
Matrix construction	brazed tubular	brazed tubular	brazed tubular	brazed tubular	-
Tube type	plain tube	dimpled tube	dimpled tube	ring dimpled	profile tube
Tube number	1920	5490	4800	2070	576
Matrix inner diameter (in.)	17	9.3	16	8.75	-
Matrix outer diameter (in.)	32	14.5	21	15.23	-
Tube diameter (in.)	0.25	0.1	0.1	0.1	-
Tube length(in.)	40	9.8	16.2	9.3	-
Tube wall thickness (in.)	0.007	0.004	0.004	0.007	-
Recuperator weight (lb)	224	51	76.6	56	-
Recuperator material	347 SS	347 SS	Inconel 625	Inconel 625	Ceramic

Table 2.1: Primary features of previous investigated recuperated helicopter turboshaft engines [1,12]

2.1.2 Performance projection for turboshaft engines

Over the past several decades, significant advancement has been achieved in turboshaft engine performance over a wide power range, and Figure 2.7 shows the SFC tendency for different technology strategies and engineering levels. It represents a follow-on to work published by McDonald in 2008 [63] with updated information for the curve of state-of-the-art technology on the basis of numerous operating engine data collected in Ref.[64], and basically in the helicopter market, helicopters could be divided into light singles (<500 kW), light twins (500-1500 kW), intermediate (1500-4000 kW), medium (4000-7000 kW) and heavy-class (>7000 kW) by their shaft power [65,66]. Besides that, light singles and twins class represent more than 60% of the civil market. Higher engine shaft power generally represents larger geometric dimensions, which typically contributes to better component efficiencies for turbine, compressor, combustor etc. Therefore, the SFC shows a consistent decrease tendency with engine shaft power as depicted in Figure 2.7, though these two parameters are indirectly relevant to each other. According to these engine data, Rolls-Royce RTM 322 series show the best reported case with the lowest SFC value of 0.424 lb/(hp.h) (i.e. 0.258 kg/(kW.h)) in 2400-2600 hp (1790-1939 kW) engine power. McDonald also made an estimation for the SFC band of recuperated turboshaft engines, based on scatter of data collected from previous introduced cases of recuperated engines, and then extrapolate to higher power levels. He estimated the performance of recuperated turboshaft engine for service in 2010-2015 with an appealing SFC of 0.34 lb/(hp.h) (i.e. 0.207 kg/(kW.h)), but this is just tentative, and no such engine has been reported.

Apparently, despite the significant improvement in simple cycle engines over these decades, it reveals a tremendous gap in terms of SFC when compared to recuperated turboshaft engines. As can be noted, it would be a formidable challenge to develop a recuperated turboshaft for the engine power range below 1500 hp (1118.5 kW), achieving an ambitious SFC of less than 0.3 lb/(hp.h) (i.e. 0.182 kg/(kW.h)). The continuous performance promotion of simple-cycle turboshaft engines, especially in the era of low fuel price, together with the weight, volume and reliability concerns for high temperature heat exchangers, which have been improving in recent years, have delayed the further application of recuperated engines for helicopter propulsion.

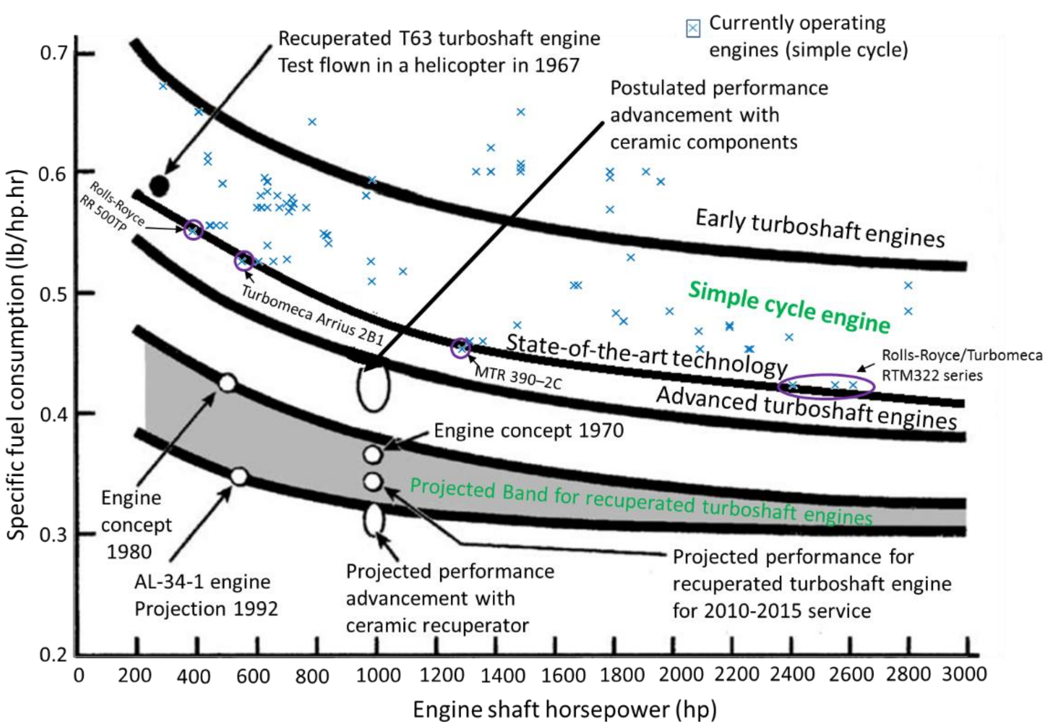


Figure 2.7: Simple cycle and recuperated turboshaft engine performance projection [57]

In addition to the identified benefits of fuel economy, the use of a recuperator also contributes to a lower noise level. According to the 50 h flight worthiness test for the recuperated T63 engine, a noise level measurement revealed that the noise would reduce 1-3 decibels in contrast to the same type of simple-cycle engine operated in the identical helicopter. With regards to military applications, another merit worth mentioning while introducing a recuperator is the significantly decreased infrared signatures attained by the reduction of exhaust plume temperature. In particular, the addition of the recuperator lowered the exhaust temperature by more than 200 K for the Allison 250 engine, as stated in Ref.[55].

2.2 Types of candidate recuperators

Recuperators have been widely used and are recognized as necessary to achieve high thermal efficiency in micro gas turbine system for distributed power generation. However according to the early development work and subsequent studies, only single prototype was build and tested, but not deployed for rotorcraft applications partly due to early heat exchanger impediments, such as thermohydraulic performance (pressure drop, heat transfer rate), structural integrity and reliability, weight and volume consideration, as well as the lack of market forces (e.g. simple-cycle engine performance improvement, abundance of low-cost fuel). Currently, there is a renewed interest in adopting recuperators to meet the requirement for highly efficient, environmentally friendly aero-engines in the context of the increasingly stringent emissions legislation and serious energy challenge. In this section, promising high temperature heat exchanger candidates embodying on-going technology advancements are evaluated for the sake of finding recuperators potentially applicable to aeroengines, thus enhancing the integrated performance and operational capabilities of rotorcraft powerplants. Based on the heat transfer surface geometry, heat exchangers have been used in the gas turbine systems acting as recuperators could be representatively classified into three different types, i.e., plate-fin, primary surface and tubular.

2.2.1 Plate-fin geometry

Plate-fin heat exchangers mainly consist of a series of fin surfaces together with flat separators knows as parting sheets. The main attribute of plate-fin surface is that the introduced fins work as secondary heat transfer surface and in the meanwhile provide mechanical support against internal pressure differentials between layers. The plate-fin type has been widely used in decades for a range of gas turbine applications [67-70], and the manufacturing technologies are quite mature. Various fin designs have been developed including plain, offset strip, wavy etc., and plenty of flow and heat transfer characteristics data regarding these fin channels were reported on the basis of experimental work [71] which provide a solid foundation for the recuperator design. However there are some significant limitations for plate-fin designs including limited material flexibility, long braze cycle, complex assembly and high capital cost etc. [72]. Most importantly, the bulky weight of matrix has essentially eliminated them for further consideration in recuperated helicopter turboshaft engines.

2.2.2 Primary-surface geometry

The primary surface recuperator comprises corrugated thin sheets stacked together with gas (hot) stream and air (cold) stream flowing through alternate layers, and the main characteristic of this kind of construction is that heat transfer takes place directly through these thin plates without secondary surface fin efficiency effects. With regards to tightness, sealing between cold/hot stream passages could be accomplished by welding rather than the time consuming high-temperature furnace brazing operation required for plate-fin types. The primary surface recuperator is suitable for relatively low pressure (LP) ratio engine applications, like many helicopter turboshafts engines. In addition, it is not feasible to incorporate this type of recuperator into high pressure (HP) ratio engines due to the lack of supporting structural elements between flow passages. Fabricated in cube-shaped or annular configurations, several applications of primary surface recuperators in gas turbine systems have been reported previously [73-76], which give good performance and demonstrate a high degree of structural integrity. Furthermore, the manufacturing of primary surface recuperators is amenable to high-volume manufacturing processes, which leads to lower cost. For these reasons, it would be therefore a promising candidate for further consideration.

Produced by pressing, stamping or folding of thin metal sheets, a primary surface heat exchanger has different patterns including cross-corrugated (CC) [77, 78], cross-undulated (CU) [79] and cross-wavy (CW) [80, 81], as shown in Figure 2.8. Besides the most commonly used sinusoidal profiles, the corrugation profiles would also be isosceles triangular, trapezoidal, rectangular, and elliptic etc.. Zhang and Che [83] conducted a numerical analysis to investigate the influence of corrugation profiles on pressure drop and heat transfer performance of CC plates. It was found that theoretically the optimal structures were obtained for smooth corrugation shapes with small inclination angles. Utriainen and Sundén [84] made a comparison for the CC, CU and CW surfaces in terms of thermohydraulic performance, and the results revealed that CC surface showed the best potential for utilization in compact recuperators of the future with a relatively small volume and weight of the heat transfer matrix.

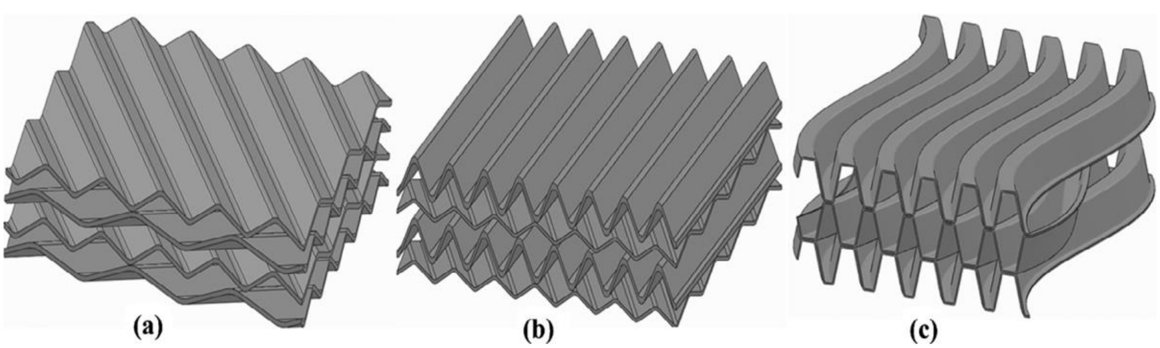


Figure 2.8: Traditional primary surface geometries: a). cross corrugated (CC) surface, b). corrugated undulated (CU) surface, c). cross wavy (CW) surface [82]

Recently, unlike the traditional periodic profiles with simple geometry construction, some novel primary surfaces having more complex 3D CC geometries are proposed for aero-engine applications [85-90]. Specifically, Doo et al.[85, 86] developed three modified primary surfaces based on the conventional sinusoidal corrugation, i.e. anti-phase secondary corrugation, in-phase secondary corrugation and full-wave rectified trough corrugation, as shown in Figure 2.9 (a-c). The obtained three dimensional numerical simulation results indicated that, in comparison with the conventional sinusoidal corrugation, a pressure drop reduction of approximately -15% was estimated for the antiphase and full wave rectified secondary corrugation models without big changes to the predicted heat transfer capacity.

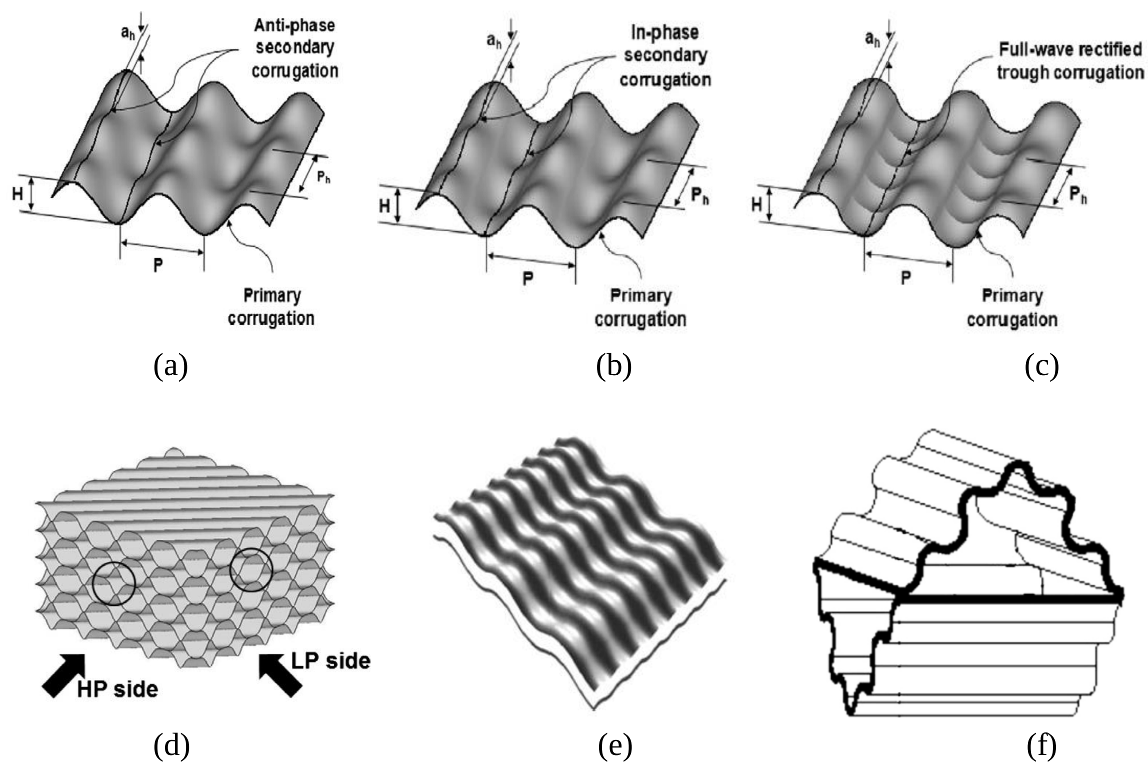


Figure 2.9: Configurations of modified primary surfaces with: a). anti-phase secondary corrugation [85], b). in-phase secondary corrugation [85], c). full-wave rectified trough corrugation [85], d). asymmetric profile [87], e). double-wave surface [89] and f). corrugations [90]

Considering the different operating pressure and pressure drop requirements on the hot and cold sides, Kim et al.[87] investigated the aerothermal performance of CC primary surface heat exchanger having asymmetric cross-sectional profiles, as shown in Figure 2.9 (d). Based on the calculation results, it is observed that the asymmetric profile can balance the pressure drops on both sides with reduced weight and volume of heat exchanger matrix, though this comes with a slight loss of effectiveness. Lee et al.[88] conducted a follow-on work and tested the above-mentioned anti-phase secondary corrugation and asymmetric profile using a Transient Liquid Crystal (TLC) heat transfer measurement technique. It is concluded that to minimize the weight of the heat exchangers in aero-engine application, the asymmetric geometries are more favorable with appealing values of area and volume goodness factors. Kim and Baik et al.[89] performed an experimental study on a cross-flow air-cooled heat exchangers with newly double-wave CC primary surface, as depicted in Figure 2.9 (e). From the tests, double-wave prototype heat exchanger shows approximately 50% enhanced heat transfer performance at the cost of 30% additional pressure drop while compared to single-wave structure. Liu et al.[90] analyzed fluid flow and heat transfer characteristics of microchannel in a CC primary surface recuperators with corrugations, as shown in Figure 2.9 (f). According to the obtained CFD calculation results, the heat transfer performance in surface with corrugation would increase 10% in contrast to that without corrugation.

2.2.3 Tubular geometry

Tubular recuperators are made up of numerous tubes within an outer shell, and they have favorable pressure containing capability. According to the early development activities in the 1960-1970 time frame and subsequent intermittent researches by the end of 20th century, tubular type was normally considered as the first choice for recuperated aero-turboshaft applications, primarily due to its high reliability based on technologies prevailing in that era, as well as the paramount requirement for light weight by the very nature of aero-engine applications. In order to develop lightweight tubular recuperators, small tube diameters and compact geometries are utilized which necessitates brazing the assembly together [91]. It could be essentially concluded that technology has not advanced much in dimpled tube recuperator technology which would contribute to significant reduction in recuperator size and weight, while comparing the initially proposed recuperated T63 turboshaft engine in 1967 with the 500 hp (372.3 kW) recuperated turboshaft engine concept in 1980. Highly compact tubular heat exchangers with tube diameters as small as 1 mm were fabricated in early 1990s with automated manufacturing processes [92], and the high cost and fabrication complexity limited their use for most applications.

Compared to rectangular cross sectional geometry, a circular tube matrix has typically smaller surface area for a given flow area with lower heat transfer coefficient. Therefore focus is given on using oval tubes to obviate these performance disadvantages. Previous studies indicated that profile tubes (also known as oval tubes) arranged in bundles showed superior fluid flow and heat transfer characteristics, and therefore adopted in early exploration of recuperated helicopter turboshaft engines [23,28,35]. A particularly interesting example is the aforementioned two-pass cross-counterflow recuperator pioneered by MTU Aero Engines. The recuperator matrix consists of numerous rows of profile tubes, and the profile tubes (see Figure 2.10) are folded from sheet metal and welded at their mating faces, subsequently, these profile tubes are bent into the different U-shapes. The recuperator is basically made of Alloy 625 except the wire-spacing and cushion wire-netting where Inconel 600 material is used [48]. This type of construction showed the high life potential in a severe thermal cyclic environment in terms of low-cycle fatigue, creep and vibration.

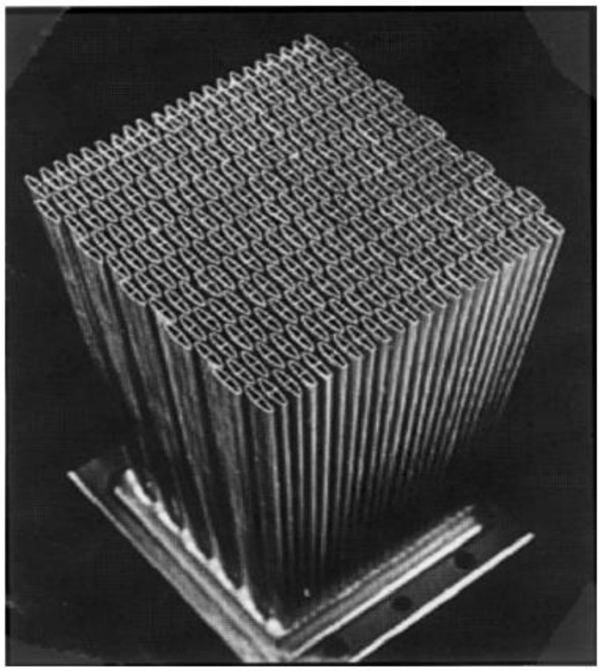


Figure 2.10: MTU profile tube recuperator module [93]

2.3 Comparison of recuperators

Plate-fin and tubular recuperators would withstand quite high pressure operating conditions, as they can additionally employ the fins or baffles as supportive elements [94]. With regards to a primary surface recuperator, though multiple contact points between plates contribute to high compressive strength and structural stability, the high pressure passages may bulge into the nearby low pressure passages when being exposed to high-temperature creep conditions. This is particularly acute for large ICR turbofan engines where the internal pressure difference in the recuperator could be as large as 40 atmospheres [12]. Plate-fin and primary surface recuperators have the advantage of being able to achieve fairly high effectiveness, however they are difficult to assemble due to the large number of plates. Besides that, highly stressed welding or brazing operations for the sake of sealing would bring about the risks of leakage or failure. Because of the bulky weight of plate-fin recuperators, they are excluded from recuperated helicopter propulsion. Ward et al. [95] pointed out that to meet the given thermal duty, the needed unit volume for plate-fin and tubular recuperators are respectively 2.8 and 11.8 times that of primary surface types.

The required recuperator operating characteristics for aero-turboshaft engines are: high mass flow rate, large heat transfer effectiveness, moderate pressure containing capability, high temperature resistance, and small pressure drop. Additional important performance requirements include light weight, compact size and high reliability. Since the additional weight of the recuperator could act as a direct penalty in the overall performance of the rotorcraft and therefore should be strictly controlled, based on previous researches, in the past only tubular recuperators were deployed where moderate loss of heat transfer effectiveness was tolerated, and they exhibited a relatively low effectiveness of 60-70%.

The current evolution tendency of heat transfer enhancement technology is towards smaller hydraulic diameters, thus increasing compactness [94]. Mehendale et al. [96] reviewed the fluid flow and heat transfer characteristics in channels with hydraulic diameters in the range of 1 um to 6 mm. Utriainen et al. [97] compared the thermal and hydraulic performance of various primary surface recuperators (CC, CW, CU configurations), and the hydraulic diameter is chosen to be as small as 1.54 mm. They all show superior performance when compared to the available examples of operating recuperators, and their volumes are approximately 30% less than expectation based on the portrayal of data collected from actual cases. The limits are, flow maldistribution, longitudinal conduction effects and fouling when used as a recuperator for heat transfer between exhaust gas and compressed air in the gas turbine system. Doo et al. [98] conducted a quantitative assessment using CFD simulation to study the longitudinal heat conduction effect on the traditional CC primary surface heat exchanger. A maximum performance degradation of 8.4% is predicted in their numerical studies.

Technology advancements have been made in recent years in the field of high temperature heat exchanger and new surface geometries have emerged, especially for primary surface types. With proven structural integrity, compact tubular recuperator with small tube diameters (or even micro-channels), and novel primary surface recuperator may be the appropriate choices for future recuperated rotorcraft propulsion development, on the condition that moderate fabrication cost is expected when manufactured in large production quantities.

2.4 Material selection and manufacturing technology

Normally due to cost considerations, most recuperators utilize existing metallic materials, 347 stainless steel (347 SS) in particular, and Inconel 625 for higher temperature limitation (as also presented in Table 2.2). In order to meet the projected targets for environmentally friendly future aero-engines, the potential of novel materials particularly ceramic recuperators in the gas turbine systems is well recognized. The operating temperature of recuperators is essentially limited by the resistance of the material to corrosion, oxidation and creep deformation. The severe thermal cycling environment (especially during take-off, landing) inherent to aero-engines would be posed as a major threat for the long-term integrity (leak-tightness) and reliability of recuperators.

Oak Ridge National Laboratory (ORNL) has made a continuous effort to evaluate candidate alloys, with primary focus on microturbine market [99-103]. Aquaro and Pieve [104] also provide an overview of metallic recuperators for high temperature requirements, as well as similar work done by McDonald [93] and Matthews et al.[105,106]. Based on their research, several commonly considered candidate metallic recuperator materials are summarized in Table 2.2 in terms of material cost (using 347 SS as a baseline), maximal metal temperature and density. According to laboratory testing, alloys with better creep-rupture resistance include Haynes 120, Haynes 230 and modified Alloy 803. Besides that, Haynes 214 and Alloy 625 exhibited much better creep strength. 347 SS is widely used in recuperator industry with a fairly low material cost, but it has a temperature limit of 675 ℃ (948 K) due to the accelerated corrosion by water vapor contained in the exhaust gas. For higher temperature service, super alloys with a larger nickel content are of interest. Alloy 625 and Haynes 120 show excellent corrosion resistance in foil form. Alloy 625 would be the very high performance alternative for use at temperature up to 800 ℃ (1073 K), and has the most cost-effective improvements contrast to 347 SS, though at a material cost factor of 4-5. Besides the extensively demonstrated recuperator materials 347 SS and Alloy 625, with respect to chemical composition and cost, modified Alloy 803 and Haynes 120 could extend their application to about 750 ℃ (1023 K), having approximately twice the creep resistance of 347 SS with a reasonable cost of 3-3.5 times. Therefore, they are recognized as possibly the best alternatives to 347 SS for higher temperature. Even though Haynes 230 and 214 possess much larger temperature capability for using to 850 ℃ (1123 K) or even higher, the substantially greater material cost essentially eliminates their widespread application in recuperator industry.

Since light weight is a key recuperator requirement for aero-engine application, except for creep strength and corrosion resistance, density is another identified factor for consideration during material screening and selection. As presented in Table 2.2, the densities of these metallic materials are essentially in the range of 7.85-8.43 g/cm^3, except for Haynes 230 (8.96 g/cm^3) and oxide dispersion strengthened (ODS) alloy PM 2000 (7.16 g/cm^3). ODS PM 2000 have potential use for temperatures where otherwise ceramic materials would have to be taken into consideration [107]. The interesting bi-metallic approach is also suggested, where costly super alloy is only adopted in the hot end of the recuperator, and the rest is fabricated by 347 SS. The samples of thin-foil austenitic 347 SS (77%) and Alloy 625 (23%) were laser welded together by Toyo Radiator Company in Japan which showed satisfactory welded joint with no cracks, voids or obvious defects. The potential material cost savings were expected to be over 60% compared with an all Alloy 625 recuperator matrix [93].

	347 SS	Alloy 803	Haynes 120	Alloy 625	Haynes 230	Haynes 214	ODS PM 2000	Bi-metallic
material cost factor*	1	3	3.5	4-5	7	9	10	1.92
maximal temperature (°C)	675	750	750	800	850	900	1050-1150	-
density (g/cm^3)	7.96	7.85	8.07	8.43	8.96	8.05	7.16	-

Table 2.2: Comparison of high temperature metallic recuperator materials

In comparison with metallic recuperators, ceramic recuperators show superior performances in term of high temperature mechanical properties and oxidation resistance. Another significant performance advantage is that the fairly low density of ceramic materials (typically around 3 g/cm^3) would considerably reduce the recuperator matrix weight by more than 50% relative to metallic counterparts. Ceramic recuperators have been fabricated and tested over years [108-111], however they appear to be still in the infant stage with no reported ceramic recuperated gas turbine widely used for commercial operation as a result of their excessively high cost. Fabricated by laminated object manufacturing methods, a compact silicon carbide micro-channel recuperator for high temperature microturbine applications was developed and tested by Ceramatec Inc [112]. Plates are the primary building blocks of the recuperator and include internal features for gas manifolding and macro-features to be integrated into to gas headers which provide a counterflow configuration for fluids. These basic plate elements are stacked to form the recuperator matrix as shown in Figure 2.11.

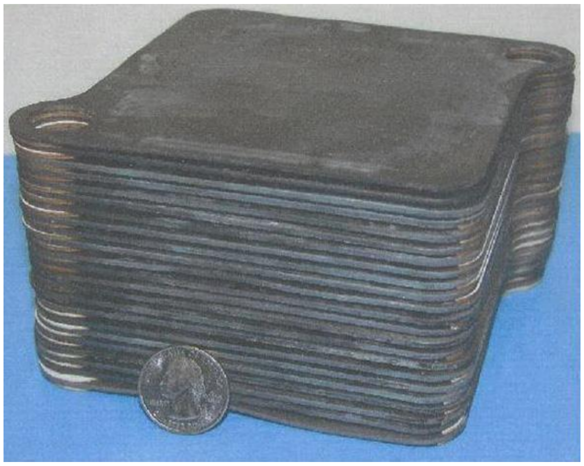


Figure 2.11: Ceramic microchannel recuperator matrix from Cermatec Inc [113]

A ceramic 7.5 kW microturbine demonstrator concept has been presented in Ref.[113] which involves the coupling of a ceramic radial flow turbine, a ceramic combustor, and a compact ceramic recuperator. Vick et al. [114] designed a 3 kW recuperated turboshaft engine in 2009 for small unmanned air vehicle (UAV) propulsion. The annular ceramic recuperator has a counter flow configuration, as shown in Figure 2.12. Exhaust gas enters the recuperator flowing in the axial direction. It then goes through separated channels in the radial direction, and is subsequently collected in integrally-formed circular tubes at the periphery. The finite volume model predicted a thermal effectiveness in the 84-87% range at a specific weight of 44 kg per kg/s of airflow. A prototype was tested at 675 ℃ (948 K) exhaust inlet temperature. It did not crack or leak, and the performance roughly matched analytical predictions [115]. They also summarized the fabrication method as: laser-cutting thin sheets of tape-cast material into complex patterns, and then laminating them together into stacks, eventually sintering at high temperature [116]. This work would be likely a good starting point, and if further flight test could be conducted after the recuperated turboshaft engine is materialized in terms of hardware, the operating experience from this would provide a technology base for future helicopter propulsion with a ceramic recuperator.

Aimed at reducing the NOx emissions, fuel burn, and noise from turbine engines, NASA Environmentally Responsible Aviation (ERA) Project also evaluated ceramic matrix composite technology for aircraft turbine engine applications, which could also be transferred for recuperator development as appropriate [117-119]. The turbine inlet temperature of a typical turboshaft engine is usually between 1250-1450 K, and with blade cooling technology being employed, a substantially increased temperature is achievable to provide higher levels of overall efficiency for gas turbine system, which necessitates the eventual use of super alloys or ceramic materials.

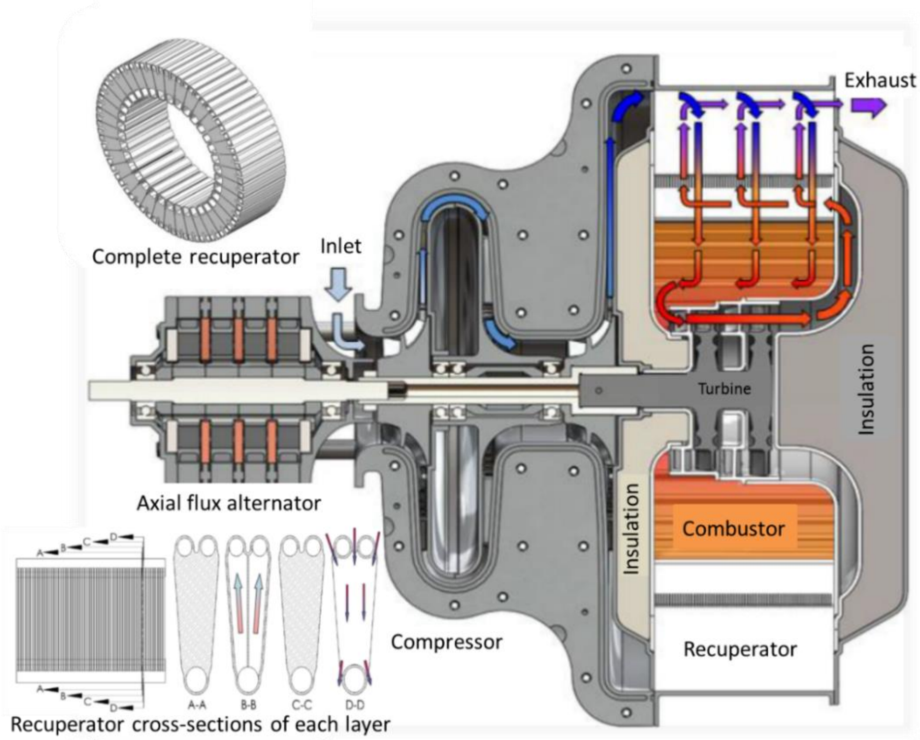


Figure 2.12: The cross-section of the recuperated ceramic turboshaft engine [115]

Heat transfer surface geometries design and material development (e.g. selection and manufacture) are two major research areas for future generation recuperators. Extensive development and testing efforts must therefore be undertaken to develop a reliable, cost-effective, high performance recuperator in the severe thermal cycling environment inherent to aero-engines.

2.5 Summary of recuperator technology status

In light of the aforementioned background related to recuperated aeroengines, especially helicopter turboshaft engines, it is revealed from the early experimental testing for retrofitted turbines and subsequent engine design concepts that although this concept has long been considered, there is still lack of systematic incentive for major modifications of engine architecture considering the on-going performance improvement of simple-cycle engines, especially in an era of low fuel price, together with the high temperature heat exchanger impediments (reliability, structural integrity) which are prevalent until about the last two decades.

After evaluating the relevance of accumulated experience derived from previous development work, three promising high temperature heat exchanger candidates, i.e. tubular, primary surface and plate fin, are assessed in the light of state-of-the-art technology advancements, aimed at finding heat exchangers potentially applicable to rotorcraft recuperators. Furthermore, emphasis has also been placed on material selection and manufacturing technology. It is concluded that for industrial and vehicular gas turbine recuperators, since minimizing the recuperator weight is not paramount, plate-fin geometries are favorable, particularly from the viewpoint of cost. However their bulky weight actually eliminate them for further consideration in recuperated helicopter turboshaft engines. Primary surface recuperators would likely be the appropriate choice for future recuperator development, implementing novel 3D CC geometries with superior heat transfer characteristics. Tubular types have been adopted in aero-turboshaft applications ever since the initial stage of development in 1960s albeit their relatively low effectiveness, as they have high reliability based on technologies prevailing in that era. An additional important factor is that, they represent the best solution, essentially based on weight consideration. Traditional profile tubes arranged in bundles are preferred for further development. Smaller hydraulic diameters, thus increasing compactness may contribute to light weight and small volume of the recuperator matrix, but flow maldistribution, longitudinal conduction effects and fouling need attention.

Operating in the high temperature and severe thermal cycling environment, super alloys and ceramic materials are suggested, but at a substantially greater projected cost relative to the commercially used 347 SS. Modified Alloy 803 and Haynes 120 seem to be the best alternatives up to 750 ℃ (1382 F) with respect to cost and creep-strength. The fairly low density of ceramic materials contributes to a significant weight reduction in recuperator matrix contrast to metallic counterparts. The advancement in heat exchanger technologies in the fields of material science, mechanical design etc., together with the urgent socio-economic considerations (e.g. strict emissions legislation, reduced fuel consumption requirement) and/or specific needs for military applications (lower infrared signature, increased flight range) necessitate more complicated aero-engine architectures for the next generation and highlight the helicopter turboshaft concept embodying a recuperator. An interesting technical strategy would be likely to firstly develop a quite small ceramic recuperated turboshaft engine for UAV applications, with the accumulated experience on bench experiment and flight testing, it could essentially provide a sound technology base for advancing to small or medium class of recuperated helicopter turboshaft engines for military service.

3. Performance evaluation of recuperated rotorcraft powerplants

Through the recuperation process of exhaust waste heat utilization, the implementation of recuperators for gas turbine systems has been proved to be a significant technical route to meet the current challenges of reduced emissions and improved specific fuel consumption (SFC) to develop highly efficient, environmentally friendly aero-engines. This is particularly attractive for today's rotorcraft powerplant, since one of its main performance disadvantages is the increased SFC during part load, where the majority of its mission time would be spent.

In this section, a computationally efficient multidisciplinary simulation framework is proposed and implemented to analyze the influence of recuperator on the whole rotorcraft powerplant system for further development of future recuperated aircrafts. The rotorcraft powerplant configuration selected in this work is a generic helicopter, which is similar to a typical multi-purpose utility helicopter Bo105, equipped with two Allison 250-C20B turboshaft engine variants. The overall methodology comprises a series of individual modeling theories in terms of helicopter flight dynamics, gas turbine engine performance, etc. which are elaborated separately in detail. The research addressed within this work could provide a solid foundation for the multidisciplinary design and optimization of future recuperated rotorcraft powerplants.

3.1 Trade-off between improved fuel economy and parasitic recuperator weight

As one of the main devices for many industrial gas turbines and microturbines, recuperator is widely adopted with good performance and proven structural integrity. However, there are several identified factors that mitigated its wide use in aircraft gas turbine engines as elaborated in Chapter 2, including lack of market forces (low fuel price, continuous performance advancements of simple-cycle engines) and high temperature heat exchanger technology readiness (particularly until about the last two decades). Furthermore, the recuperator volume and weight also need to be strictly controlled due to stringent constraints on the carrying capability and limited space of the rotorcraft in contrast to the conventional industrial microturbine. More importantly, extensive development work and testing efforts, including valuable flight worthiness test, must be undertaken before the final deployment.

The high power-to-weight ratio and good fuel economy are two of the most significant performance requirements for rotorcraft powerplant integration. Early helicopters employed reciprocating engines which provided satisfying fuel economy, and are therefore quite economical. However they have been generally replaced by turboshaft engines due to their bulky weight and considerable volume. Apparently, the implementation of recuperator inevitably increases system weight, thus worsening the attractive power-to-weight ratio offered by the gas turbine, and to some extend may even outweigh the benefits of fuel saving potential arising from the recuperated cycle. Hence, it would be regarded as a prerequisite for the rotorcraft powerplant design to have a systematic quantification of compromise between the parasitic recuperator weight and improved fuel economy, in order to create sustainable advanced aircraft design solutions with more complex engine configurations. Furthermore, the most fundamental advantage of recuperated cycle over the conventional simple cycle is the significantly reduced fuel consumption through exhaust waste heat recovery. Helicopter mission profiles that match the attractive part-load SFC characteristic of the recuperated turboshaft engine (i.e. suitable for recuperator implementation) also need to be identified.

In this work, simulated under typical mission scenarios, the interdependency and associated trade-off between fuel saving benefits and recuperator weight penalty arising from the recuperation process is comprehensively quantified within an integrated rotorcraft multidisciplinary simulation framework, among which both tubular and primary surface recuperators are taken into consideration.

3.2 System modeling

3.2.1 System simulation framework

Aimed at evaluating the performance of the recuperated rotorcraft powerplant, an integrated multidisciplinary simulation framework is developed as shown in Figure 3.1. It comprises various modules including helicopter flight dynamics, engine performance, recuperator weight estimation and mission management etc., providing a systematical performance evaluation of the recuperated rotorcraft powerplant under different flight conditions as well as at mission levels.

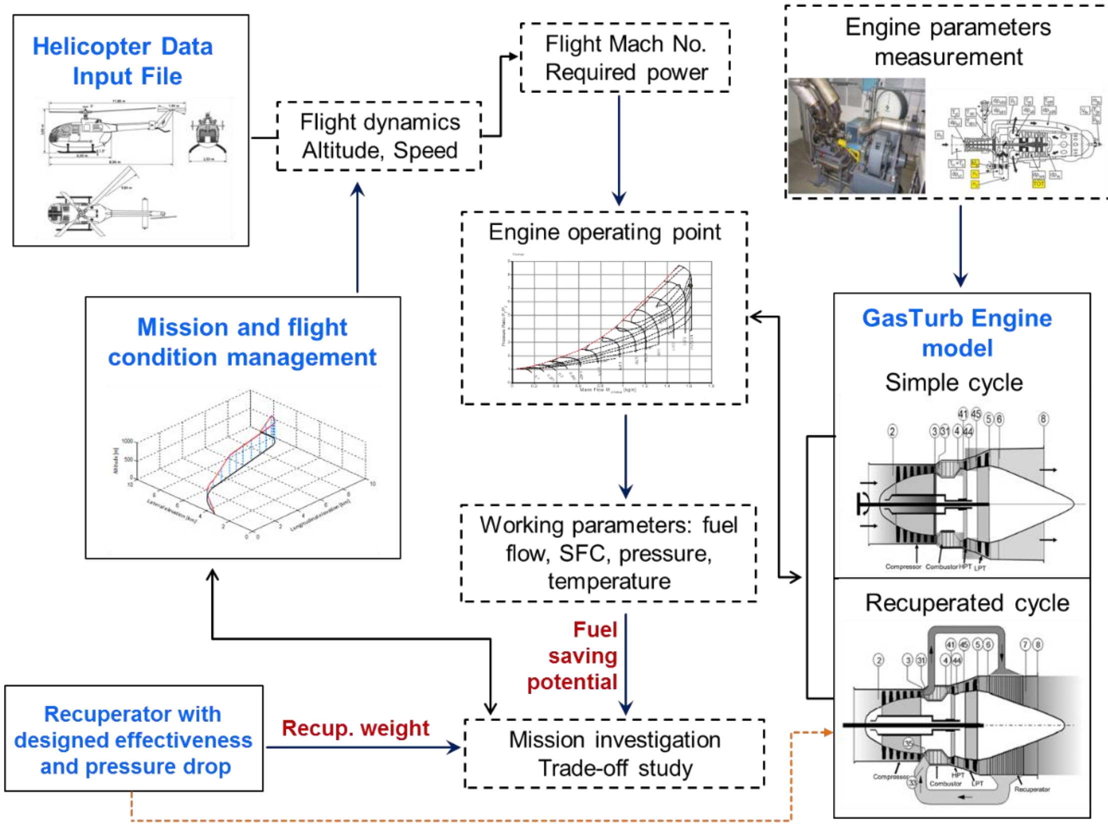


Figure 3.1: The integrated rotorcraft multidisciplinary simulation framework

A generic rotorcraft model is analyzed based on the light class helicopter Bo105 driven by two Allison 250-C20B turboshaft engines. With regards to a given mission profile, it could be normally split into several discrete segments based on user defined input values (i.e. types of operation and flight conditions). For the purpose of this study, the helicopter is assumed to be operating in trim (steady state) during each segment of the investigated mission scenario. The helicopter power requirement with the designated flight speed at a specific altitude could be calculated through the helicopter simulation model. The modeling methodology targeting realistic helicopter operations comprises herein a series of dedicated numerical formulations, and a comprehensive literature with respect to the flight dynamics is introduced in Ref.[120, 121]. With reference to the deployed Allison 250 turboshaft engine, a very extensive development and testing effort have been undertaken at Technical University of Munich [122,123]. With the established GasTurb engine model, it simulates the performance of both referenced conventional and recuperated turbine engine. In particular, it computes the engine's operating point to meet the aforementioned power requirement under specified flight conditions. Furthermore, important working parameters, like recuperator inlet/outlet temperature, introduced pressure drop, mass flow rate etc. are attained in the meanwhile, as well as the fuel saving potential offered by the adoption of recuperator. The recuperator weight estimation is mainly performed based on previous studies as functions of mass flow and thermal effectiveness. Characteristic parameters of the reference helicopter and associated engine are listed in Table 3.1.

a). Reference helicopter	
Max. takeoff weight (kg)	2400
Operational empty weight (kg)	1300
Max. fuel (kg)	460
Max. payload (kg)	1100
Service ceiling height (m)	5182
Fuselage: Length (m)	4.30
Width (m)	1.58
Height (m)	3.00
b). Engine design parameters	
Pressure ratio	7.2
Air mass flow rate (kg/s)	1.56
Turbine inlet temperature (K)	1400
Power (kW)	313
SFC kg/(kWh)	0.396
Engine weight (kg)	72

Table 3.1: a). Reference helicopter characteristics, b). Engine design point parameters

In this study, the integrated multidisciplinary simulation framework has been implemented to systematically quantify the associated performance trade-off between the improved fuel economy arising from the incorporation of recuperator and the corresponding recuperator weight penalty over a wide range of thermal effectiveness (namely 60-75% for tubular recuperator and 80-90% for primary surface type). A generic reference mission analysis is initially carried out providing general characteristics between aforementioned conflicting objectives and followed by four representative helicopter missions targeting realistic helicopter operations.

3.2.2 Recuperator weight estimation

With reference to recuperator weight, there is basically very little data available in the open publication, since rather than disclosed to the public, work done by industrial manufacturers is mostly conducted targeting defined user specifications and would be regarded as proprietary. The recuperator weight is essentially determined by various factors, including design material, operating conditions (e.g. temperature, pressure, allowable pressure drop) and flow configuration etc. The actual weight calculation of a specified recuperator is beyond the scope of this section, and would require the detailed specification for a particular case, nevertheless, based on heat exchanger information accumulated over many years by McDonald [12], Figure 3.2 shows the recuperator matrix specific weight data for tubular, primary surface and plate fin types over a wide range of effectiveness, herein installation details including header, connecting ducts, etc. are excluded from consideration.

Compared with plate-fin ones, in the construction of primary surface recuperators, heat transfer could take place directly across thin plates that are formed into elements, thus eliminating the need for secondary surface fins. With regards to tightness, these elements are seal welded, and therefore obviate the requirement of high-temperature furnace brazing operations utilized for plate-fin units [124]. Besides that, as mentioned before, from the early development activities and subsequent researches, there were essentially only tubular recuperators being materialized in terms of hardware and even tested for recuperated aero-turboshaft engines despite their relatively lower effectiveness. Typically, a basic recuperator design requirement for gas turbine aeroengines is light weight (hence reducing size), and on the basis of work done to date, tubular type represents the best solution in this respect. In this work, the upper limit of the band is defined as the installed tubular recuperator weight.

As can be observed, the recuperator weight is quite sensitive to the engine mass flow and thermal effectiveness. In particular, with the effectiveness improves from 60% to 75% for tubular geometry regime, the recuperator matrix specific weight could be approximately doubled. Complex recuperator geometry matrix tends to enhance heat transfer and obtain higher effectiveness, but mostly could also lead to the unwanted increase of weight. On the other hand, primary surface recuperators provide high heat transfer capabilities with compact size and strong mechanical strength, and they would therefore be selected for higher values of effectiveness. Since the data portrayed for primary surface recuperators is on the basis of recuperated gas turbines for power generation, where minimizing the recuperator weight is not of paramount importance, the lower limit of the band is adopted for further calculation.

The recuperator weight correlation utilized for both tubular and primary surface type is also presented in Figure 3.2. Thus, the recuperator weight could be calculated directly as a function of mass flow and thermal effectiveness. Furthermore, the total recuperator weight in the rotorcraft powerplant system should be extended for two engines for the sake of this study, as a result of the twin-engine configuration for the investigated reference helicopter in our work.

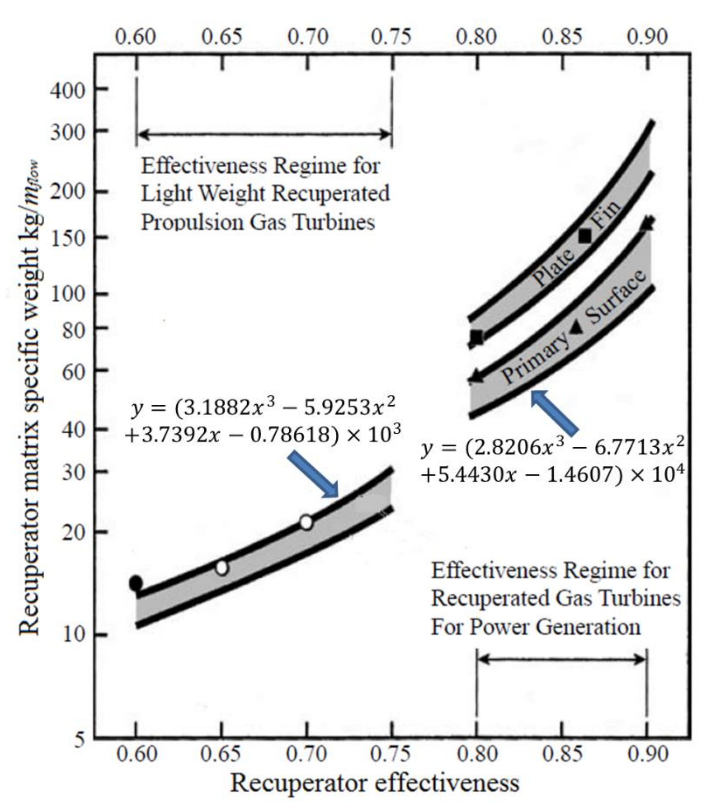


Figure 3.2: The specific weight of gas turbine recuperator for different surface geometries [12]

3.2.3 Helicopter performance prediction

The Helicopter performance prediction is simulated in the Matlab environment, and it calculates the total power required by the helicopter P_{req} for a specific flight mission segment. P_{req} mainly contains four parts, i.e. the power needed to drive the main rotor (MR) and tail rotor (TR) as well as to overcome parasitic drag, and the power of auxiliary systems and transmission losses.

$$P_{req} = P_{t,MR} + P_{t,TR} + P_p + P_{Aux+loss} \tag{3.1}$$

MR, TR power are calculated in the same way based on the energy method using momentum theory, as described in detail in Ref.[125,126]. For both MR and TR, the power is mainly the sum of induced power P_i and profile power P_o. Related equations are given as follows

Induced power:

$$P_i = kG_{sys}gv_i \tag{3.2}$$

Profile power:

$$P_o = \frac{1}{8}\rho\sigma C_{d0}Av_{tip}^3\left(1 + 3\mu^2 + \frac{3}{8}\mu^4\right) \tag{3.3}$$

Parasitic drag power:

$$P_p = \frac{1}{2}\rho v_f^3 C_D S \tag{3.4}$$

The required power to drive auxiliary system in this work is set constant to be a reasonable value of 35 kW for this Bo105 helicopter class, whose MTOW is designed to be 2400 kg. The power losses in bearing and transmission are covered by typical mechanical efficiency factors.

$$P_{loss} = \left(\frac{1}{\eta_{mec}} - 1\right)\left(P_i + P_o + P_p\right) \tag{3.5}$$

The corresponding analysis methodology block diagram for the Helicopter Performance Calculation Script (HPCS) is given in Figure 3.3. It starts with loading the required helicopter characteristics, and the next step is to setup data, which mainly covers the altitude and speed ranges to be examined, followed with the performance calculation routine, which conducts the power calculation for each item. Here the algorithm uses two loops. Particularly, the outer loop is for the defined altitude range, which also includes the calculation of the engine available power P_{avi} and specific atmospheric parameters according to international standard atmosphere (ISA). Despite the fact that with the increase of flight altitude, the reduced ambient temperature has a positive influence on the delivered power, the corresponding decrease of air density offsets this effect and leads to the reduction of the maximum available power P_{avi}. In this work, a simple correlation based on simulation model and several performance data sets has been implemented to calculate the percentage of P_{avi} at different altitudes relative to mean sea level (MSL) conditions [127], which could also be observed in Figure 3.4. Based on the given flight speed range, the inner loop subsequently calculates the power consumption of every individual component. For the sake of better code maintainability, each item is defined with a separate Matlab-function. Finally, the results could be presented graphically for further analysis and evaluation.

Figure 3.4 shows the overall power required for level flight under various flight conditions (TOW=2400kg, MSL, ISA conditions). The power difference between power required P_{req} and P_{avi} defines the power for maneuvers like turning or climbing flight. It is apparent that unreasonable points whose required power exceeds the maximal available power need to be eliminated, and this kind of operations must be prohibited. Obviously, the power required in level flight changes dramatically with the variation of flight speed. Besides that, altitude is another important operational consideration for overall helicopter performance. As shown in the figure, higher altitude would lead to increasing power requirement for the conditions of hover or lower flight speed, while lower air density at higher altitude decreases the parasitic drag which plays a dominant role for the overall power requirement at larger flight speed.

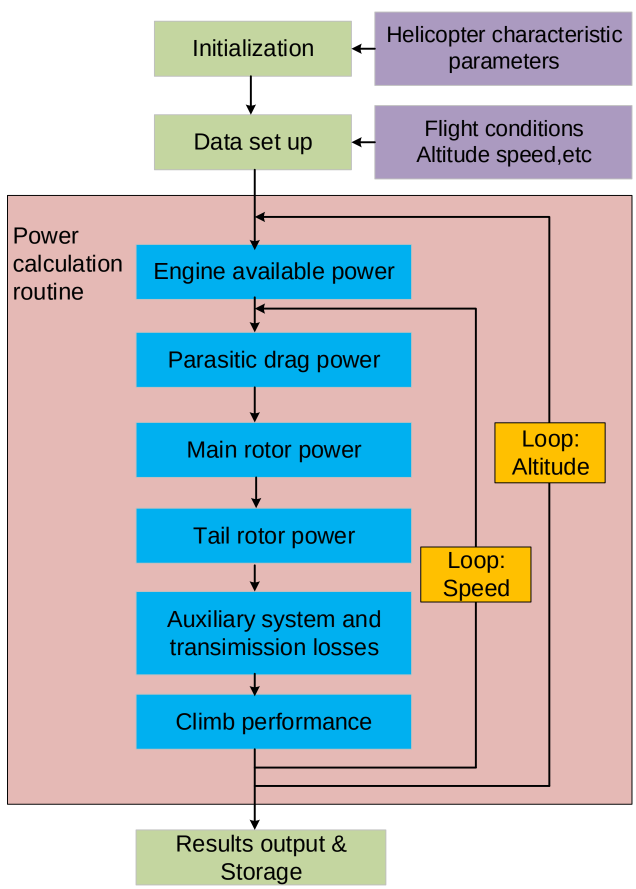


Figure 3.3: Analysis methodology block diagram of the HPCS

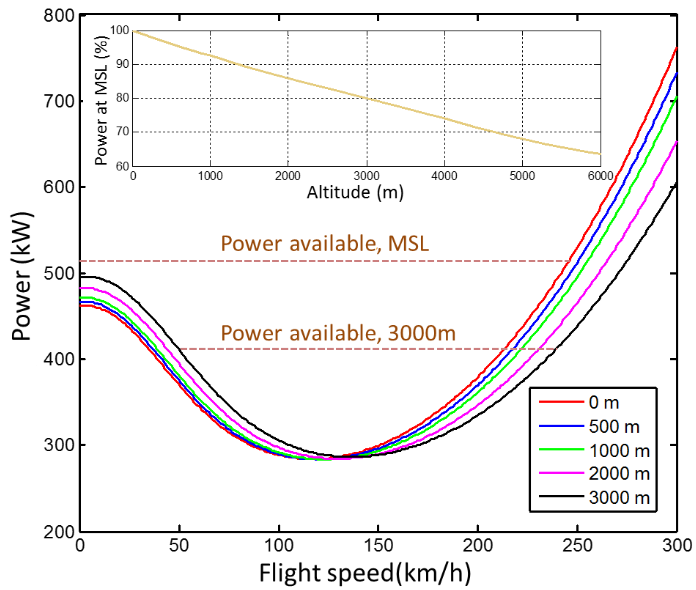


Figure 3.4: Power required for level flight at different altitudes

3.2.4 GasTurb engine performance

With regards to the employed Allison turboshaft engine, it has seen service in several applications like helicopter propulsion, turboprop drive train, etc. Allison 250-C20B is capable of delivering approximately 300 kW of maximum continuous power. The compressor consists of a combination of six axial stages and one radial stage. After compression, compressed air is guided by two ducts around the engine's center to the combustion chamber at the engine rear. After combustion, exhaust gas is expanded through a two-stage high pressure turbine (HPT) and subsequently through a two-stage free power turbine (LPT). The high-pressure turbine is mechanically coupled to the compressor through the high-pressure shaft, driving its operation. Figure 3.5 shows an overview of the instrumentation on the engine.

The installed sensors on the engine testbed mainly consists of temperatures, pressures, spool speeds, fuel balance and torque. Temperatures are measured using resistance thermometers (Pt100 sensors) and thermocouples (NiCr-Ni) for low temperature range and higher level respectively. Pressures are obtained by utilizing either a static tapping or total pressure Pitot tube. Venturi tubes are adopted to measure air mass flow rates of the inlet and bleed section. Fuel mass flow is determined via a turbine flow meter for dynamic measurements and a scale for static measurements. With the engine's internal torque metering device, engine torque is recorded.

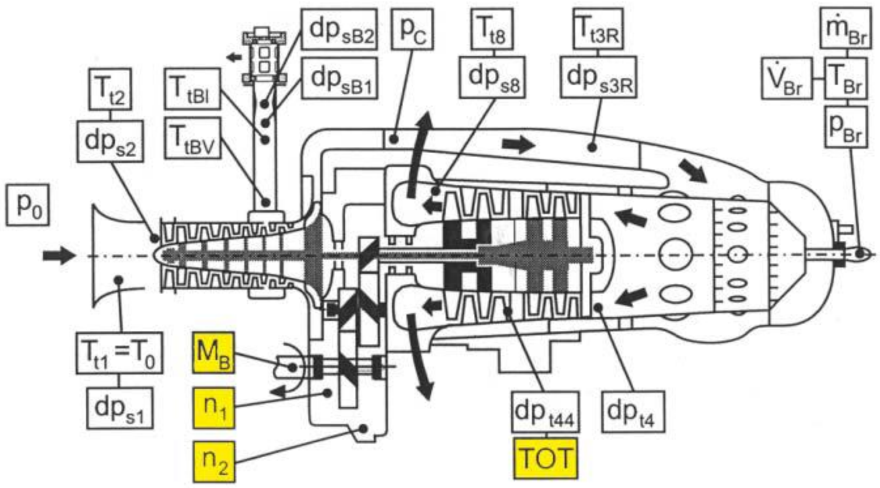
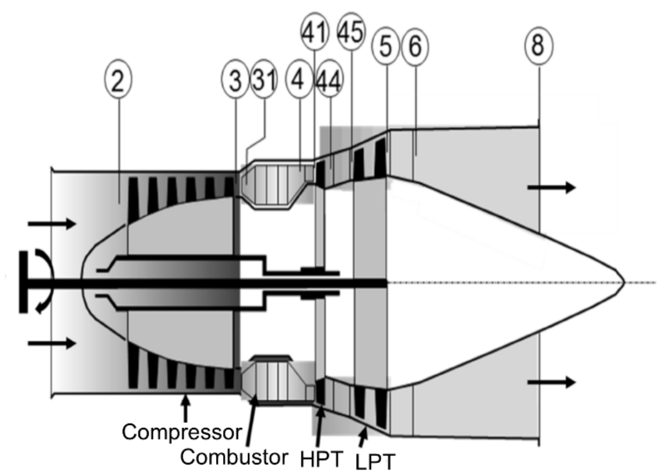
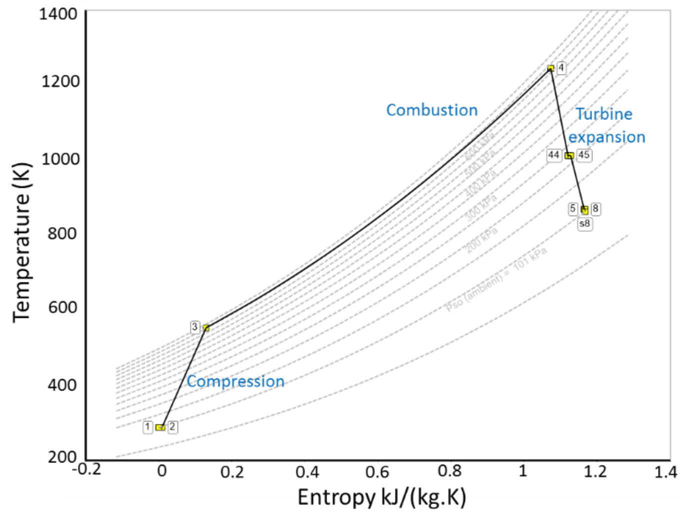


Figure 3.5: Allison engine instrumentation [123]

Extensive experimental work has been conducted with regards to the deployed Allison 250-C20B turboshaft engine at the Chair of Turbomachinery and Flight Propulsion, and in this study the reference Allison engine is introduced and implemented using GasTurb software. It is a useful tool to evaluate the design and off-design performance of the most common types of gas turbine engines. Figure 3.6 shows the thermodynamic schematic of the typical two-spool turboshaft engine in the GasTurb operational environment. The accuracy of simulation results for the reference Allison 250-C20B engine had been validated using the experimental data derived from Ref.[122] in terms of output power, corrected compressor mass flow rate and HP turbine exit temperature as given in Figure 3.7, which shows a good agreement and ensures its accuracy.



a). Illustration of a two-spool turboshaft engine based on GasTurb [128]



b). *T-s* diagram for the Brayton thermodynamic cycle

Figure 3.6: Thermodynamic schematic of a simple Brayton cycle turboshaft engine

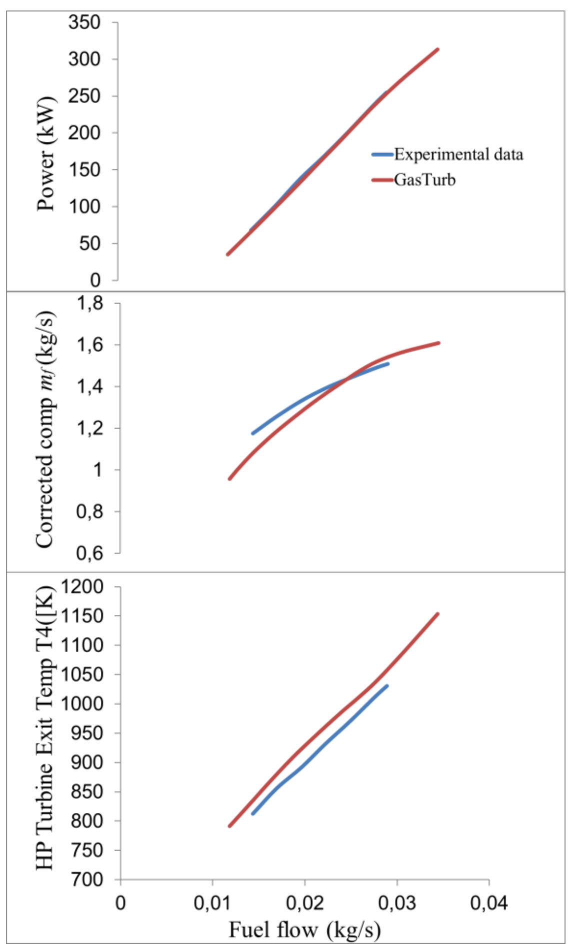


Figure 3.7: Comparison results between simulation and experimental data [122]

Mainly due to safety considerations and certification issues, helicopters are normally powered by more than one engine. In this case, if accident happens which leads to engine failure, some other engines would still provide enough power to continue the flight and make sure the emergency landing is under control. However, during the majority of mission time the available installed maximum continuous power of the engines is not required and these engines are operating at partial load, which results in non-optimum SFC characteristics.

Leishman, J.G. [125] defines the SFC vs. shaft power P on the basis of two specific characteristic parameters A_E and B_E, which are individual for each engine.

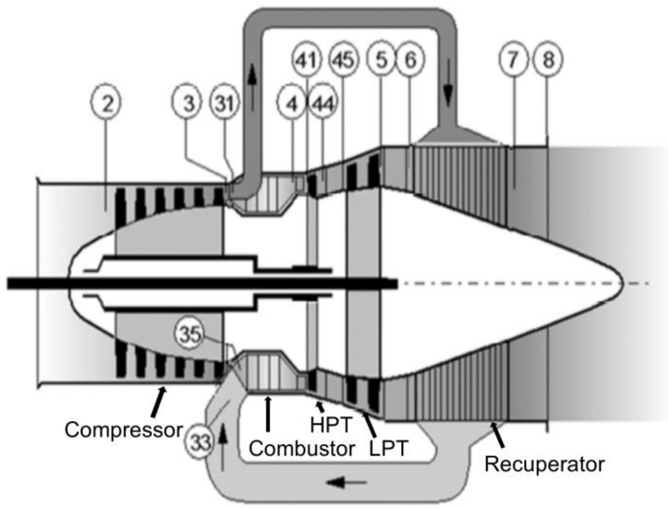
$$SFC = A_E \frac{\delta\sqrt{\theta}}{P} + B_E \tag{3.6}$$

Where $\delta = \frac{P}{P_{MSL}}$ and $\theta = \frac{T}{T_{MSL}}$, are the ratio of ambient pressure and temperature to sea level condition, showing the influence of ambient condition on power.

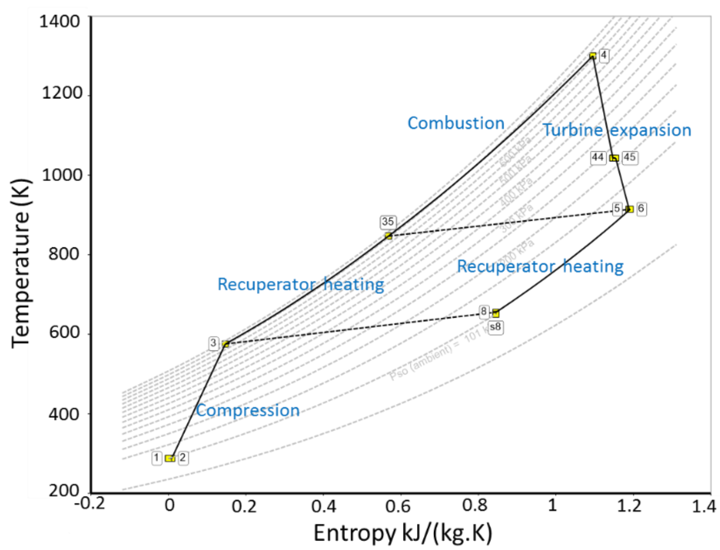
3.2.5 Recuperated turboshaft engine

The most important benefit provided by the recuperated engine over the conventional engine is the fuel consumption reduction resulting from its distinct thermodynamic cycle, which is achieved by recovering exhaust waste heat to preheat compressed air before combustion as presented in Figure 3.8. This advantage is quite appealing in the current era of high fuel price and strict regulations on acceptable emissions levels. Nevertheless, it could also lead to some drawbacks, including the additional pressure losses for both exhaust gas and compressed air, the added weight and volume of recuperator.

Apparently, the theoretically achievable benefit of the recuperator, i.e. the quantity of available exhaust waste heat highly depends on the temperature difference between the exhaust gas and compressed air. To ensure the desired heat transfer process in the recuperator, the exhaust gas temperature must exceed the corresponding compressor outlet temperature. Small temperature difference, caused by too large pressure ratio (PR), low turbine inlet temperature (TIT) etc. could have a negative effect on the benefit of introducing a recuperator. Besides that, particular attention also needs to be paid at start up conditions while taking transient performance into consideration, since the recuperator usually presences a large thermal inertia effect and may work in the reverse way with compressed air being cooled down [73,76].



a). Illustration of a recuperated two-spool turboshaft engine based on GasTurb [128]



b). *T-s* diagram for the recuperated thermodynamic cycle

Figure 3.8: Thermodynamic schematic of the recuperated turboshaft engine

Once the basic engine configuration is fixed, GasTurb provides users with additional configuration options that can be used to switch between non- and recuperated cycle modes. In off-design with the heat transfer surface remaining constant, as stated in Ref.[128], the relationship between effectiveness and mass flow rate is given as follows

$$\varepsilon = 1 - \frac{m}{m_{ds}}(1 - \varepsilon_{ds}) \tag{3.7}$$

The following formulae are given to depict the relationship of pressure losses on the cold/hot side of the recuperator between off-design and design point.

For compressor air, cold side (inlet 1, outlet 2)

$$\frac{p_1-p_2}{p_1}=\left(\frac{p_1-p_2}{p_1}\right)_{ds}\frac{\left(\frac{m_1}{p_1}\right)^2\frac{T_2^{1.55}}{T_1^{0.55}}}{\left(\frac{m_1}{p_1}\right)_{ds}^2\frac{T_{2,ds}^{1.55}}{T_{1,ds}^{0.55}}} \tag{3.8}$$

For exhaust gas, hot side

$$\frac{p_1-p_2}{p_1}=\left(\frac{p_1-p_2}{p_1}\right)_{ds}\frac{m_1^2T_1}{(m_1^2T_1)_{ds}} \tag{3.9}$$

3.3 Mission investigation

With regards to the majority of typical rotorcraft applications (e.g. surveillance, fire suppression, search and rescue etc.), the rotorcraft is often utilized for occasions where environmental concerns would be considered secondary, and the main focuses of this study are therefore placed on fuel economy improvement and system weight minimization for the purpose of maximizing rotorcraft range and payload capability.

Incorporating recuperators into gas turbine systems enables the heat transfer between the exhaust gas and compressed air, thus a remarkable increase in compressed air temperature, prior to the combustion chamber is expected. As a result, less fuel consumption is required to heat the compressed air/fuel mixture up to the desired turbine inlet temperature, indicating considerable potential for lower emissions and SFC.

The additional recuperator could definitely increase the system's overall weight, thus acting as a weight penalty for recuperated cycle performance, meanwhile, the fuel consumption for a given mission would be decreased resulting from the improved fuel economy and thermal efficiency. When considering the combined weight of the heavier engine configuration and potentially reduced fuel consumption, the point at which the amount of fuel saved could exactly compensate the additional recuperator weight is defined as the 'equilibrium point'. Apparently, for a specific mission the adoption of recuperator would be beneficial under the condition that this equilibrium point is at least satisfied, otherwise, the parasitic recuperator weight would outweigh the benefits of lower SFC. Here ΔM is denoted as the weight difference between the added recuperator and saved fuel consumption, and a positive value justifies the need for recuperated cycle, which can be utilized to increase helicopter mission range or improve the useful payload according to the actual requirements.

Table 3.2 gives the recuperator performance parameters with the designed effectiveness ε_{ds}, herein the additional recuperator pressure losses Δp for both tubular and primary surface type are assumed on the basis of engineering judgment and similar reported cases for industrial gas turbines with the identical heat exchanger category under the same range of recuperator effectiveness [11,82]. It should be noted that in terms of early development activities of tubular recuperator for rotorcraft powerplant applications, they actually exhibit pressure drops of 6% and even more, which is much larger than the ones obtained from current technology level [12,35]. Obviously, as can be observed from the table, the addition of the recuperator could reduce the exhaust temperature by more than 200℃, thus significantly lowering the associated infrared signature and in the meanwhile reducing helicopter vulnerability in hostile situations, which is of great importance for military applications.

Recuperator type	ε_{ds}	Δp (%)	Weight (kg)	Air temp. (K) inlet/outlet	Gas temp. (K) inlet/outlet
Tubular	60%	3	2*19.1	576/817	977/754
	65%	3	2*24.2	576/837	977/733
	70%	4	2*31.6	576/858	978/714
	75%	4	2*44.8	576/879	978/693
Primary Surface	80%	5	2*61.4	576/ 900	980/ 673
	85%	5	2*84.6	576/920	980/652
	90%	5	2*138.6	576/ 940	979/ 630

Table 3.2: Recuperator parameters with the designed effectiveness

A factor of about 1.5 times the material cost has been suggested as a goal for the fabrication of recuperators in very large quantities [84]. As the one of the main parameters that affect the final manufacturing cost, it would save a substantial amount of money, if the recuperator weight could be reduced significantly with the on-going technology advancements in manufacturing production. Furthermore, for current heat exchangers applied for gas turbine systems, existing metallic materials are normally utilized out of cost considerations, such as the well-known 347 stainless steel, and Inconel 625 for higher temperature limitation. Bi-metallic approach could also be proposed in which expensive super alloy is only adopted in the hot end of the recuperator, while the rest part uses conventional stainless steel to extend the high temperature service range and meanwhile avoid a large final cost. For even higher temperature service, ceramics are of interest with superior performances in term of mechanical strength and oxidation resistance [124]. However, the reliability and durability of a compact ceramic recuperator in an environment of highly contaminated hot process gases has to be confirmed [13]. Certain obstacles need overcoming, including ceramic-metallic mechanical sealing, fabrication costs and manufacturing methods, and their brittleness in tension (especially for monolithic ceramics) etc.[129].

3.3.1 Generic mission analysis

A generic reference helicopter mission, which is assumed to fly a straight line trajectory, basically comprises the following segments: idle before take-off, hover, climb, cruise to destination, descent and hover for final landing, as given in Figure 3.9. For the sake of simplification and consistency, in this study the recuperator is only implemented during long time hovering and cruise condition, as a result, it doesn't immediately work to present fuel saving potential as the mission begins.

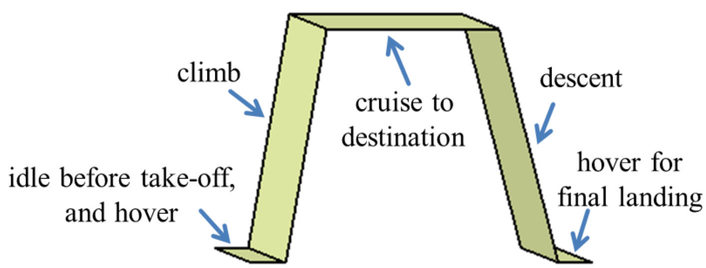


Figure 3.9: The generic reference helicopter mission

With prime focus on the cruise condition, Figure 3.10 depicts the variation of delta fuel consumption (i.e. fuel burn reduction in contrast to simple cycle helicopter) against recuperator designed effectiveness ε_{ds} for different mission ranges, while the helicopter cruises at the altitude of 500 m with a flight speed of 180 km/h. It is well understood that the fixed mission range imposes a constraint on the maximum achievable fuel consumption reduction, and large mission range offers a substantial amount of fuel saving. The basic benefit arising from the distinct recuperated cycle is the significant reduction in SFC and fuel consumption, achieved through heat transfer between exhaust gas and compressed air. Compared to tubular recuperator, the primary surface type with larger values of thermal effectiveness indicates a more complete utilization of exhaust heat, thus providing higher fuel saving potential over the original simple cycle.

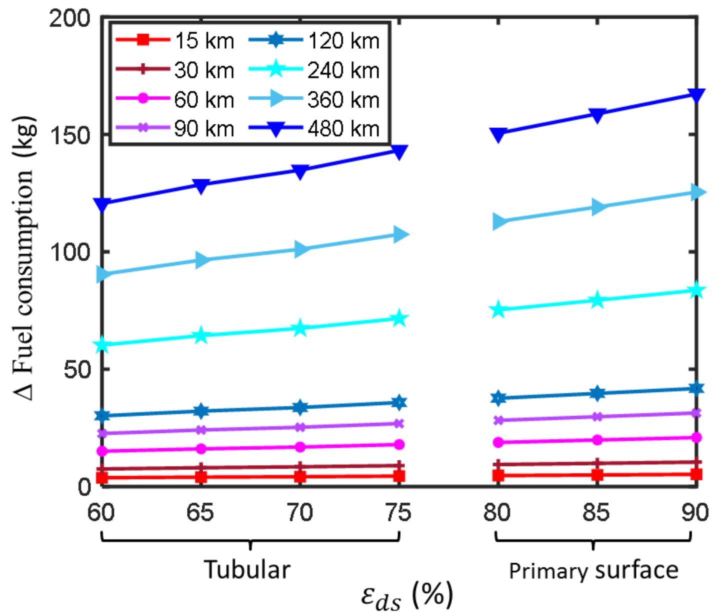


Figure 3.10: Delta fuel consumption versus ε_{ds} for different mission ranges

Considering the effect of the parasitic recuperator weight, as can be noticed from Figure 3.11, the variation tendency of ΔM initiates with a negative value, since the additional recuperator weight would act as a weight penalty for the proposed recuperated cycle. The fuel saved during the mission in comparison with the reference simple cycle follows a proportional increase with mission time (more specifically the cruise flight time). As a result, ΔM grows consistently, and at a certain moment, the amount of reduction in mission fuel consumption could exactly compensate for the parasitic recuperator weight and obtain a balance (i.e. ΔM=0). The subsequently acquired positive ΔM enables the helicopter to increase its mission range or improve the useful payload depending on the actual preference and requirement. With respect to the ε_{ds} range of 80-90%, the bulky weight of primary surface recuperator evidently necessitates much longer operation time, so as to allow sufficient fuel reduction before reaching the balance. Considering the limited fuel carrying capability in the helicopter, for ε_{ds} of 85% and more, the required mission time, i.e. break-even time would even exceed the maximum flight duration of around 3 h for this flight condition.

Particular attention is paid to the mission time required to reach the equilibrium point, as given in Figure 3.12. For the sake of variation tendency evaluation, calculation was extended to include results for ε_{ds} of above 85% ignoring the actual constraint in fuel carrying capacity, as displayed in dashed line. The recuperator weight increases dramatically as a function of recuperator effectiveness, and the growth rate rises as well (see in Figure 3.2), although the fuel saved per unit time relative to the non-recuperated simple cycle is for certain larger with higher recuperator effectiveness, the dramatic increase in recuperator parasitic weight essentially demands longer flight duration and larger mission range to ensure the required level of fuel reduction achieving through the recuperation of exhaust heat. Typically, the break-even mission time is within 2 h while implementing tubular recuperator whose ε_{ds} is in the range of 60-75%.

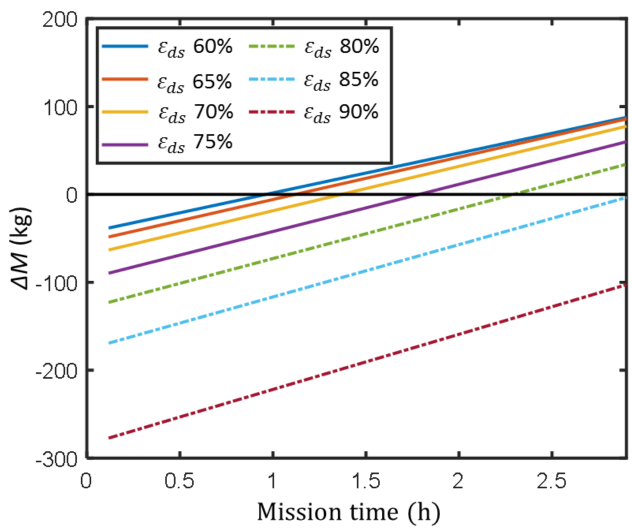


Figure 3.11: The variation of ΔM versus mission time

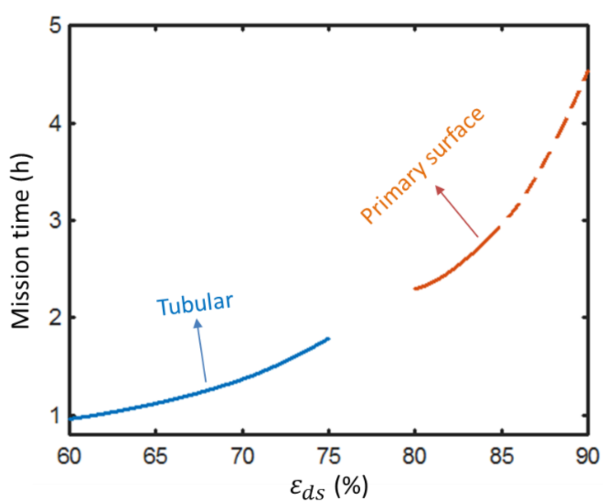
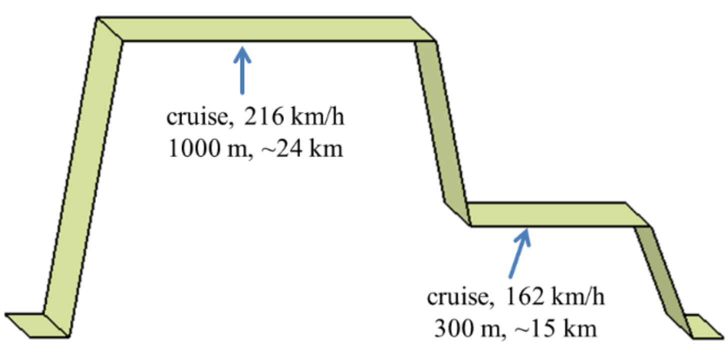


Figure 3.12: Mission time required to research the equilibrium point for different ε_{ds} values

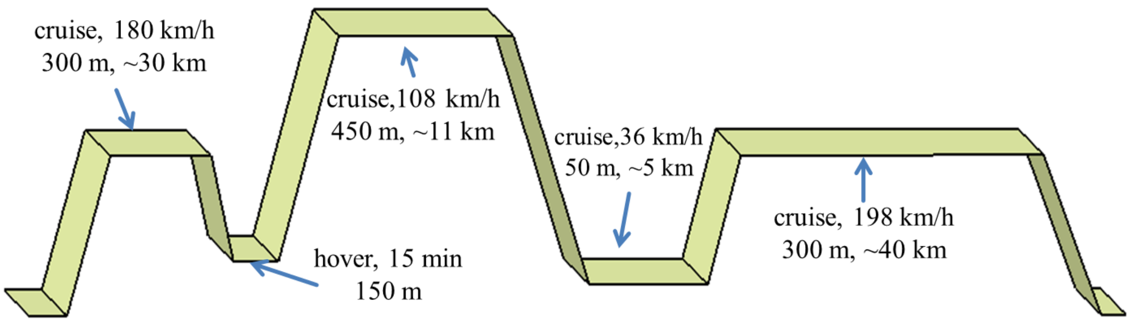
3.3.2 Representative mission analysis

Helicopters would find acceptance for civil and military applications, and they could be used to perform a variety of tasks. They play an irreplaceable role in some specific fields of the air transportation, and in the context of this study mission analysis was carried out targeting realistic helicopter operations, so as to assess the recuperated helicopter performance comprehensively. Under the international standard atmosphere (ISA) conditions, four representative mission scenarios are selected for investigation, throughout which every single flight segment and operating condition is given in detail, as shown in Figure 3.13 a-d.

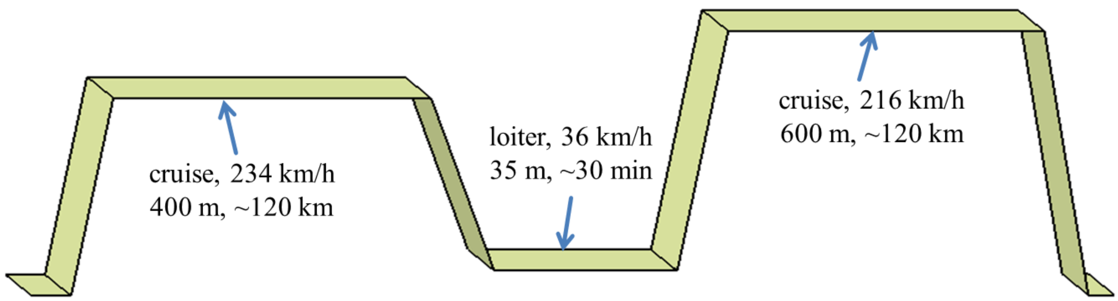
A typical passenger air taxi (PAT) mission shows that designated passengers are transported from the airport to a crowded city where it has to lower the flight altitude until final landing. The police surveillance (PSV) mission scheduled indicates that the helicopter takes off and flies first to a spot over the city and hovers for 15 min, afterwards it moves to a river and flies along the river bed for a distance of around 5 km. The helicopter ends up returning back to the starting point. The search and rescue (SAR) mission designed for the purpose of this study assumes that the helicopter searches castaways at the sea, specifically, it flies first rapidly to the search area and then performs a search pattern for 30 min. It finally returns to the coast station where it starts up. An offshore transportation (OTS) mission designated assumes that two maintenance technicians are transported from a heliport to an offshore oil platform, and subsequently the helicopter comes back with another two passengers.



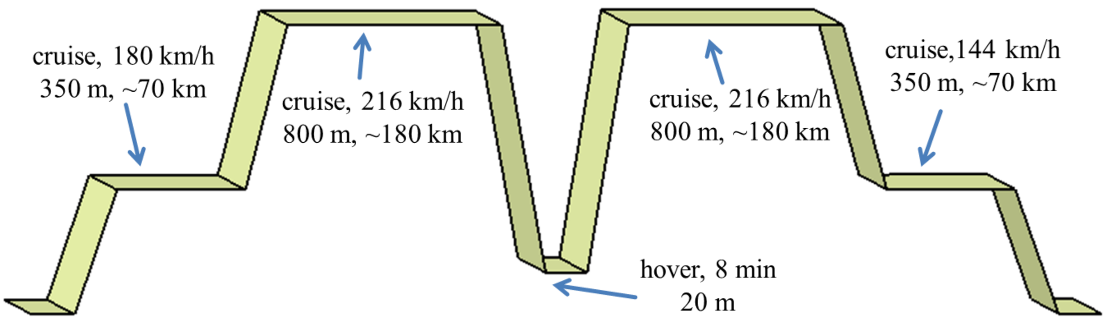
a). The passenger air taxi (PAT) mission



b). The police surveillance (PSV) mission



c). The search and rescue (SAR) mission



d). The offshore transportation (OTS) mission

Figure 3.13: Mission segment information for selected missions

Table 3.3 summarized the mission fuel consumption and fuel saved (in contrast to non-recuperated simple cycle) for all simulated mission scenarios, obviously, a substantial amount of fuel burn reduction could be realized with the integration of recuperator for all investigated missions throughout the assumed scope of thermal effectiveness ε_{ds}. Approximately, for the designated PAT mission 28-34% reduction in mission fuel consumption is attained at ε_{ds} of 60-75% while adopting tubular recuperator, accordingly, the reduction is of the order of 35-40% for primary surface type with ε_{ds} varying from 80% to 90%.

Recuperator Type	ε_{ds}	PAT		PSV		SAR		OTS	
		consum. (kg)	saved (kg)	consum. (kg)	saved (kg)	consum. (kg)	saved (kg)	consum. (kg)	saved (kg)
Tubular	60%	23.59	9.36	107.91	40.89	210.55	76.03	322.34	124.41
	65%	22.96	9.99	104.85	43.95	204.58	82	313.54	133.21
	70%	22.47	10.48	102.47	46.33	199.96	86.62	306.68	140.07
	75%	21.81	11.14	99.3	49.5	193.84	92.74	297.59	149.16
Primary Surface	80%	21.25	11.7	96.65	52.15	188.77	97.81	289.88	156.87
	85%	20.59	12.36	93.43	55.37	182.5	104.08	280.64	166.11
	90%	19.93	13.02	90.22	58.58	176.22	110.36	271.59	175.16

Table 3.3: Calculated results for all representative missions in terms of fuel consumption and saving

Figure 3.14 gives the trade-off results for PAT mission in terms of fuel consumption and engine weight. With simple cycle (SC) acting as the baseline, for recuperated cycle (RC) the engine weight increases resulting from the incorporation of additional recuperator. On the other hand, less mission fuel consumption is projected as ε_{ds} increases due to the distinct thermodynamic performance of recuperation process. Taking the sum of engine weight and fuel consumption into consideration, apparently, ΔM is found to be negative on the condition that the 'Total (RC)' dashed line lies above the corresponding baseline 'Total (SC)', as presented in Figure 3.14a.

The calculated results of negative ΔM values (see Figure 3.14b) for the 39 km PAT mission suggest that this mission profile cannot fulfill sufficient reduction in fuel consumption to compensate for the additional recuperator weight within the whole scope of thermal effectiveness ε_{ds}, corresponding to the case of both tubular and primary surface recuperator. Generally, this short range mission appears to be an adverse operation for recuperation employment and would therefore be excluded from further engine design consideration.

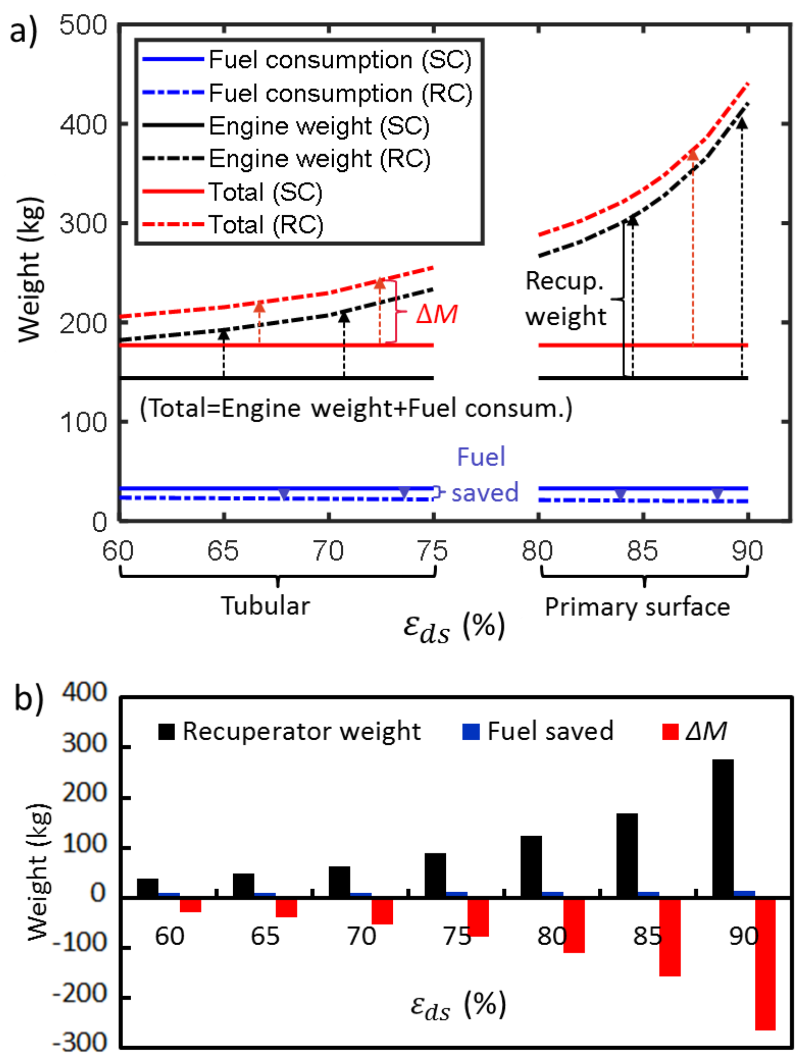


Figure 3.14: Trade-off results for PAT mission: a). Influence of ε_{ds}, b). Variation of ΔM

Benefit from the recuperated cycle, PSV mission is capable of exhibiting significant fuel burn reduction compared to the PAT mission, with more than 40 kg fuel being saved throughout the investigated recuperator effectiveness range. It could be noted from the mostly overlapped lines in Figure 3.15a for the baseline simple cycle, that the mission fuel consumption is approximately the same as the engine weight. As shown in Figure 3.15b, the benefits of recuperated cycle are almost negligible while ε_{ds} varies from 60% to 65% (ΔM changes from 2.69 to -4.45 kg). Afterwards, the tendency of the negative ΔM turns sharply due to the dramatically increased recuperator weight. It is well recognized from the simulated mission analysis results that, while the helicopter performs a specific task, the level of fuel saving potential gained from recuperation process is mainly dependent on factors including: the recuperator thermal effectiveness, the defined mission profile and type of operation.

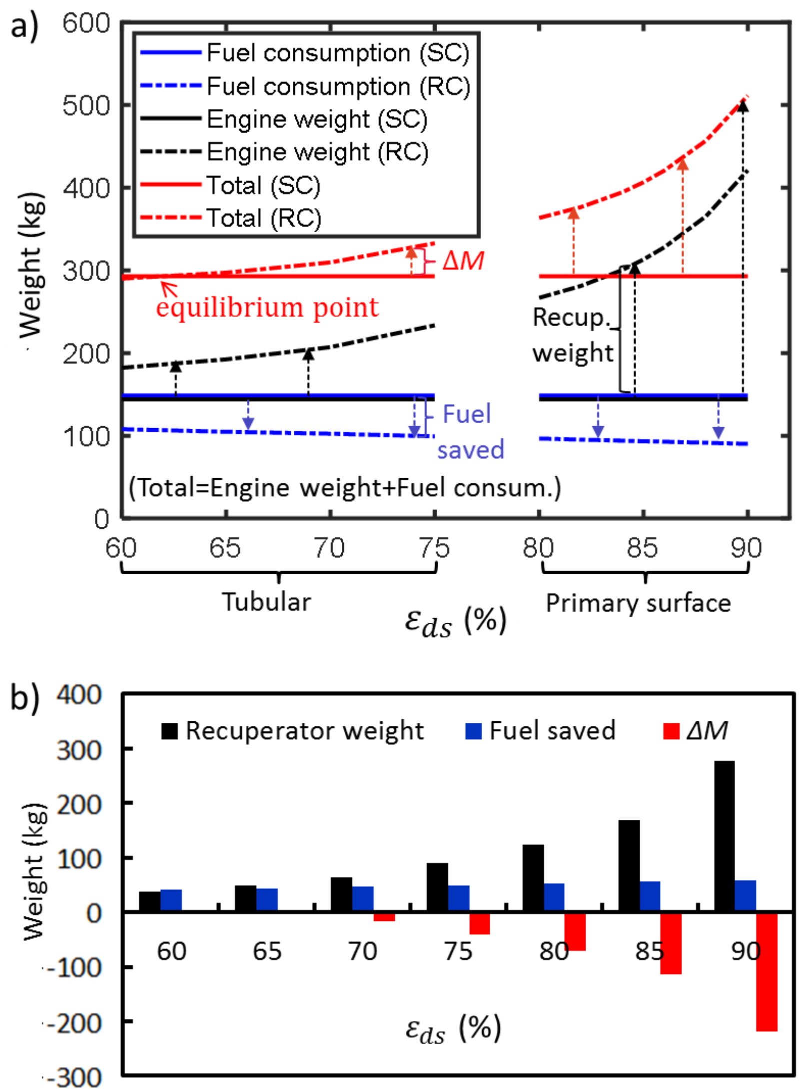


Figure 3.15: Trade-off results for PSV mission: a). Influence of ε_{ds}, b). Variation of ΔM

For the proposed SAR mission with the long range of around 250 km, a fuel consumption reduction of 26.53% and 32.36% are achieved at ε_{ds} of 60% and 75% respectively while utilizing tubular recuperator. Because of the substantial amount of fuel saving, ΔM remains to be positive for the effectiveness ε_{ds} of up to about 75%, until the equilibrium point appears as given in Figure 3.16a. ΔM remains negative while implementing primary surface recuperator for high designed effectiveness of 80-90%. The fixed SAR mission range and duration limits the room for improvement in terms of maximum achievable fuel saving benefits. Besides that, the recuperator designed effectiveness is a key design parameter affecting the engine weight and fuel economy. In this work the optimal recuperator designed effectiveness targeting this defined mission is 60% with the fuel bun reduction of 76.03 kg in comparison with the baseline simple cycle, as given in Figure 3.16b.

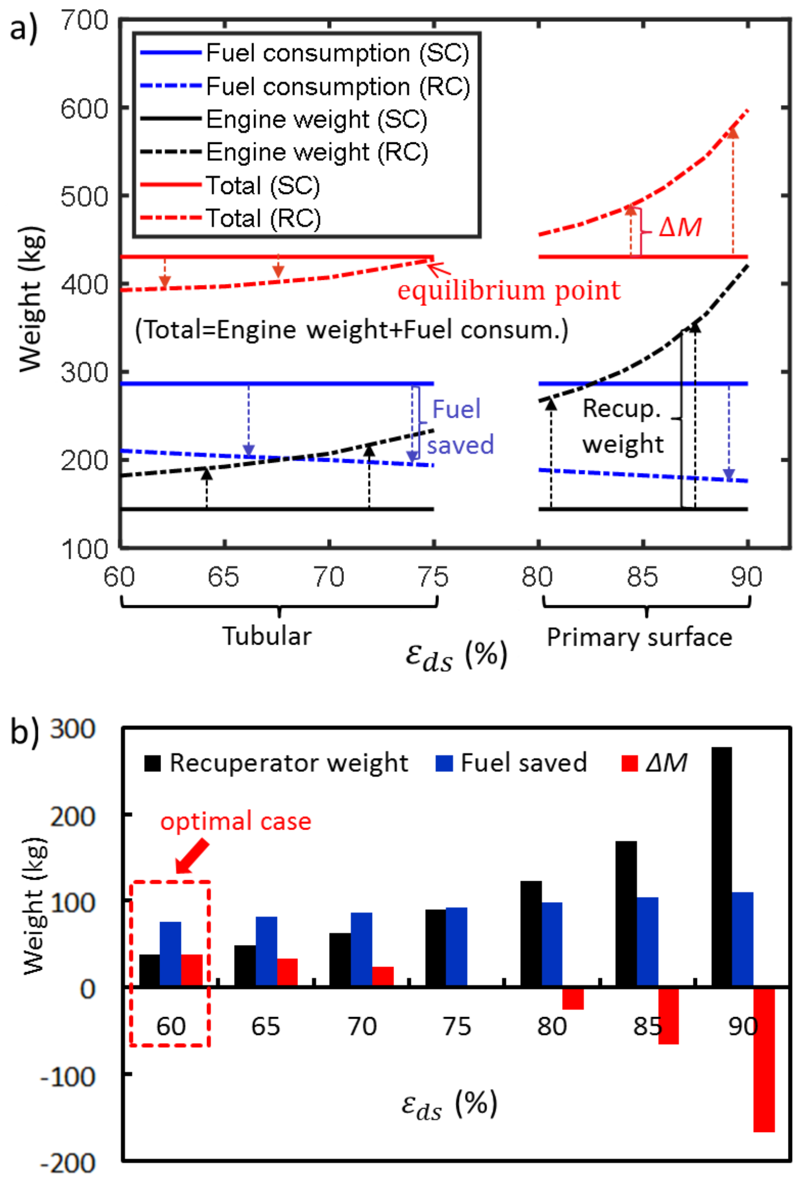


Figure 3.16: Trade-off results for SAR mission: a). Influence of ε_{ds}, b). Variation of ΔM

The deployed OTS mission proves to be a beneficial operation with the adoption of tubular recuperator for the relatively low effectiveness range of 60-75%, which shows much positive and favorable ΔM values (see Figure 3.17b) for the employment of recuperated cycle in contrast to the low range PAT and PSV missions. While adopting primary surface recuperator, ΔM initiates with a positive value of 34.07 kg (ε_{ds}=80%), as ε_{ds} rises the benefits offered by the recuperator are generally offset with ΔM gradually diminished and turned negative at ε_{ds} of 85% and above, as shown in Figure 3.17a. Evidently, the maximum ΔM of 86.21 kg is realized with the optimal ε_{ds} of 60% for the case of using tubular recuperator.

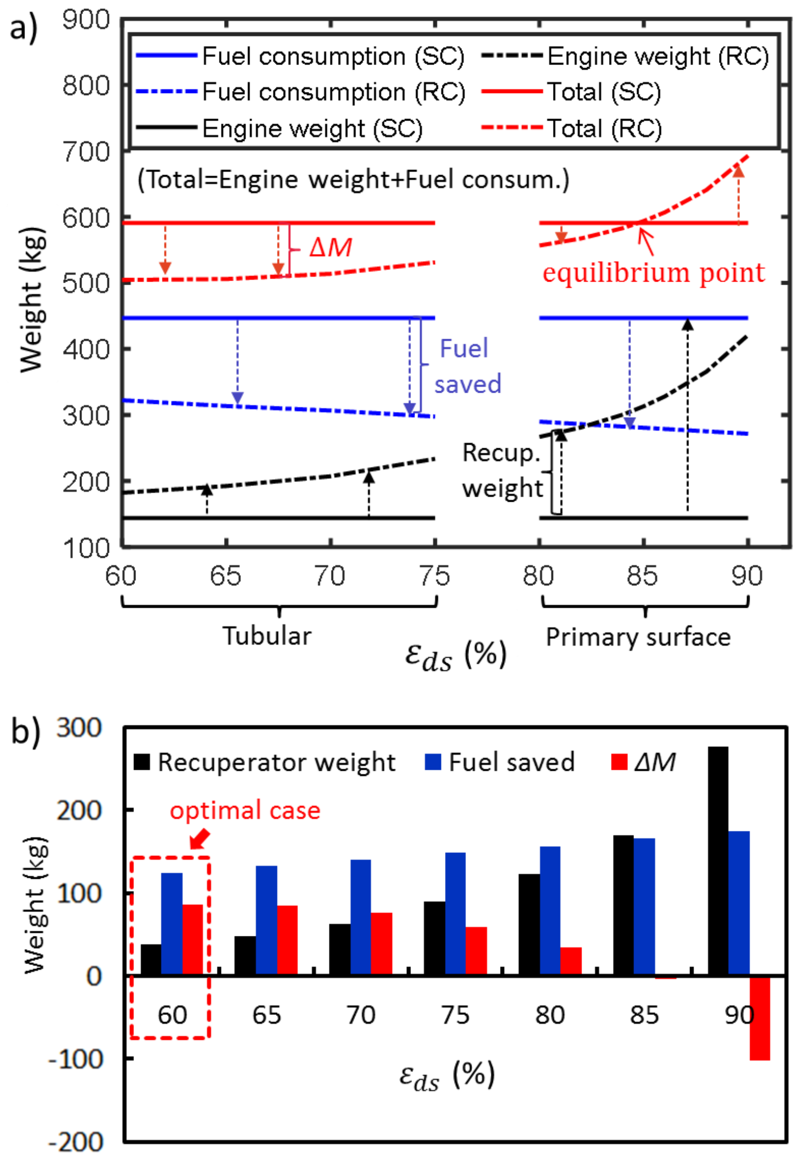


Figure 3.17: Trade-off results for OTS mission: a). Influence of ε_{ds}, b). Variation of ΔM

It is found that ΔM remains negative with ε_{ds} of 90% for all simulated missions, highlighting the requirement for the new generation of lightweight, highly effective, compact heat exchanger. Probably because of the small hydraulic diameter, in Ref.[97] the calculated results for the design of primary surface recuperator applicable to microturbines exhibit much smaller weight and volume compared to available examples of operating recuperators. In fact, their volumes are approximately 30% less than the expectation made on the basis of primary surface recuperators of actual cases. Primary surface geometry with smaller hydraulic diameters (thus increasing compactness) may be an appropriate candidate for future highly effective rotorcraft recuperator, however, associated limitations includes flow maldistribution, longitudinal conduction effects and fouling.

3.4 Summary

Even though the benefits of implementing recuperators have long been recognized, and recuperators have been widely accepted as necessary components to achieve high thermal efficiency for microturbines, they have not found good acceptance in aircraft applications. The operating characteristics of rotorcraft impose unique requirements on engine propulsion systems in contrast to industrial gas turbines, among which a major recuperator demand is light weight. Besides the appealing fuel saving advantage, the integration of recuperators definitely weakens the attractive power-to-weight ratios provided by gas turbines in comparison with reciprocating engines. As a result, the adoption of recuperators therefore leads to conflicting design requirements. Based on previous development activities of recuperated rotorcrafts, tubular recuperator is primarily considered with relatively low effectiveness, while primary surface type would be an appropriate choice for higher level of effectiveness. In this work, it has been proposed to quantify the interrelationship and associated trade-off between improved fuel economy and unfavorable parasitic weight in the recuperated cycle for a wide range of effectiveness, saying 60-75% for tubular recuperator and 80-90% for primary surface type.

An integrated multidisciplinary simulation framework has been implemented to comprehensively assess the performance of the proposed helicopter at mission levels for both simple and recuperated cycles. Extensive comparisons are carried out and presented for a generic reference mission providing general characteristics between aforementioned conflicting objectives and four representative missions targeting realistic helicopter operations. The trade-off study at mission levels has been developed to identify the optimal recuperator design effectiveness that represents the maximum fuel saving potential applicable to the specified mission for the investigated recuperated helicopter. The fuel saving capacity of the adopted recuperator is highly dependent on the mission profile and flight duration. It has been emphasized that although the employed recuperated engine could substantially improve thermal efficiency and reduce fuel consumption, the selection of high value of effectiveness (with the implementation of primary surface recuperator) may not be suitable in certain cases (particularly missions with short range) for further recuperator design, considering the inherited dramatic growth in weight penalty.

4. The potential of rotorcraft powerplant incorporating highly effective recuperators

Incorporating recuperators into gas turbines shows considerable potential for lower emissions and fuel consumption. Nowadays the technology readiness of advanced compact heat exchanger has provided a solid foundation for the availability of lightweight, higher efficient recuperators which would find good acceptance on the rotorcraft without penalizing the operational capabilities.

In this work, the previously developed system simulation methodology and performance assessment approach corresponding to a typical multi-purpose utility helicopter Bo105, has been further implemented to evaluate the potential of recuperated helicopter turboshaft engine, which is equipped with compact primary surface heat exchanger for a high level of thermal effectiveness, saying 80-90%. The improved part-load performance against the reference non-recuperated simple cycle is discussed at first, and the study is then extended to evaluate the fuel saving potential of recuperated helicopter under the flight condition of 0-250 km/h and 0-3000 m, with regards to different recuperator design effectiveness values. This is achieved through the quantification of the helicopter flight time required to provide enough saved fuel, so as to compensate for the additional recuperator weight. Furthermore, the influence of recuperator size and corresponding installation have been also taken into consideration.

4.1 Highly effective primary surface recuperator

A recuperator exhibits tremendous potential in the gas turbine system to reduce fuel consumption and improve thermal efficiency. With regards to its application on aeroengines, in addition to cost considerations, generally the main features of performance required for recuperators are good thermal performance, low pressure losses, high reliability, light weight and compact structure. More specifically, following criteria need to be satisfied:

- Controlling the size and weight strictly because of the extremely limited carrying capability and space of the aircraft. The recuperator weight could also have a direct influence on the final cost.

- Ensuring a high thermal effectiveness with low pressure losses: This has a great impact on the system overall thermal efficiency. In general, enhanced heat transfer surfaces would also lead to increased fluid flow friction and pressure losses [130].

- Achieving high reliability and low maintenance: A long operation life time is expected with minimal maintain costs. Recupereator should show proven long-term structural integrity in the severe thermal cyclic environment.

The employment of recuperator has long been considered for aircraft and helicopter applications to enhance their operational capabilities. As elaborated earlier, although various recuperator designs have been conducted, they have not been widely deployed in actual aircraft aero-turboshaft engines thus far. With respect to early development activities, tubular recuperators were generally adopted due to their high reliability and mature manufacturing in contrast to other heat exchanger types, together with the weight consideration. Besides that, these reported recuperators usually exhibit relatively low effectiveness values, saying around 60-70% [1,12,124]. Currently, with the development of advanced materials and manufacturing technologies, the new generation of compact heat exchangers has started to emerge with good thermal performance and satisfying reliability, highlighting the incorporation of recuperators into rotorcraft powerplant systems without penalizing the normal operation of existing components. Ref.[82] reviewed recuperators for micro gas turbines, and it is concluded that primary surface recuperators shows superior thermal performance with good compactness. It comprises corrugated thin metallic plates stacked together to form passages with small hydraulic diameters, and heat transfer takes places directly across these plates. This type of recuperator has seen service in the microturbine field and normally presents high levels of effectiveness values. Besides that, the manufacturing of primary surface recuperators is also amenable to high-volume automated fabrication, which leads to lower cost. It has been recently proposed as a promising heat exchanger candidate that may meet the aforementioned demanding requirements for recuperated gas turbine aeroengines.

4.2 Recuperator volume estimation

As discussed in Chapter 3, the recuperator matrix specific weight is actually affected by many factors such as material type, hydraulic diameter, operating conditions and flow configuration. The weight estimation for primary surface recuperator is conducted based on the correlation highlighted in Figure 3.2. Besides that, it is not the purpose of this section to provide in-depth technical analyses on the actual sizing of a specific recuperator, which involves detailed recuperator design (we would discuss it in the later Chapter). However, a generalized discussion on the recuperator volume is germane by taking some major size-related factors into consideration. It is suggested that the recuperator matrix volume could be considered approximately proportional to the following group of parameters, including engine power related function, recuperator performance parameters and heat transfer surface geometry characteristics [131].

$$V \propto \frac{P}{\sqrt{PR}} \cdot \left(\frac{\varepsilon}{1-\varepsilon}\frac{1}{\sqrt{\Delta p/p}}\right) \cdot \left(\sqrt{\frac{f}{j^3}\frac{1}{\beta}}\right)$$

(Power parameter) (Recuperator parameter) (Surface geometry)

Derived from Ref.[132], Figure 4.1 represents a supplement to work presented previously for weight estimation, and now also includes information about the recuperator volume. It shows the influence of thermal effectiveness on recuperator specific weight and volume. It is well recognized from the portrayal of data that similar to the parameter of recuperator specific weight, the specific volume is also very sensitive to thermal effectiveness. The plots are merely for the recuperator matrix, which do not include installation details such as casings, supporting structure and connecting ducts etc. The data portrayed is based on accumulated heat exchanger information collected by McDonald for recuperated gas turbines in power generation applications, where minimizing the recuperator weight and volume is not paramount. Compared with conventional industrial and vehicular gas turbine recuperators, for aeroengines the recuperator volume and weight need to be strictly controlled during design and manufacture process. For the purpose of this study, the lower limit of the band is defined as the installed volume. Due to the twin-engine configuration of the investigated reference helicopter, the gross recuperator weight and volume corresponding to the helicopter needs to be extended for two turboshaft engines while considering the potential installation, additional recuperator weight penalty as well as associated fuel saving benefits.

The additional recuperator pressure loss Δp at the design point is assumed to be 5% when the ε_{ds} is in the range of 80-90% based on engineering judgment and reported cases [11,84] for microturbine applications under the identical recuperator effectiveness scope. Correspondingly, Table 4.1 presents related recuperator parameters for the turboshaft engine at the design point. To integrate a recuperator into the existing simple cycle helicopter turboshaft engine, the recuperator installation should have minimal influences on the helicopter fuselage aerodynamic profile, as well as system size and volume.

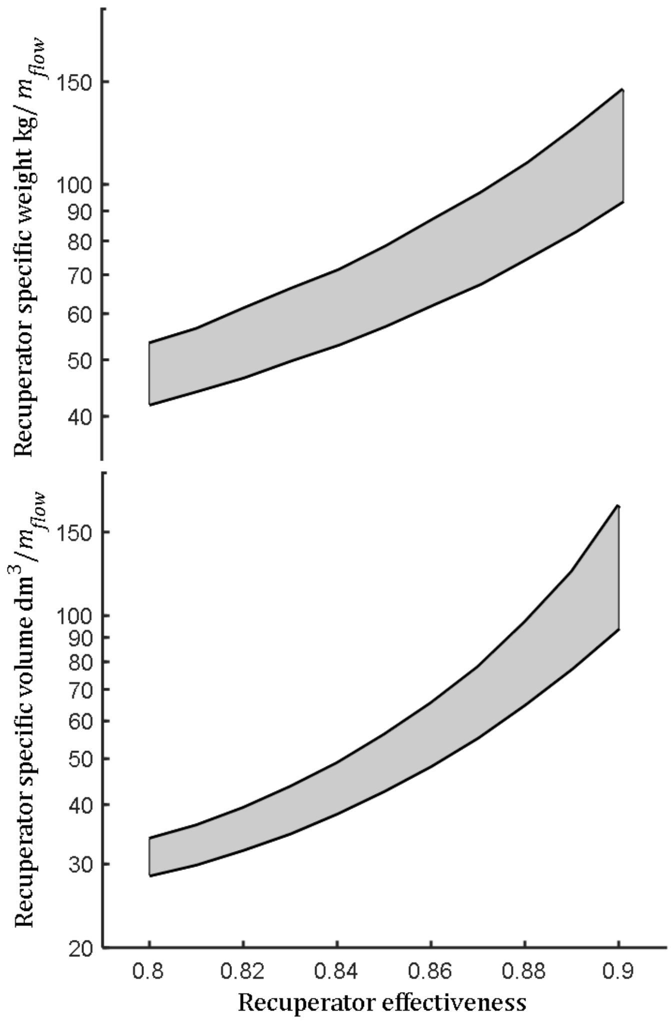


Figure 4.1: Gas turbine recuperator specific weight and volume tendency for primary surface geometry (derived from Ref.[132])

ε_{ds}	Weight (kg)	Volume (m^3)
80%	2*61.4	2*0.0416
85%	2*84.6	2*0.0627
90%	2*138.6	2*0.1401

Table 4.1: Recuperator weight and volume with the designed effectiveness

4.3 Recuperated engine part-load performance

Due to the heat transfer between compressed air and exhaust gas prior to the combustion chamber, less fuel consumption would be required to heat the compressed air/fuel mixture up to the desired turbine inlet temperature, which serves as a fundamental advantage offered by the recuperated cycle.

Performance data for this turboshaft engine considering the influence of PR and TIT on SFC and SP are given on Figure 4.2. To enable a comparison to be made with the original non-recuperated engine at the design point, a compressor pressure ratio of 7.2 and TIT of 1400K are maintained. Based on the GasTurb simulation results, the SFC and SP are 0.268 kg/(kW.h) and 184.7 kW/(kg/s) respectively, for the assumed recuperator designed effectiveness of 80%, which present a remarkable 32.3% improvement in terms of SFC. The rise of pressure ratio could promote the performance of the simple Brayton cycle, while on the contrary mitigate the benefit of the added recuperator in the recuperated cycle. In particular, with large PR the compressor outlet temperature increases prominently which leads to a smaller temperature difference between exhaust gas and compressed air, as a result, less exhaust gas heat would be available to be transferred to compressed air during the heat transfer process happened in the recuperator. Sometimes if the PR is too high, the use of a recuperator would not even be beneficial as can be observed from the slight variation in SFC values for the operational point at which PR=10 and TIT=1100K in both cycles. The recuperator concept may find good acceptance for low overall pressure ratio engines, including most Rolls Royce Model 250 family of turbine engines, which are equipped in popular aircrafts and helicopters such as the Bell 206B/TH-67, MD500 and Bo105 series.

For a typical modern rotorcraft, it basically operates at full power during take-off or climb to altitude, whereas much of its mission time is spent at part load cruise power. A comparison indicating the difference in terms of SFC for simple cycle and recuperated engine operation is given in Figure 4.3. As can be observed in this figure, generally a remarkable 32%-47% SFC improvement over the non-recuperated reference simple cycle is achieved when ε_{ds} is in the range of 80-90%. The beneficial fairly-flat SFC curve of the recuperated cycle shows attractive part-power SFC characteristic which emphasizes the requirement of developing low-cost, reliable recuperators with high effectiveness for the intended use in rotorcraft applications.

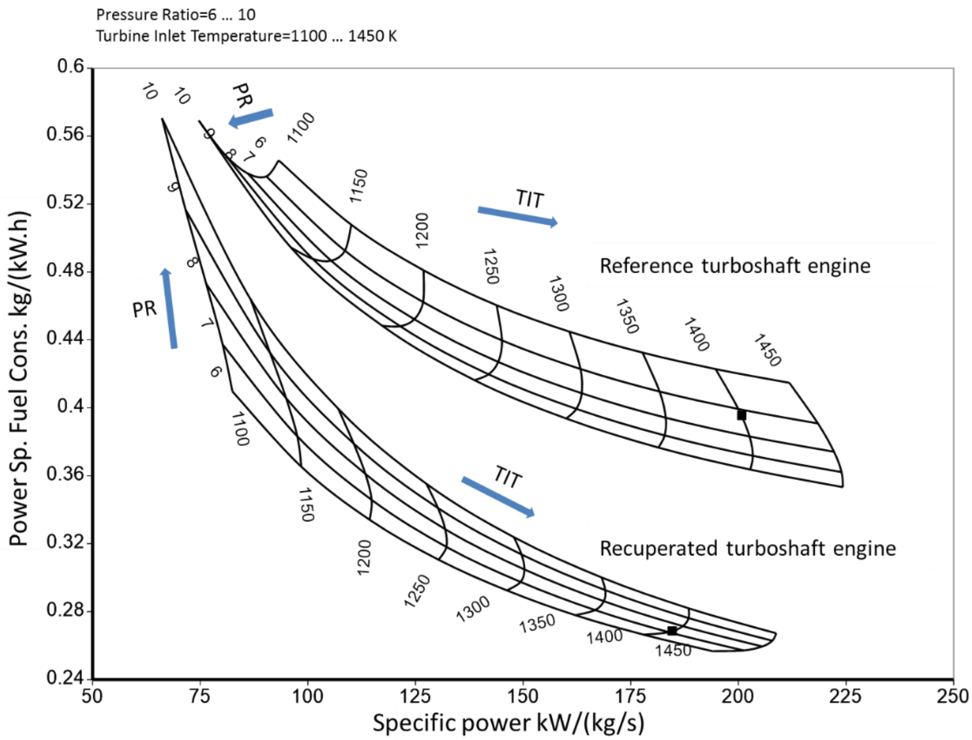


Figure 4.2: Design parameter study for turboshaft gas turbines with/without recuperator

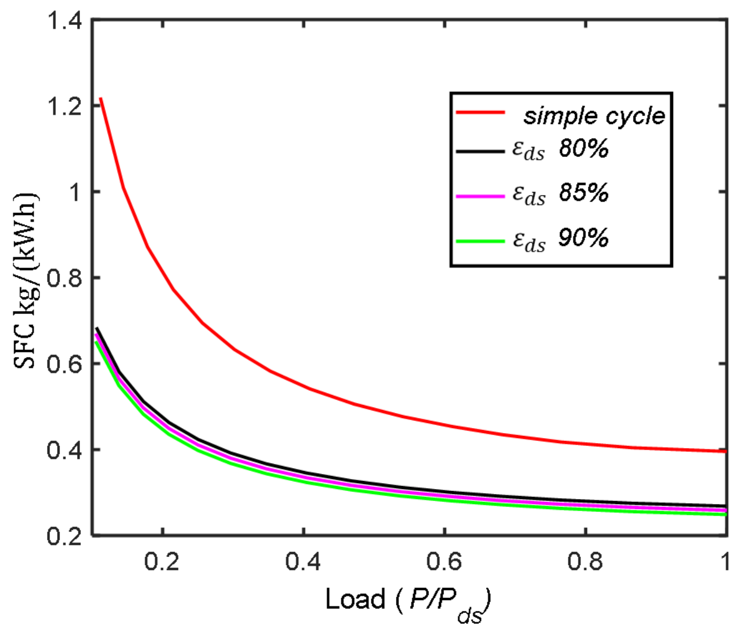


Figure 4.3: The variation of SFC at various working load for different design effectiveness (MSL, ISA conditions)

The recuperator performance in partial load is shown in Figure 4.4. At the design point, the pressure losses on the cold and hot sides are 2% and 3% respectively, while design effectiveness ε_{ds} is 80%. Apparently, in off-design the thermal effectiveness increases at part power, since the mass flow decreases while the heat transfer surface remains constant. The pressure losses on the cold side (i.e. compressed air side) increase in partial load as a result of the increased heat transfer while the exit corrected flow keeps approximately constant. On the other hand, the pressure losses of exhaust gas decline obviously at part load because of the significant decrease of corrected flow at the inlet. The total pressure losses as a whole show an increase tendency with engine load, amounting to 5% at the design point.

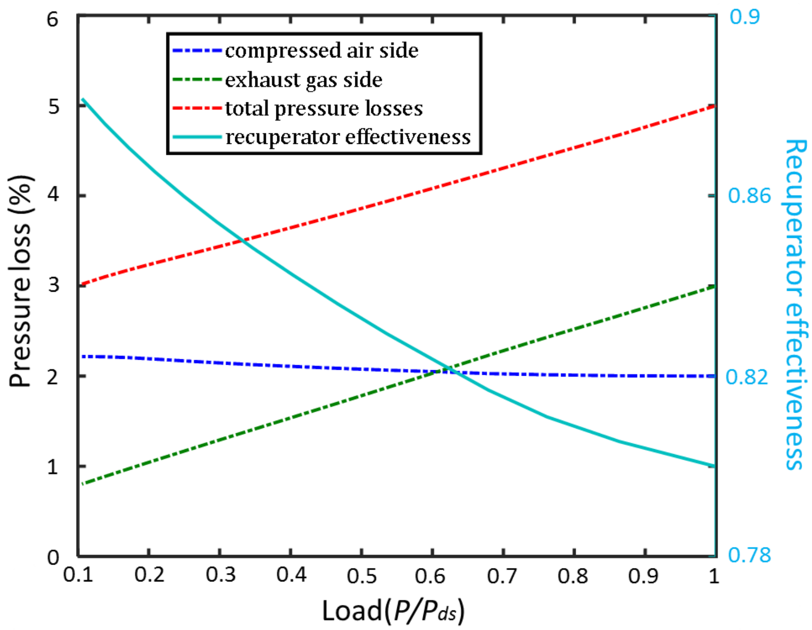


Figure 4.4: The performance of recuperator at part load

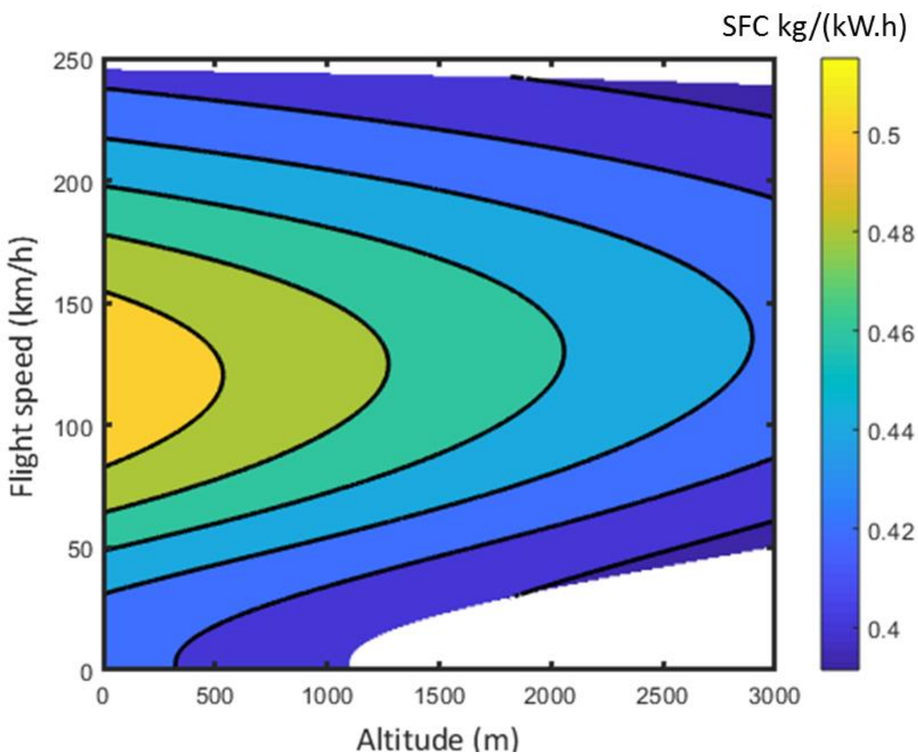
4.4 Various flight conditions

4.4.1 Comparison analysis

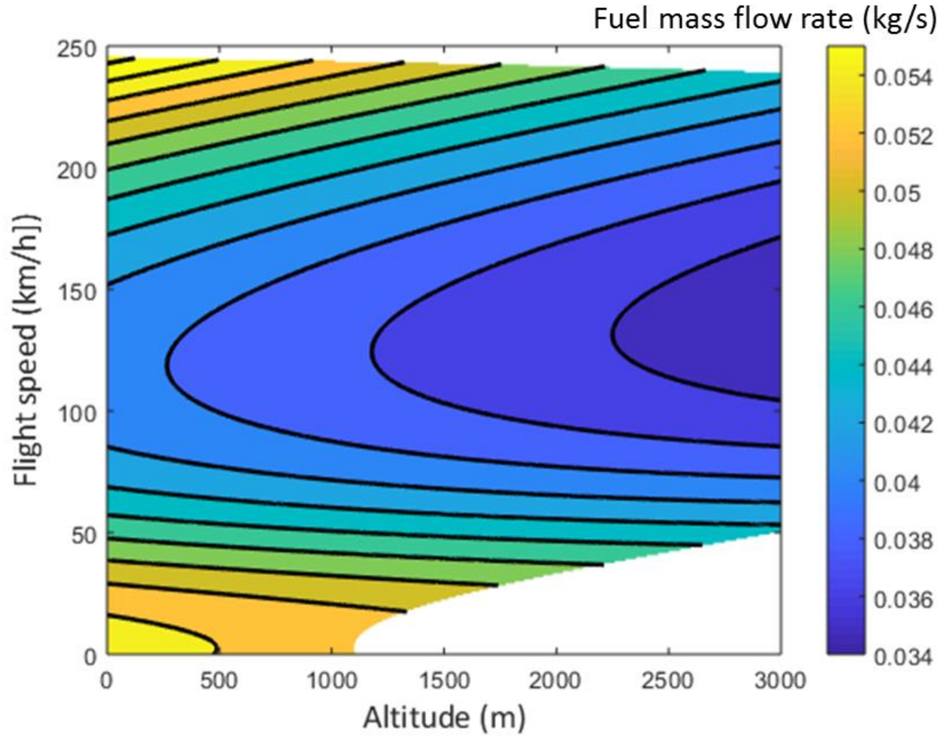
Figure 4.5a and b depicts SFC and fuel mass flow rate of non-recuperated helicopter under various flight conditions, correspondingly, in comparison with this referenced simple cycle, the promoted performance while implementing recuperator (ε_{ds}=80%) could be obtained as well (see Figure 4.6a and b). Results presented are based on the level flight, and are extended for two turboshaft engines based on the twin-engine configuration. Apparently a significant SFC reduction and fuel economy promotion could be achieved while integrating recuperator under a wide range of flight conditions. Specifically, throughout the whole investigated region, generally for the recuperated helicopter a fuel consumption of 0.022-0.038 kg/s which means a proximately 30% and above fuel reduction when compared with the original reference helicopter. In this work, unreasonable points at which the maximal available power could not meet the actual power requirement under the given flight condition are eliminated.

Due to the dominant role they play in helicopter propulsion, for both military and civil applications, turboshaft engines are of great interest to be equipped with recuperators. The rapidly increased fuel price, stringent emissions legislation, together with some other special requirements (e.g. reducing exhaust thermal signature in military helicopter) would all stimulate technical interest to develop “greener”, more efficient recuperated turboshaft engines. However before widespread deployment, sufficient valuable flight worthiness testing would be required to ensure their integrity and reliability.

From previous discussion, the fuel saving capacity of recuperated cycle is well recognized. Considering the very nature of helicopter application, size and weight are critical issues that have negated the widespread use of recuperators in the past. Continuous effort is therefore required to downsize the recuperator and reduce its weight for universal application.

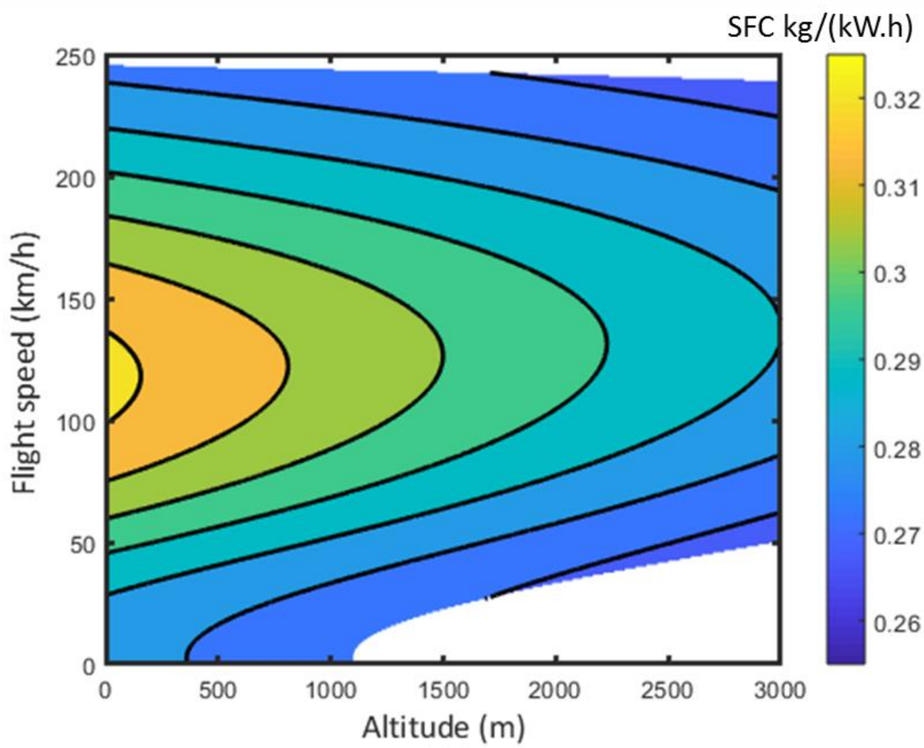


a). SFC variation

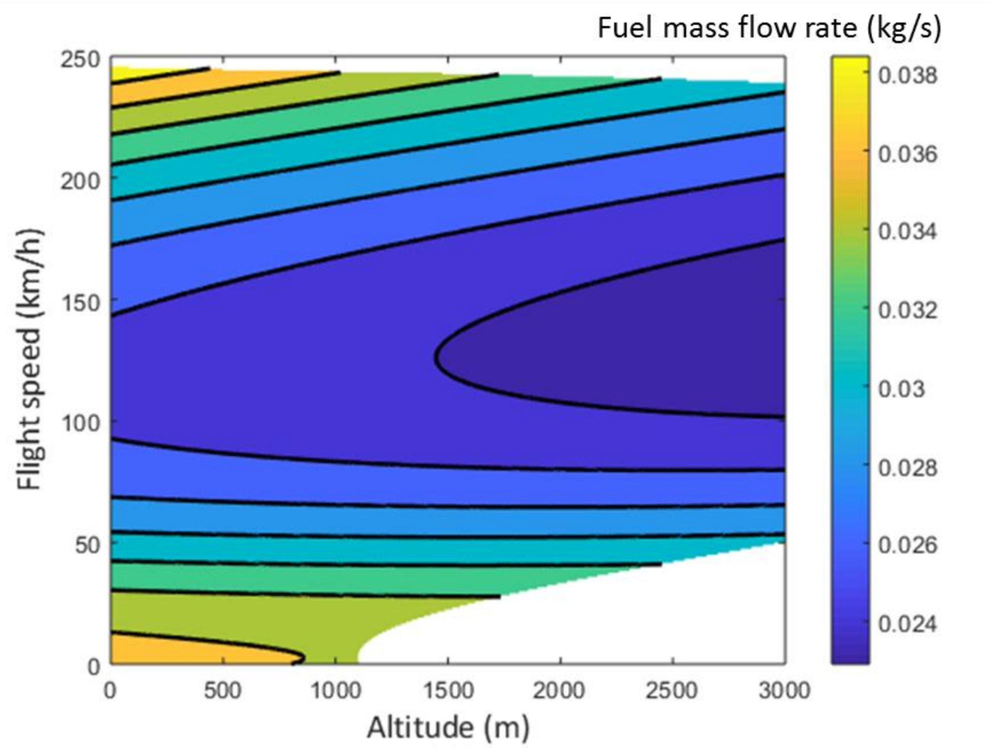


b). fuel mass flow variation

Figure 4.5: Non-recuperated helicopter performance under various flight conditions



a). SFC variation

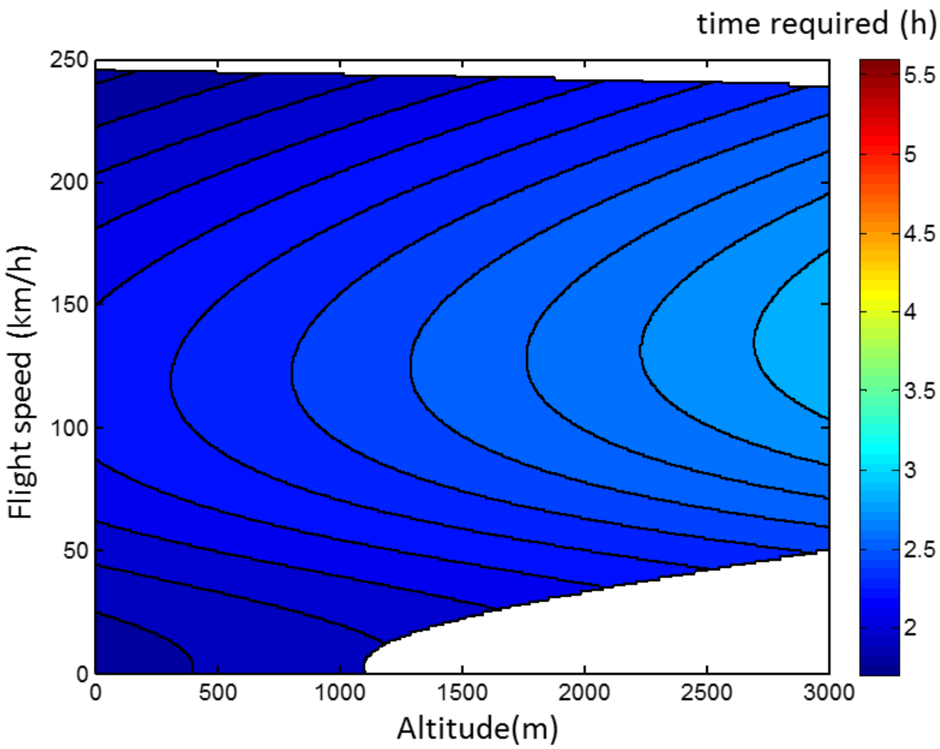


b). fuel mass flow variation

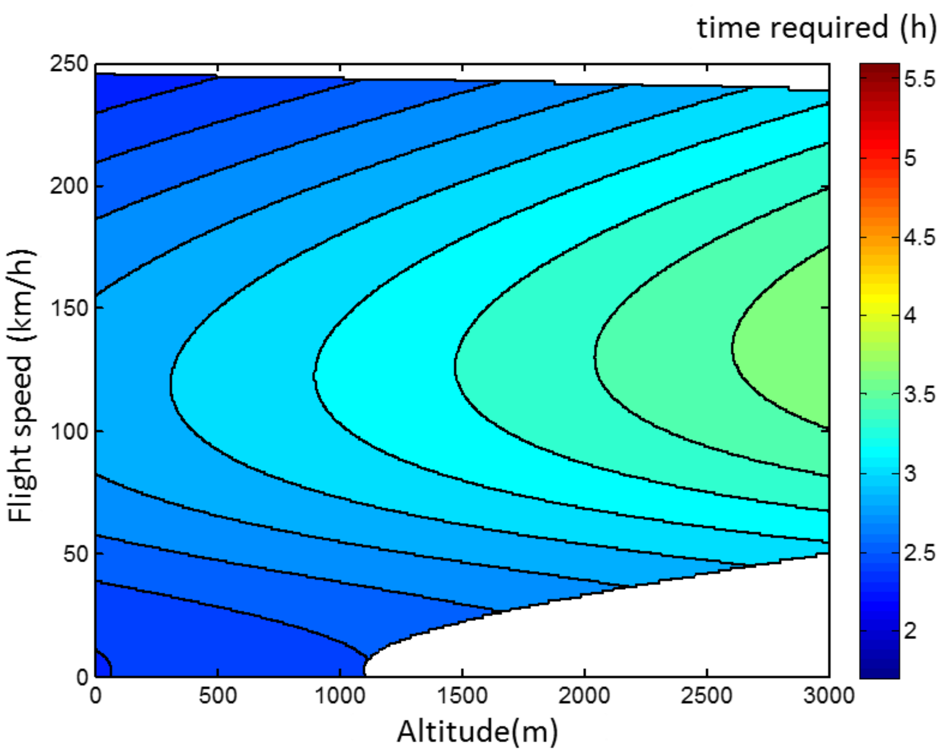
Figure 4.6: Recuperated helicopter performance under various flight conditions (ε_{ds}=80%)

4.4.2 Fuel saving potential investigation

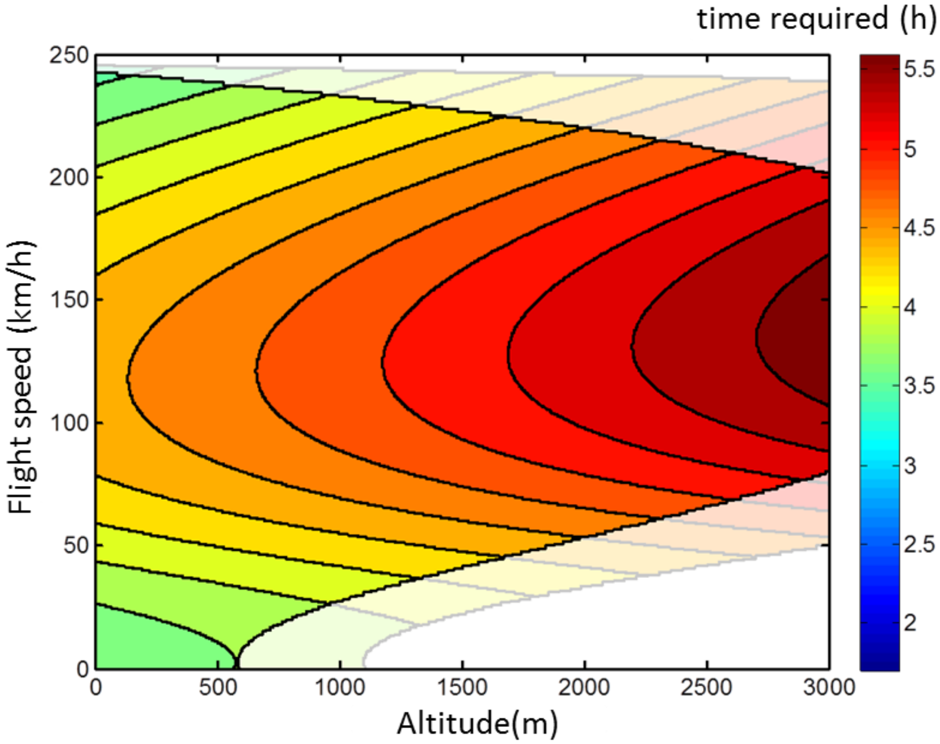
The recuperated cycle could achieve a substantial amount of fuel consumption reduction under different flight conditions, thus extending the flight range and endurance for helicopters while performing different tasks. In terms of a specific cruise flight condition with given speed and altitude, the saved fuel consumption grows proportionally with mission time (more precisely the cruise flight time). Higher recuperator effectiveness shows larger fuel saving capacity, but in the meanwhile this could also lead to the nonlinearly increased recuperator matrix weight as depicted in Figure 3.2. Figure 4.7 a-c present the flight time required to compensate for the additional recuperator weight, i.e. reach the equilibrium point (ΔM=0) with different ε_{ds} values when the TOW=2400 kg at the maximal fuel capacity.



a). ε_{ds}=80%



b). ε_{ds}=85%



c). ε_{ds}=90%

Figure 4.7: Cruise flight time required to compensate the added recuperator weight (i.e. ΔM =0)

Obviously, in order to ensure the economical feasibility of recuperated helicopter, the equilibrium point must be satisfied while incorporating a recuperator into the existing powerplant system. Generally, as can be observed from this figure, more than 2 hours would be needed to offset the parasitic weight of the recuperator. Resulted from the significant addition of weight obtained from the highly effective recuperator, the break-even time is basically more than 3.5h for the case of ε_{ds}= 90%, which is too long for typical flight missions. In some cases, it would even exceed the maximum flight duration of this flight condition as shown from the grey area in Figure 4.7c. It has been established that the growing recuperator weight penalty associated from increased heat exchanger effectiveness generally demands the helicopter to extend its flight duration in order to benefit from the incorporation of recuperators.

With reference to recuperator design, the selection of actual effectiveness is mainly dependent on the commonly adopted mission profile and flight duration. For modern rotorcraft powerplant applications, identified factors including: advanced compact heat exchanger concept, innovative materials, etc. would all be of great significance to overcome the conflict between the inherited recuperator weight penalty and valuable fuel saving benefits.

4.5 Recuperator installation consideration

Being functions of mass flow and effectiveness, the recuperator volume grows significantly with the effectiveness, especially for higher ε_{ds} values (see Figure 4.1). Increasing the effectiveness from 85% to 90% would lead to a dramatic growth in recuperator size by a factor of about 2.2 as can be obtained in Table 4.1. A complete full-scale 3D engine bay of the reference helicopter is modeled by using CATIA V5 to visually illustrate the influence of recuperator volume on the installation of the turboshaft engine, as shown in Figure 4.8. The helicopter is powered by two turboshaft engines which display a symmetric configuration in the compartment, and here only an engine on one side is given for illustration.

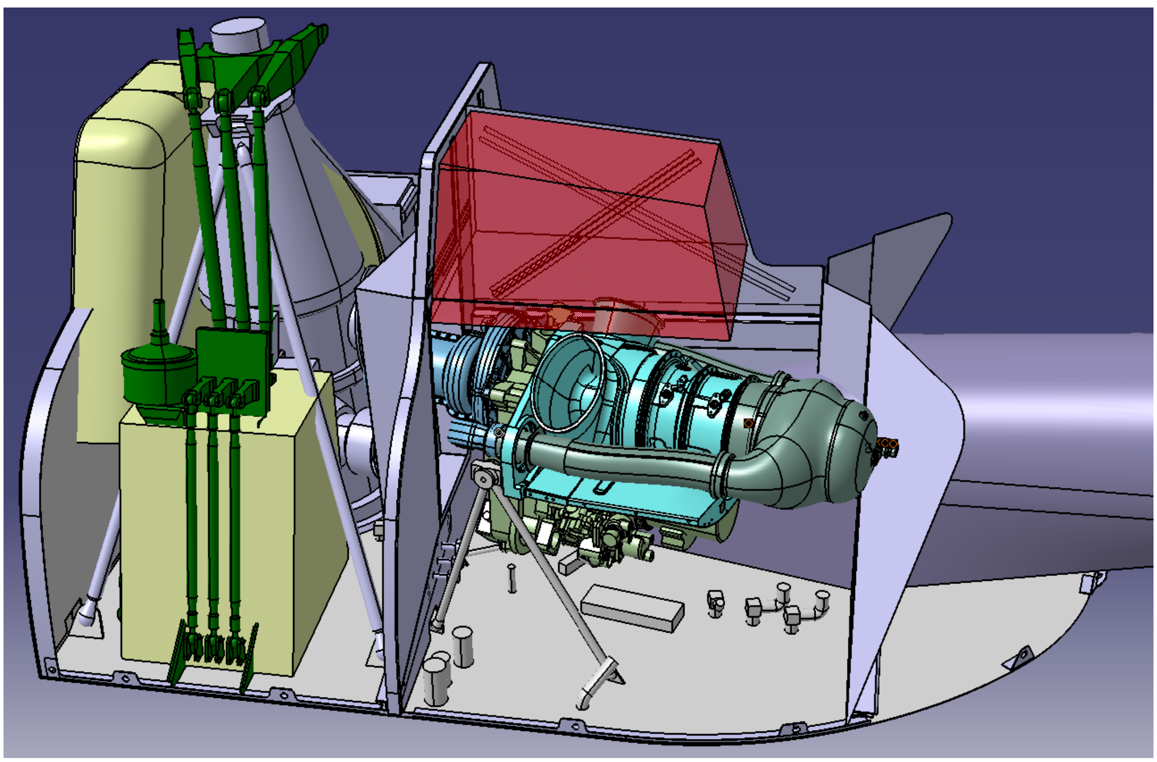


Figure 4.8: The internal structure of the engine bay with integrated engine model

It is interesting to note from Figure 4.8 that for the Allison 250 engine series, the compressed air is ducted through two diffuser tubes to the combustor at the engine rear, after combustion the exhaust gas flows in a reversed direction to the turbine located intermediate the combustor and compressor. Such configuration makes the investigated turboshaft engine especially suitable to be retrofit to incorporate a high performance recuperator without unduly changing the air flow path of the whole system. In the engine compartment, above the engine unit it provides available space for the installation of recuperator. Take ε_{ds}=85% as an example, the cube shaped recuperator configuration, with a corresponding matrix volume of 0.0627 m^3, is adopted using primary surface geometry. Nevertheless, the potential installation space identified in red from Figure 4.8 offers an available volume of 0.043 m^3 which is not sufficient to meet this size requirement. Actually, this available space could only enable the incorporation of recuperator with a maximum designed effectiveness of approximately 80% in this work.

The excessive weight and bulky size of early heat exchangers are some of major factors that impede the wide acceptance of recuperated aeroengines, and therefore light weight, compact volume and compatible gas flow paths are all deemed as necessary features while developing candidate recuperators for future propulsion gas turbines.

It is accepted that meeting increasingly stricter future economic and environmental requirements will inevitably have a profound impact on aeroengines' design and operation, which has also contributed to the current interest in developing high performance heat exchangers in the aeroengine industry. For helicopter turboshaft engines, the major advantage of the recuperated cycle over the conventional Brayton cycle is the improved SFC at partial load, where the majority of the engine operating time would be spent. Primarily due to the increased engine cost, weight and volume, as well as reliability concerns, at present the recuperated helicopter has not yet come to fruition. Novel compact heat exchangers with light weight, small volume and high effectiveness are projected to improve rotorcraft performance with advanced materials and improved manufacturing technologies.

4.6 Summary

In light of the previous researches on recuperator technology with respect to its application to rotorcraft powerplants. Focus was primarily put on tubular recuperator with a relatively low thermal effectiveness. Nowadays, primary surface recuperator would be regarded as a promising candidate considering the current technology readiness on high temperature heat exchanger.

For the purpose of this study, the integrated multidisciplinary rotorcraft simulation framework has been further implemented to evaluate the potential of recuperated helicopter turboshaft engine, adopting highly effective primary surface recuperator for a higher level of thermal effectiveness, saying 80-90%. The improved part-load performance of recuperated engine in contrast to the simple cycle counterpart is investigated in detail, followed by the analysis and evaluation of fuel saving potential under various flight conditions (with the flight speed of 0-250 km/h and altitude of 0-3000 m). The impact of recuperator volume and potential installation are discussed as well.

The obtained results suggest a considerable reduction in fuel burn and therefore have great potential in enhancing the helicopter operational performance (e.g. rotorcraft range and payload capability) while incorporating highly effective recuperators into rotorcraft systems. However, it would not give favorable performance for short-term flight duration, especially while conducting the flight at high altitude, as the fuel consumption reduction of recuperated cycle during the whole mission is not sufficient to offset the added parasitic weight of the recuperator.

5. Multi-objective design and optimization of recuperator

Targeting higher efficiency and lower emissions, the employment of recuperators in helicopters is well recognized as an attractive technical strategy to enhance the operational capabilities. Primary surface heat exchanger is proposed for such applications, as its favorable characteristics of good heat transfer performance and compact structure enable a light weight recuperator design in the aeroengine industry. In the present study, aimed at designing a primary surface recuperator (PSR) potentially applicable to rotorcraft powerplants, initially, promising heat transfer surface geometries are evaluated based on their aerothermal performance. In the next phase of this research, through the execution of multi-objective genetic algorithm (GA) optimization, the interdependencies between recuperator weight and thermal effectiveness are quantified under specific constraints, with respect to the selected heat transfer surface geometries. Eventually, the acquired results of optimal designs (four optimized recuperator design solutions) are selected and further analyzed within the previously proposed rotorcraft multidisciplinary simulation framework, which enables a comprehensive performance assessment of complete helicopter operations under different flight conditions as well as at mission levels, while adopting promising recuperators.

5.1 Research background

The main requirements on recuperators for aeroengine systems include desirable aerothermal performance, low introduced pressure losses, light weight, compact size as well as high reliability. Primary surface heat exchanger is proposed for such application, and it is known to have a relatively high volume goodness factor with good thermal effectiveness, which shows great potential for use in desirable compact recuperator designs. Primary surface recuperators have been utilized in micro gas turbine systems for distributed power generation, which give satisfying performance and demonstrate a high degree of structural integrity in the meanwhile.

Lots of researchers have carried out experimental and numerical investigations to reveal the flow and heat transfer characteristics of primary surface heat exchangers [133-144]. In particular, Focke et al. [133] used the electrochemical mass transfer method to investigate the influence of the corrugation angle on the thermalhydraulic performance of cross-corrugated (CC) plates. Blomerius et al. [134] conducted parametrical investigations to analyze the convective heat transfer and pressure drop of wavy plates in the laminar and transitional flow regimes. Stasiek et al. [135,136] investigated the influence of the Reynolds number, the corrugation angle and geometric parameters on the performance of corrugated passages, from the viewpoint of both experimental work and numerical simulation. Yin et al. [137] analyzed fluid field and heat transfer in a cross-corrugated plate with laminar flow assumption by utilizing CFD simulation. Elshafei et al. [138] performed experiments on corrugated channels of uniform wall temperature and of fixed corrugation ratio over a wide range of Reynolds number (i.e. $3220<Re<9420$). The influences of channel spacing and phase shift variations on convective heat transfer and pressure drop characteristics were also discussed in detail. Turbulent complex three-dimensional air flow and heat transfer inside a cross-corrugated triangular duct was numerically studied by Zhang [139], employing four different turbulence models: standard k- ε model (SKE), Renormalized k- ε model (RNG-KE), the low Reynolds k- w model (LKW), and the Reynolds stress models (RSM).

Heat exchanger design is a complex procedure, which involves a compromise of different conflicting design objectives. The overall recuperator design methodology for an intended application normally includes thermal design, mechanical analysis and manufacturing consideration [145]. The main objective of recuperator design is to determine the heat transfer surface geometry and recuperator dimensions, finding the best compromise among normally conflicting design requirements in terms of high effectiveness, allowable pressure drop, compact structure and low cost etc..

In recent years many investigators have applied intelligent algorithms for heat exchanger design optimization [146-150]. Based on specific constraints and evaluation criteria, various targets could be suggested as priorities. Wang et al. [146] conducted multi-objective optimization for geometrical parameters of corrugated-undulated heat transfer surfaces, so as to achieve a maximum heat transfer capability and a minimum pumping power. Liu et al. [147] presented optimization for the primary surface recuperator (PSR) by combining heat transfer effectiveness, exchanger weight and pressure drop into an overall objective function. Selecting the entropy generation rate and total annual cost as objects, Liang et al. [148] optimized an air-to-air heat exchanger with cross-corrugated triangular ducts. A framework is suggested in Figure 5.1 [82] by considering the recuperator performance and system efficiency criterion, and it indicates the general flow chart of recuperator optimization.

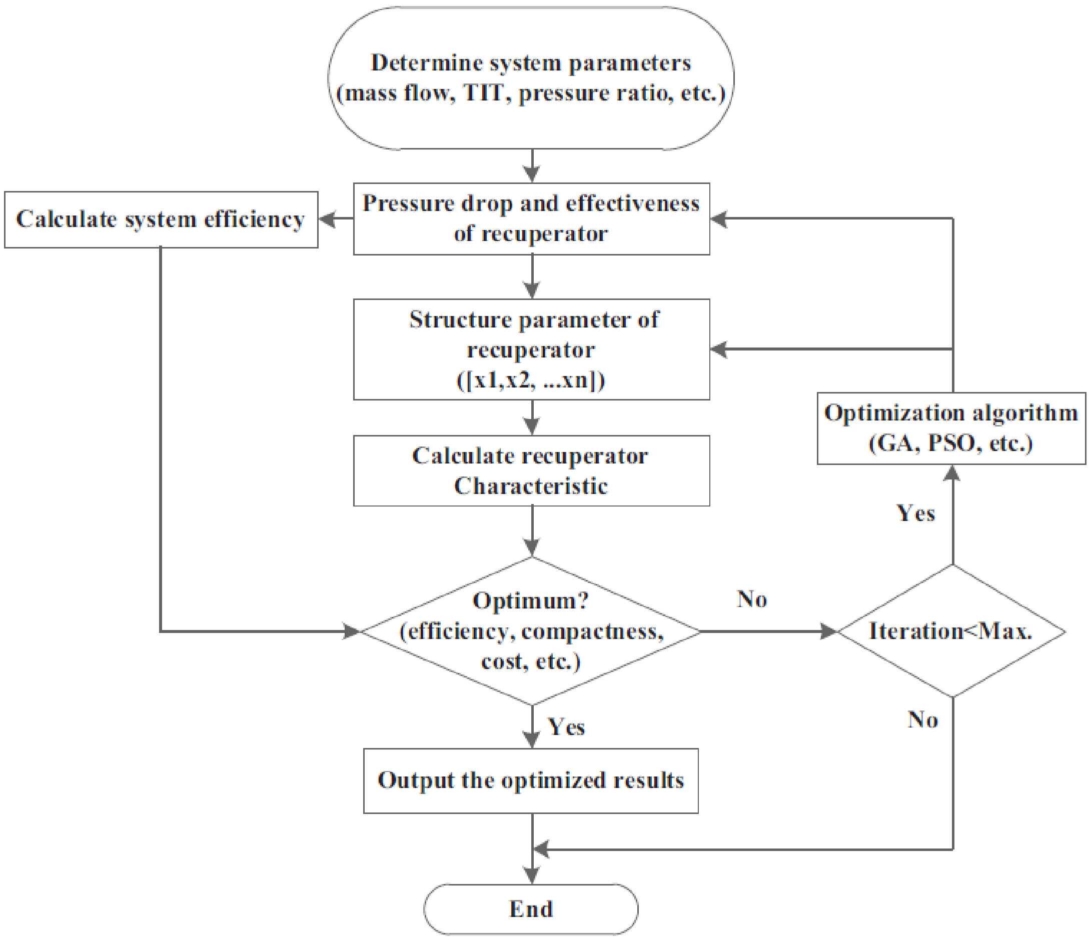


Figure 5.1: General flow chart of recuperator optimization [82]

In this work, in order to obtain the optimal PSR design applicable to a 300 kW-class helicopter turboshaft engine, multi-objective genetic algorithm (GA) optimization is employed to derive the Pareto front model, which quantifies the trade-off between the recuperator weight and thermal effectiveness under defined constraints, such as the allowable pressure drop, available space dimensions. Afterwards, the study is further extended to systematically evaluate the recuperated rotorcraft performance with the selected optimal recuperator design solutions under an integrated multidisciplinary simulation framework at mission levels. The methodology deployed within this study provides a comprehensive solution to address the design complexity and interdependencies associated with the incorporation of high performance recuperator into rotorcraft powerplant system.

5.2 Characteristic parameters of PSR

In the initial stage of this research, geometrical configuration and parameterization of the proposed primary surface have to be defined. Cross-corrugated (CC) surface is selected for the purpose of this study as it is observed that the cross-wavy and cross-corrugated surfaces show superior performance in terms of volume and weight of the heat transfer matrix. However, cross-corrugated surface is better documented in the open literature, and it is also probably easier to manufacture with small passage dimensions in comparison with the cross-wavy ones, thus would be the first choice for further investigation in actual application [84].

As the key heat transfer component of the recuperator, its core represents the majority of weight and volume. In this section, with prime focus on the recuperator matrix design, installation details including header, connecting ducts, casing etc. are therefore excluded from the present study. Taking the recuperator weight into consideration, a coefficient of correction (setting to be 1.25 hereafter) is introduced for calculation on the basis of the recuperator core weight. The matrix of the investigated PSR consists of numerous corrugated plates that are stacked in order to form passages with small hydraulic diameters, as shown in Figure 5.2 [83]. Multiple contact points between plates contribute to high compressive strength and structural stability even with small values of plate thickness. Apparently, the geometry is basically specified by the corrugation pitch P, internal height H_i, plate thickness δ and corrugation angle θ. For the purpose of this study, the wall thickness δ is assumed to be 0.15 mm, which is commercially available in fabrication. Furthermore, the material used is chosen to be stainless steel with a typical density ρ_m of 7.9 g/cm^3.

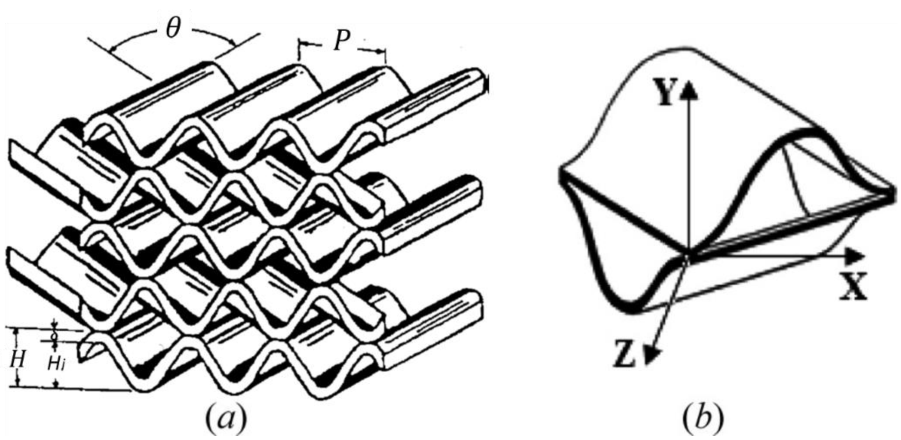


Figure 5.2: a). Typical cross-corrugated (CC) plates, b). unitary cell [83]

Taking the unitary cell into account, the hydraulic diameter could be expressed as

$$D_h = \frac{4V}{S} \quad (5.1)$$

where *V* is the internal volume of the unitary cell for the cross-corrugated matrix, and *S* is the corresponding wetted surface.

Based on the mass flow rate m_f, and the corresponding flow cross-sectional area A_c, the mean velocity ν in the main flow direction is defined as

$$\nu = \frac{m_f}{\rho A_c} \quad (5.2)$$

Accordingly, the Reynolds number *Re* is calculated out as

$$Re = \frac{\rho \nu D_h}{\mu} \quad (5.3)$$

Prandtl number $Pr = \frac{c_p \mu}{\lambda}$ (5.4)

Fanning friction factor *f*, Nusselt number *Nu*, Stanton number *St* and Colburn factor *j* are other important dimensionless parameters, characterizing the heat transfer and flow performance of the plate.

$$f = \frac{\Delta p D_h}{2\rho \nu^2 L} \quad (5.5)$$

$$Nu = \frac{h D_h}{\lambda} \quad (5.6)$$

$$St = \frac{Nu}{Re \cdot Pr} \quad (5.7)$$

$$j = St \cdot Pr^{2/3} \quad (5.8)$$

where L is the extent of the unitary cell along the main flow direction, and h is the convective heat transfer coefficient.

The volume and area goodness factors, which indicate the volume and frontal area (namely the weight and size) requirements respectively [151], could be used to comparatively evaluate the aerothermal performance of different surface geometries.

Volume goodness facto $G_{vol} = \frac{St}{f^{1/3}}$ (5.9)

Area goodness factor $G_{area} = \frac{j}{f}$ (5.10)

Typically, for a given pumping power with constant fluid thermo-mechanical properties, a higher volume goodness factor represents a smaller heat transfer surface area, which contributes to lower volume (and weight) for the heat exchanger matrix, while a larger area goodness factor yields correspondingly a smaller heat exchanger frontal area [85]. Apparently, a desirable heat transfer surface geometry should exhibit high Nusselt number and low Fanning friction factor, thus contributing to large G_{vol} and G_{area} values in the compact heat exchanger design.

5.3 Simulation methodology

5.3.1 Physical model and thermodynamic calculation

A reference rotorcraft considered for the sake of this work is modeled after helicopter Bo105, which is powered by two Allison 250-C20B turboshaft engine variants displaying a symmetric configuration in the compartment (see Figure 4.8). As explained earlier, in the engine compartment, above the engine unit it provides potential installation space for the recuperator. The schematic configuration of the V-shaped recuperator with two individual single-pass, counter-flow arrangement modules is given in Figure 5.3 to meet the required heat transfer capacity.

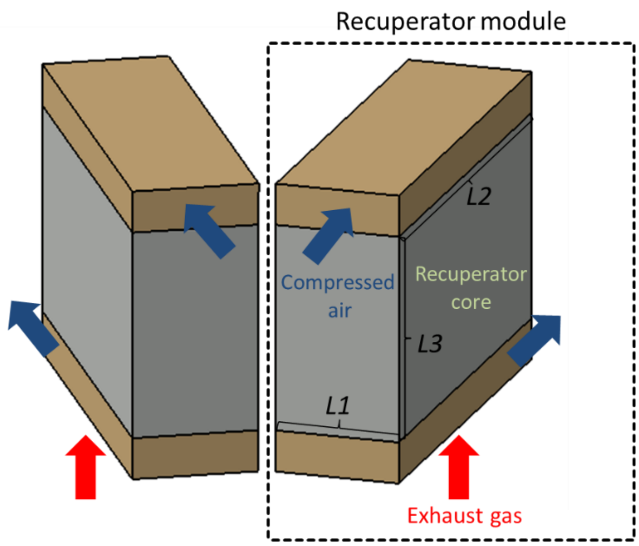


Figure 5.3: Schematic configuration of the V-shaped recuperator with two modules

In the present study, a single recuperator module having matrix dimensions: width *L1*, length *L2* and height *L3*, is considered for the heat exchanger sizing optimization. The main operating parameters with respect to the integrated helicopter-engine system are summarized in Table 3.1, and Table 5.1 lists the recuperator design requirements. Out of economic consideration, the recuperator effectiveness should be no less than 75%. As stated in Ref.[152], the cycle performance does not change significantly if the total pressure drop of gas and air sides remains constant. Therefore the total pressure drop is considered as a restraint, instead of the values of each side. Although, primary surface recuperators have been under development for some years, the optimization design still proves to be evolving and challenging [145]. It is well recognized that the development of recuperator is embraced with compromise among various conflicting design targets for the sake of accomplishing a series of performance requirements.

Parameter	Hot side	Cold side
Working substance	exhaust gas	compressed air
Mass flow rate (kg/s)	0.752	0.735
Inlet temperature (K)	975	576
Inlet pressure (kPa)	108.32	707.65
Effectiveness ε	≥75%	
Allowable pressure drop Δp_{max}	5%	
Width $L1$ (m)	0.05~0.28	
Length $L2$ (m)	0.05~0.48	
Height $L3$ (m)	0.05~0.2	

Table 5.1: Recuperator module design requirements

The implementation of recuperator design optimization is based on Matlab programing, and herein comprises two procedures, i.e. thermodynamic model for recuperator performance calculation and multi-objective genetic algorithm, as shown in Figure 5.4. For the purpose of this study, the heat transfer element (ε-NTU) method is utilized for thermodynamic calculation to predict the recuperator performance, and the corresponding flow chart is also indicated (see Figure 5.4). The effectiveness ε for the counter-flow configuration is presented as

$$\varepsilon = 1 - \frac{1-\exp[-NTU(1-C^*)]}{1-C^*\exp[-NTU(1-C^*)]} \tag{5.11}$$

Here $C^* = \frac{(c_p \cdot m_f)_{min}}{(c_p \cdot m_f)_{max}}$ is the heat capacity ratio of the fluids, and the number of transfer units $NTU = \frac{UA}{(c_p \cdot m_f)_{min}}$, among which, U and A indicate the overall heat transfer coefficient and heat transfer area, respectively.

The accuracy of the established thermodynamic model with respect to recuperator performance prediction has been validated by comparing the present calculation results with Ref.[97] for three typical symmetric sinusoidal geometry structures under the identical conditions. With a recuperator effectiveness of 87%, the exhaust gas and air inlet temperature are 637 ℃ and 194 ℃ respectively, while the mass flow rate of gas is 0.494 kg/s. As presented in Table 5.2, the discrepancy is within an acceptable range which proves the accuracy of the thermodynamic calculation, and actually the maximal relative error of 3.92% is achieved in terms of recuperator weight for the case of CC2.2-75 (i.e. CC surface with P/H_i=2.2 and corrugation θ=75°).

	CC2.2-75	Cal.	Error	CC3.1-60	Cal.	Error	CC4-45	Cal.	Error
Re	534	526	1.50%	346	336	2.89%	409	401	1.96%
Volume(dm^3)	6.29	6.45	2.54%	13.8	14.0	1.62%	21.9	22.3	1.78%
Weight (kg)	5.1	5.3	3.92%	11.2	11.5	2.68%	17.7	18.3	3.39%
Length (m)	0.067	0.068	1.49%	0.094	0.096	2.13%	0.175	0.179	2.29%
Δp (%)	3	2.89	3.67%	3	2.93	2.33%	3	2.91	3.00%

Table 5.2: Comparisons between calculated results and Ref.[97]

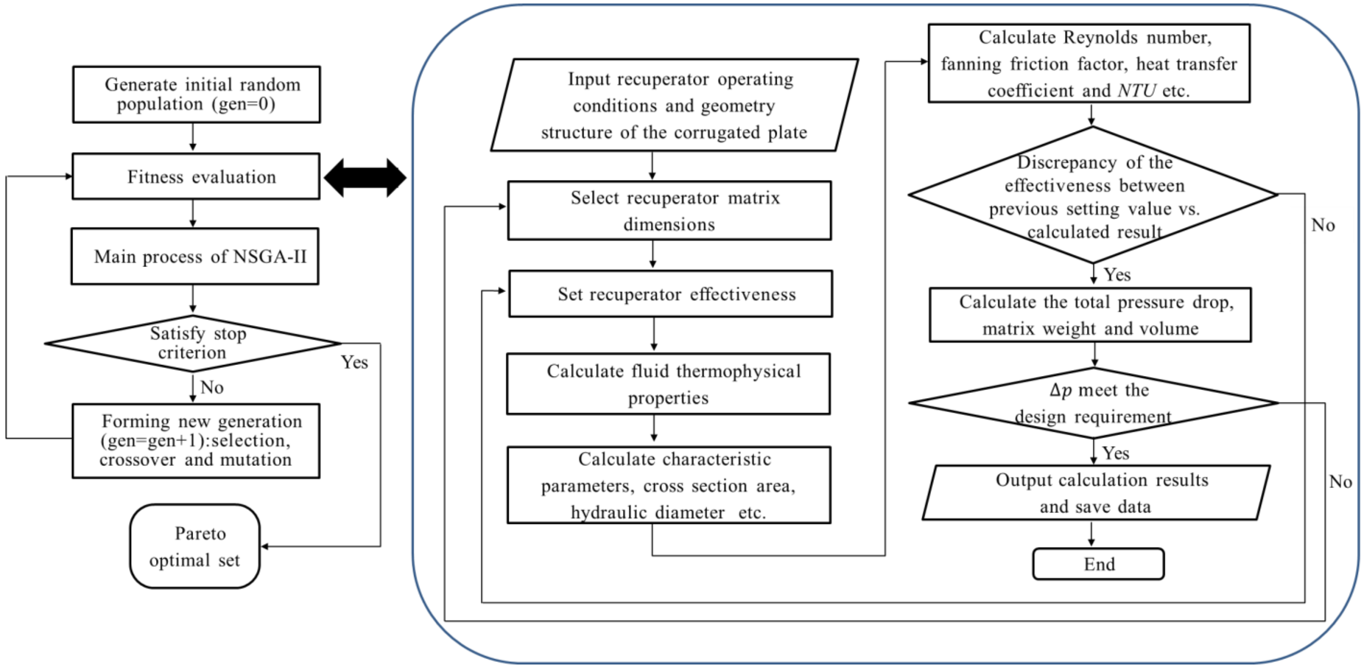


Figure 5.4: The flow chart of optimization process integrating the established thermal modeling

5.3.2 Multi-objective genetic algorithm optimization

The actual design of recuperator in the field of thermal engineering involve simultaneous optimizations of multiple objectives, since various factors could be pursued as priorities, such as weight, volume, heat transfer performance. By the very nature of this particular application for aeroengines, the basic recuperator design requirements are light weight (hence reducing size) and high effectiveness with allowable pressure drop. Resulting from the absence of welding or brazing processes, the material quantity, which relates to the recuperator weight directly, would be the primary factor that affects the final cost. The goal of multi-objective optimization is to obtain the best compromise solutions among different conflicting criterions [149].

The mathematical expression of a typical multi-objective optimization problem would be given as

$$[f_1(X), f_2(X), \dots\dots, f_k(X)]_{min}$$

where variables $X = \{x_1, x_2, \dots\dots, x_j\}$ subject to limitations

$$g_m(X) \leq 0, m = 1,2, \dots$$

$$h_n(X) = 0, n = 1,2, \dots$$

The classical approach to solve the multi-objective optimization problem is to assign a so-called weighting parameter w_i to every single objective, thus obtaining an overall objective function, i.e.

$$\text{Min } F(X) = \sum_{i=1}^{k} w_i f_i\,(X) \qquad (\text{here } \sum w_i = 1) \tag{5.12}$$

The inherent disadvantage of this methodology is that the final optimization results depend strongly on the selection of weighting parameters, and would vary significantly for different weighting parameter combinations. When a complicated multi-objective optimization engineering problem is performed, the objectives under consideration are generally in conflict with one another, and in most cases, it is hence impractical to find a solution that simultaneously provides the optimal performance in terms of every single optimization item. A reasonable approach is to analyze a set of potential optimal solutions, each of which satisfies the objective functions at an acceptable level without being dominated by any other feasible solution. Based on the theory of Pareto optimality, solution A dominates solution B, if and only if,

$$\left(\forall i: f_i(A) \leq f_i(B)\right) \cap \left(\exists j: f_j(A) < f_j(B)\right)$$

In that way, all non-dominated solutions or Pareto front, represent the best trade-off between the involved objective functions, which means it is impractical to obtain a better solution for one objective without worsening the others, as these requirements are mostly inconsistent with one another.

In this study, Non-dominated Sorting Genetic Algorithms (NSGA-II) [153] is utilized to attain these conflicting goals under the defined constraints, as presented in Figure 5.4. Inspired by Charles Darwin's theory of natural evolution, which could be summarized as survival of the fittest, the genetic algorithm (GA) is a powerful tool in many real-life problems according to the specified objectives under defined constraints. The procedure could be shortly descripted as follows: different design variables are encoded into corresponding binary strings, and these binary strings are subsequently grouped into a long string, which represents an individual. Each individual is assigned a fitness value based on its performance under the given environment. New generation of solutions, so called child individuals are produced through the process of survival selection, crossover and mutation between fit parent individuals. After several generations the algorithm would converge to present optimal results.

In our calculation, a population size of 50 has been chosen, and the evolution is controlled to be within 400 generations, besides that, the stall generations are set to be 150, which means the algorithm would also be terminated if the average change in the spread of the Pareto front over 150 generations is less than function tolerance (i.e. 10^{-3}). The conflicting objectives of recuperator weight penalty and associated thermal effectiveness should be optimized simultaneously according to the design constraints as presented in Table 5.1. With regards to the investigated multi-objective optimization problem, the Pareto optimal set would be finally obtained, among which the best compromise solution could be found, and potential recuperator designs are suggested.

5.3.3 Multidisciplinary simulation framework

Apart from the aforementioned optimization strategy for recuperator design, the present work also requires the deployment of integrated rotorcraft simulation framework which involves multidisciplinary knowledge including helicopter flight dynamics, turboshaft engine performance and flight mission analysis etc., so as to systematically evaluate the performance of the proposed recuperator on the whole rotorcraft powerplant under different flight conditions.

As shown in Figure 5.5, the overall methodology combines the established multidisciplinary rotorcraft simulation framework with the employment of recuperator multi-objective genetic algorithm optimization. The aero-thermal performance of various heat transfer surface geometries could be comparatively evaluated in terms of the volume and area goodness factors G_{vol} and G_{area}, and promising candidates are then selected for further geometry parameters and recuperator sizing optimization. Aimed at the maximization of recuperator effectiveness and minimization of the corresponding weight, and a set of multiple optimal solutions, namely Pareto optimal solutions would be attained quantifying the interrelationship and trade-off between these two confliction under specified limitations, e.g., thermal duty, spatial constraints. The recuperator information including weight, volume, operating performance (designed effectiveness, pressure drop, etc.) would be achieved based on multi-optimization processes. Acquired results of optimal recuperator designs could be subsequently applied for mission investigation targeting realistic helicopter operations within the established rotorcraft multidisciplinary simulation framework.

With primary emphasis placed on the improvement of helicopter engine performance and operational benefits arising from the implementation of recuperator, the scope of this work is to further extend the integrated rotorcraft multidisciplinary simulation framework through the employment of multi-objective GA optimization for recuperator design, targeting at finding high performance heat exchangers potentially applicable to rotorcraft powerplants. As a computationally efficient and cost-effective tool, the overall approach can be effectively extended and applied to conduct multidisciplinary design and optimization for recuperated rotorcraft at mission levels.

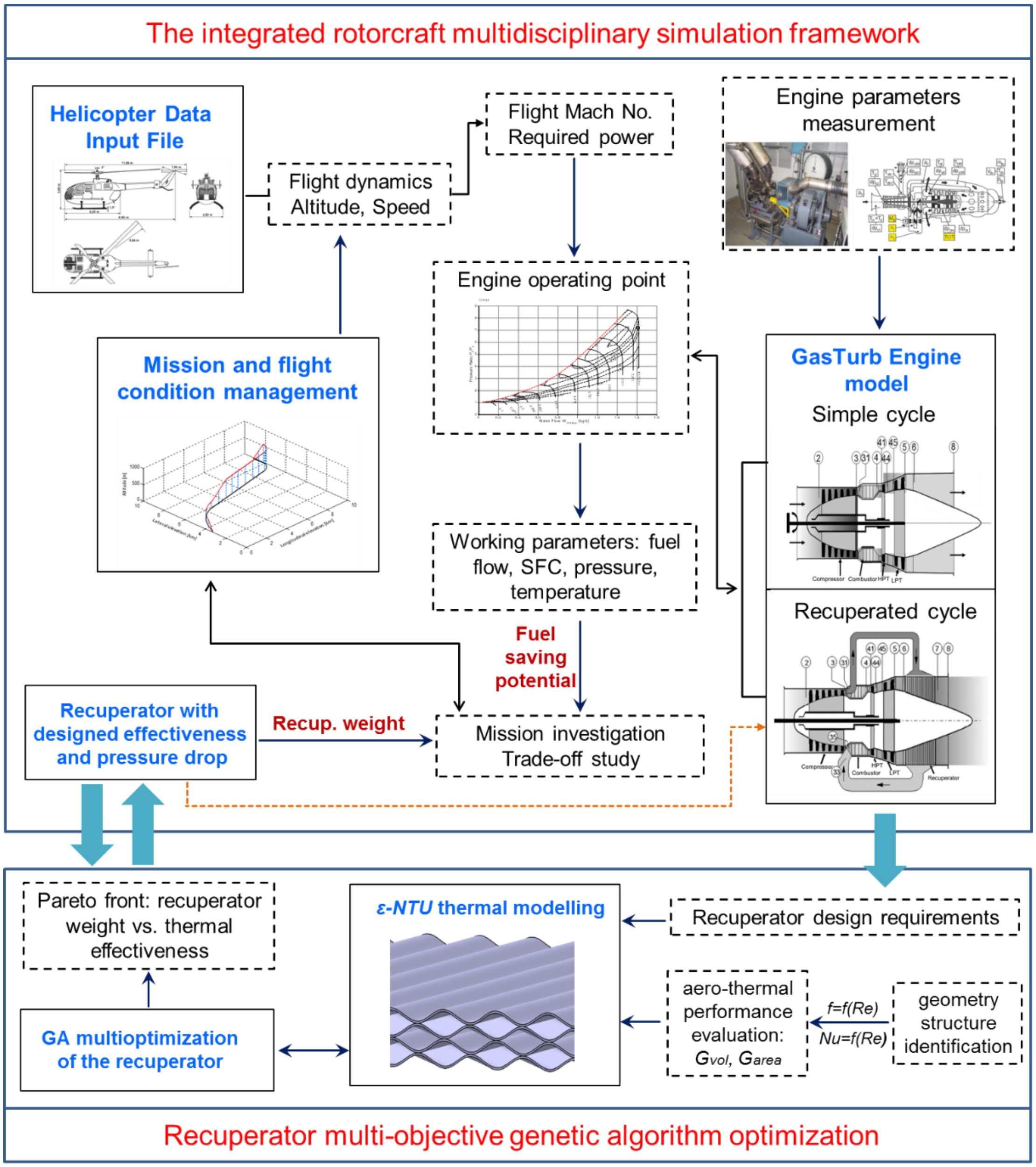
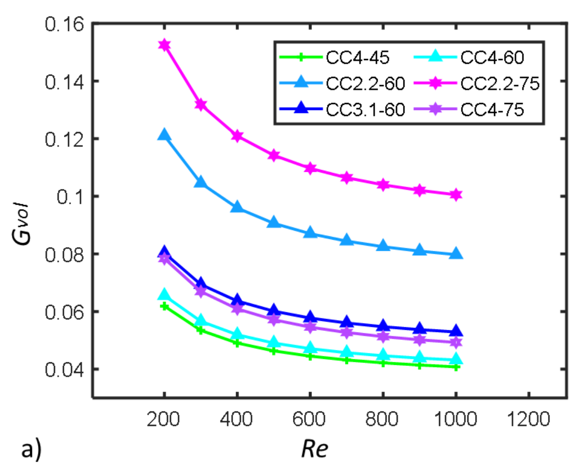


Figure 5.5: The integrated rotorcraft multidisciplinary simulation framework incorporated with optimized recuperator

5.4 Evaluation of heat transfer surfaces

The pitch to height ratio P/H_i and corrugation θ are two identified parameters that mainly determine the heat transfer and flow characteristics of the cross-corrugated (CC) passages. Corrugation θ directly affects the basic flow structure, and therefore influences the thermalhydraulic performance. Geometry with a higher P/H_i value indicates a smoother corrugation profile, whereas a lower value represents a more prominent undulation. Work done by industrial vendors regarding the thermalhydraulic performance of the CC surface is often proprietary and rarely reported in the open literature. Based on the heat transfer and pressure drop correlation equations derived from experimental data [84,97], surface geometry variables (i.e. P and H_i for fixed values of corrugation angel θ), as well as the recuperator matrix dimensions ($L1$, $L2$ and $L3$) were optimized from the viewpoint of the proposed conflicting targets of recuperator weight and effectiveness. In this study, H_i is in the range of 0.6-1.4 mm while various ratios P/H_i (2.2, 3.1 and 4) are considered for calculation, furthermore, different corrugation angles θ (45°, 60° and 75°) have been evaluated. Simulation is conducted for typical run conditions of the adopted recuperator, corresponding to relatively low Re values below 1200, considering the operating mass flow rates and small values of the hydraulic diameter [84].

The aerothermal performance of various geometries was assessed in terms of volume and area goodness factors G_{vol} and G_{area}, in order to justify the selection of surface geometry parameters for the optimized design, as shown in Figure 5.6. Calculations were performed for Prandtl number of 0.7. G_{vol} generally reduces with Reynolds number, while the variation tendency of G_{area} is relatively gentle. Apparently CC surface with P/H_i=2.2 and corrugation θ=75° (denoted as CC2.2-75) has the similar large G_{area} value (slightly higher) under the same Reynolds number in contrast to CC2.2-60, and their G_{vol} values are also significantly higher than other geometries, thus providing the greatest advantage. Since the values of G_{vol} and G_{area} vary with Re, the choice of geometry for the purpose of minimum volume and frontal area requirements is therefore dependent on the operating Reynolds number. In this work, promising geometries candidates, CC2.2-75 and CC2.2-60 are selected for further recuperator design optimization due to their superior performance over other geometries.



a)

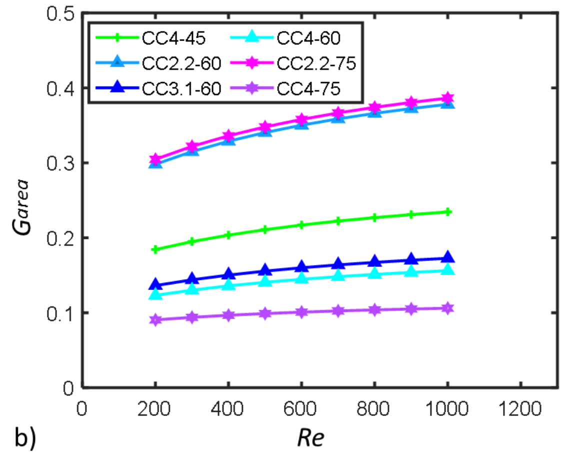


Figure 5.6: Variation of goodness factors as function of Reynolds number for various geometries, a). G_{vol}, b). G_{area}

5.5 Multi-objective optimization

The design of recuperator applicable to rotorcraft attaches much importance to the recuperator weight and volume due to the limited carrying capability and space of the aircraft. It is essentially a complicated and challenging multi-objective optimization problem targeting the best compromised solutions under various constraints. To maximize the effectiveness value and in the meanwhile minimize the recuperator weight, geometry parameters and recuperator sizing optimization were conducted to obtain the best compromises. Under the condition that these design variations are in the aforementioned ranges, Figure 5.7 shows the visualization of the Pareto front for the recuperator module, which clearly reveals the conflict between the two proposed objectives. Obviously, based on the acquired Pareto front, any geometrical change that provides further increased effectiveness would always lead to the growth in recuperator weight, highlighting the employment of multi-objective optimization strategies. Here, manufacturers or engineers could select reasonable CC plate parameters and recuperator dimensions by Figure 5.7 based on their own purpose and preference. The discrete distribution of solutions is collected from the multi-objective optimization results with a step of 0.1mm for H_i variable definition (for manufacturing reasons).

Considering the obtained Pareto front models, CC2.2-75 provides much better solutions in contrast to CC2.2-60 with regards to the conflicting design requirements associated with both objectives, therefore focuses would be given on CC2.2-75 surface for the next stage. It is noticed that the minimum recuperator module weight exists at design point *A* with a smallest effectiveness value of 76.1%. On the other hand, the maximum effectiveness of 89.34% is achieved at design point *D*, correspondingly, the recuperator module weight is also maximal at that point. Points *A* and *D* would be separately regarded as the optimal situations, at which recuperator weight and effectiveness are the single objective functions respectively. The determination of final solution among the optimum points existing on the Pareto front is mainly dependent on engineering judgment for the intended application. For the purpose of this study, four representative recuperator optimal design points *A*-*D* would be recommended for further helicopter performance evaluation with desired thermal performance and reasonable recuperator weight, and Table 5.3 gives the corresponding optimized results of these points.

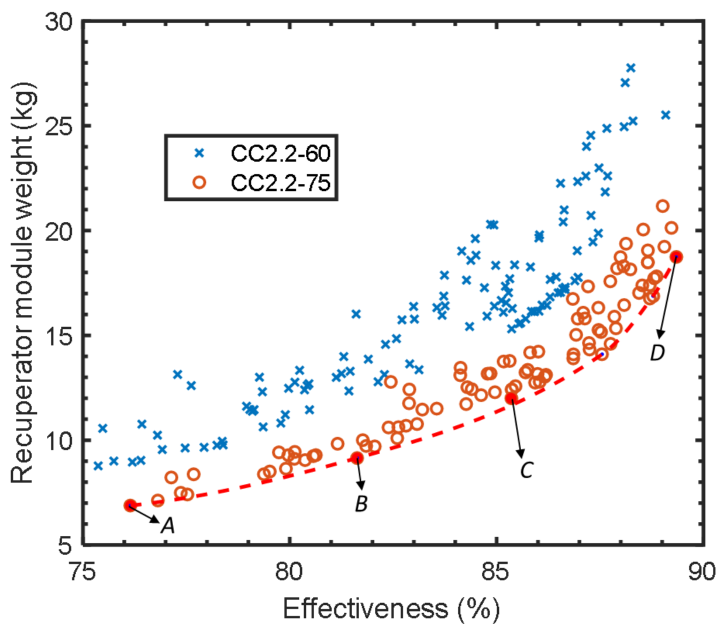


Figure 5.7: Multi-objective results, Pareto front for recuperator module weight and thermal effectiveness with respect to two geometry candidates

	θ	*P* (mm)	H_i (mm)	*L1* (m)	*L2* (m)	*L3*(m)	Δp (%)	ε (%)	*W* (kg)
A	75 °	2.86	1.3	0.232	0.384	0.054	4.15	76.1	6.87
B	75 °	2.2	1	0.235	0.433	0.05	4.79	81.61	9.14
C	75 °	1.98	0.9	0.263	0.445	0.053	4.92	85.52	12.2
D	75 °	2.2	1	0.28	0.48	0.078	4.91	89.34	18.75

Table 5.3: Different recuperator module design solutions in the optimal Pareto front with their objective functions

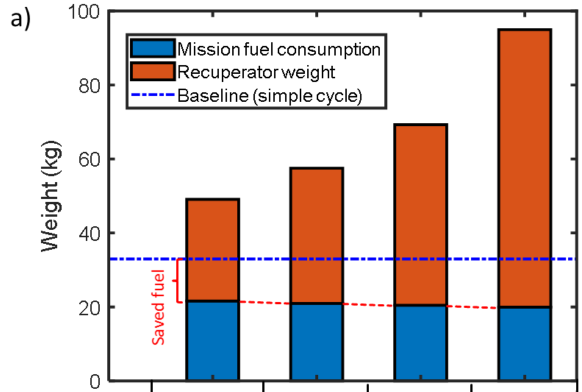
5.6 System evaluation

The helicopter plays an inimitable role in air transportation, and it is often used for occasions including medical rescue, surveillance, law enforcement, fire suppression, etc., where environmental concerns would be considered secondary. The execution of this study for system evaluation is therefore primarily devoted towards the fuel economy improvement and associated system weight increment (namely parasitic recuperator weight) arising from the incorporation of recuperator in optimized design solutions *A*-*D*, so as to maximize rotorcraft range and payload capability in contrast to the conventional non-recuperated helicopter. Comprehensive assessments are carried out in the rotorcraft multidisciplinary simulation framework for three previously defined helicopter missions, i.e. passenger air taxi (PAT), police surveillance (PSV) mission, and search & rescue (SAR) mission, with the mission range varying from around 39 to 240 km, corresponding to modern rotorcraft powerplant operations. To maintain simplification and consistency, in the present work the helicopter only operates in the recuperated cycle under long time hovering or cruise conditions.

The twin-engine, multi-purpose utility helicopter, based on the Bo105 configuration, has been modified by incorporating two V-shaped recuperators in aforementioned optimal designs. Simulated on representative mission scenarios, extensive comparisons are carried out between helicopters employing the conventional simple cycle and advanced recuperated turboshaft engines. While the integrated recuperator contributes to lower fuel input requirement with higher thermal efficiency through the process of preheating compressed air prior to the combustion chamber, the additional recuperator weight also acts as a penalty for the limited carrying capability of the rotorcraft. In contrast to the existing non-recuperated helicopter, the interdependency and associated trade-off between saved fuel consumption offered by the adoption of recuperator and corresponding weight penalty needs to be thoroughly quantified at mission level. Figure 5.8 depicts the calculation results for different recuperator design solutions *A*-*D* with respect to the proposed helicopter missions.

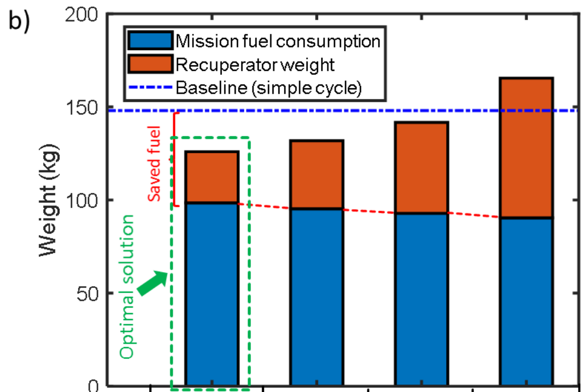
Regarding the mission fuel consumption of the non-recuperated reference helicopter as the baseline, as can be observed, a significant reduction in mission fuel burn is achieved for all selected recuperator designs. Generally, the fuel consumption reduction is of the order of around 33-40% for all proposed solutions, with regards to these three designated missions.

a)



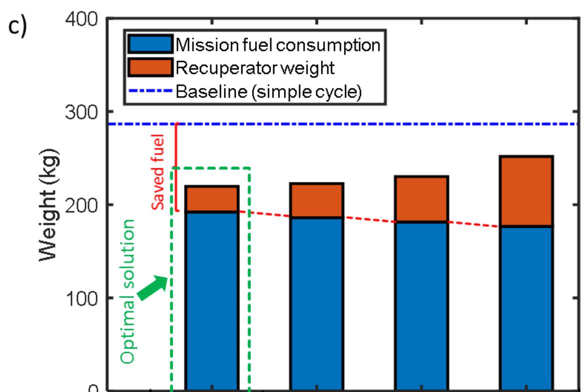
Unit (kg)	*A*	*B*	*C*	*D*
Saved fuel	11.34	12	12.49	12.99
Recup. weight	27.48	36.56	48.8	75
Difference	-16.14	-24.56	-36.31	-62.01

b)



Unit (kg)	*A*	*B*	*C*	*D*
Saved fuel	50.35	53.53	55.95	58.37
Recup. weight	27.48	36.56	48.8	75
Difference	22.87	16.97	7.15	-16.63

c)



Unit (kg)	*A*	*B*	*C*	*D*
Saved fuel	94.39	100.48	105.18	109.91
Recup. weight	27.48	36.56	48.8	75
Difference	66.91	63.92	56.38	34.91

Figure 5.8: Trade-off results in terms of saved mission fuel consumption and increased parasitic recuperator weight, a). PAT mission, b). PSV mission, c). SAR mission

To ensure a recuperated helicopter to be economically viable, the fuel saving should at least be able to compensate for the additional recuperator weight. Obviously, results (the sum of mission fuel burn and additional recuperator weight) exceed the indicated simple cycle baseline would be regarded as an adverse operation for the implementation of recuperator, such as all four solutions *A*-*D* for the PAT mission (see Figure 5.8a). The weight difference between the increased weight and saved fuel are also listed in the table below the figure, and positive values justify the need for recuperated cycle. It is noted that the adoption of recuperator may not be suitable for certain type of helicopter operations with short flight duration. The low range of 39 km for the assumed PAT mission appears to be not sufficient to provide the required level of fuel reduction that could offset the added recuperator weight in terms of all proposed recuperator design solutions *A*-*D*. Representatively, the employed recuperator effectiveness is accepted as the key design parameter that affects the improved fuel economy and associated weight penalty in the recuperated cycle.

The PSV mission shows much positive and satisfying results for the potential of recuperator utilization in contrast to PAT mission. Although the reduction in mission fuel burn relative to non-recuperated simple cycle increases from solution *A* to *D* as a result of the rising recuperator effectiveness, the dramatically increased recuperator weight penalty gradually offsets the expected fuel saving benefits provided by the recuperation process. The PSV mission would even turn into an unfavorable operation for recuperation employment while recuperator design solution *D* is adopted, with a fuel burn reduction of 58.37 kg for the excessive recuperator weight of 75 kg (see Figure 5.8b). It is noted that the fixed mission range and flight duration imposes a maximum achievable fuel saving limitation while the helicopter conducts a specific task. Solution *A* proves to be optimal case for the designated mission with the maximum weight difference between saved fuel and added recuperator weight, and this obtained weight margin can either be utilized to increase helicopter mission range or improve the useful payload depending on the actual requirements and user preferences.

For recuperator optimized solutions *A*-*D*, the recuperator designed effectiveness varies from 76.1% to 89.34%, while the total recuperator weight also increases significantly from 27.48 kg to 75kg. With a substantial amount of fuel saving (94.39-109.91 kg) as given in Figure 5.8c, the SAR mission appears to be a favorable and beneficial operation for all considered recuperator design solutions. This mission profile could fulfill sufficient fuel consumption reduction to compensate for the parasitic recuperator weight. It is well concluded from the deployed mission analysis that the level of fuel reduction during a specific helicopter mission is basically dependent on factors including the mission profile, flight duration, recuperator effectiveness as well as type of operation. Higher thermal effectiveness implies greater fuel saving potential with a more complete utilization of exhaust waste heat, however it usually also necessitates larger recuperator weight penalty. Due to the enormously increased tendency of required recuperator weight over the thermal effectiveness, the optimal case is also obtained for solution *A* with respect to the deployed SAR mission.

5.7 Summary

In this work, the multi-objective genetic algorithm optimization for recuperator design is coupled with the integrated rotorcraft multidisciplinary simulation framework capable of computing the helicopter flight dynamics and associated turboshaft engine performance at mission levels, thus acting as a computationally efficient methodology to perform a specific and comprehensive performance assessment of the rotorcraft powerplant incorporating a potentially suitable, high performance recuperator. The main works and findings could be summarized as follows:

1) The aero-thermal performance of various heat transfer surface geometries has been considered and comparatively evaluated in terms of the volume and area goodness factors G_{vol} and G_{area}, and promising candidates CC2.2-60 and CC2.2-75 are selected for further geometry parameters and recuperator sizing optimization in recuperator design.

2) The recuperator effectiveness maximization and corresponding weight minimization are regarded as objective functions, and a set of multiple optimal solutions, namely Pareto optimal solutions have been attained quantifying the interrelationship and corresponding trade-off between these two conflicting goals. It is revealed that the recuperator weight increases exponentially to achieve a high thermal effectiveness of 75% and above.

3) Four typical solutions were selected in optimal designs, and they have been further evaluated under three representative mission scenarios targeting realistic helicopter operations in an integrated multidisciplinary environment. It is concluded from the substantial reduction in mission fuel consumption that the optimum level of recuperator effectiveness is at around 75% for deployed mission scenarios within flight range of up to 240 km, considering the parasitic recuperator weight.

6. Conclusions and outlooks

Air transportation is nowadays expanding remarkably with continuous growth in aviation industry, and as an irreplaceable role, helicopters would find acceptance for both civil and military applications in occasions like surveillance, fire suppression, search and rescue etc. Turboshaft engines play a dominant part in helicopter propulsion, and they provide attractive power-to-weight ratios in comparison with reciprocating engines. Significant development efforts have been made to progressively improve engine efficiency involving advanced manufacturing technologies, turbine blade cooling, compressor and turbine aerothermal improvement etc. However, after several decades' development, it is generally accepted to be increasingly difficult to achieve any further promotion in thermal efficiency without major changes in engine architecture. Besides that, from the start of the 21st century, environmental issues also pose a major challenge for aeroengine design which attract great attention. The Advisory Council for Aerospace Research and Innovation in Europe has set some ambitious goals on fuel saving and emission reduction by 2020.

In order to meet the growing demand for highly efficient, environmentally friendly aero-engines in the context of the increasingly stringent emissions legislation and serious energy challenge, there is currently renewed interest in recuperated aeroengine configurations for higher efficiency and lower emissions. Actually, the beneficial recuperated cycle has long been recognized, it is well recognized that early development activities and subsequent studies basically focused on utilizing tubular recuperators exhibiting relatively low effectiveness of 60-70%, as they have high reliability based on the then-current manufacturing technologies, together with the paramount design requirement for light weight by the very nature of rotorcraft powerplant applications. However, these recuperators have not been deployed due to early heat exchanger impediments in terms of thermohydraulic performance, structural integrity, as well as weight and volume consideration, along with the lack of market forces (i.e. simple-cycle engine performance advancements, particularly in an era of low fuel cost).

6.1 Summary and conclusions

In this paper, to evaluate the operational performance of recuperated rotorcraft powerplant, an integrated rotorcraft multidisciplinary simulation framework capable of computing helicopter flight conditions and associated engine performance has been proposed and developed adopting tubular or primary surface recuperator. The proposed methodology is implemented to conduct a parametric investigation on recuperated rotorcraft performance for any given flight condition as well as at mission level. The performance of reference rotorcraft powerplant, modeled after the Bo 105 helicopter with twin-engine configuration, has been initially assessed for a generic reference mission scenario, and the overall approach and proposed methodology is then further extended for four representative missions. The obtained results suggest that in spite of the substantial reduction in mission fuel consumption, the deployment of recuperator may not be favourable and beneficial for certain type of missions involving short duration and/or small flight range, especially considering the prominent increase in recuperator weight penalty.

In recent years, advancements in high temperature primary surface heat exchangers with light weight, high effectiveness and improved reliability has started to emerge with the development of advanced materials and improved manufacturing technologies, highlighting its application to aeroengines without penalizing the operational capabilities of existing rotorcraft powerplants.

In the next stage of our study, to understand the impact of recuperator on the whole system for further development of future recuperated helicopter, it is proposed to assess the potential of recuperated rotorcraft powerplant, with emphasis placed on highly effective primary surface recuperator. The improved part-load performance against the reference non-recuperated cycle is analyzed, and the beneficial fuel saving potential of rotorcraft is evaluated under the flight condition of 0-250 km/h and 0-3000 m for different recuperator design effectiveness values. It is suggested that the selection of recuperator effectiveness should be dependent on the most commonly involved mission profile and flight duration, in order to offset the added parasitic weight of the recuperator. The integrated rotorcraft multidisciplinary framework proves to be an effective tool to conduct a comprehensive assessment for the recuperated helicopter under different flight conditions.

Besides that, we’ve further extended the established rotorcraft multidisciplinary simulation framework through the employment of multi-objective GA optimization for recuperator design, aimed at finding high performance primary surface heat exchangers for applications to rotorcraft powerplants. A Pareto front model is obtained quantifying the associated trade-off between the parasitic recuperator weight and thermal effectiveness under defined constraints. Four optimal design solutions are selected, and through the analysis of three representative helicopter missions, it is found that the optimum trade-off between fuel saving benefits and associated recuperator weight penalty is attained for the employed effectiveness of 76.1% with recuperator weight of 27.48 kg. The overall methodology essentially constitutes an enabling technology for the multidisciplinary design and optimization of the rotorcraft powerplant system incorporating a potentially suitable, high performance recuperator.

6.2 Outlooks

In continuation of the presented work, some further studies could focus on:

1) The investigation on environmental performance of recuperated rotorcraft. The rotorcraft is typically used for occasions where environmental concerns would be placed secondary (e.g. surveillance, law enforcement, military combat etc.). Hence, this study mainly focuses on the fuel economy improvement and system weight minimization to enhance rotorcraft range and payload capability. However, in today's climate of the increasingly stringent emissions legislation, the environmental impact of civil aviation must be managed in the long-term considering the expanding air transportation. With the adoption of recuperator, its influence on combustion process and emissions would be of interest for analysis.

2) Specific design of recuperator with novel geometries. In our work, the design of primary surface recuperator is performed with the selection of some cross-corrugated heat transfer geometries. With the aid of computational fluid dynamics (CFD), heat transfer coefficient and flow resistance of novel plate geometries could be calculated, which could be potentially suitable for the intended use of our application with good thermal performance, light weight and compact structure. Besides the investigation of heat transfer performance of the recuperator matrix, some other important aspects need taking great care in recuperator design, including longitudinal conduction effects, flow maldistribution and fouling etc.

3) Experimental work and related testing. With regards to the Allison turboshaft engine, extensive development work and measuring efforts have been undertaken at the Chair of Turbomachinery and Flight Propulsion. If the recuperator could be fabricated and

materialized in terms of hardware, experimental analysis is required to prove its structural integrity and reliability while operating in the severe thermally cyclic environment. Besides that, particular attention also needs to be paid to the dynamic performance of recuperator (especially at start up conditions), due to the thermal inertia effect.

7. List of publications

7.1 Journal publications

1. Zhang, C. and Gümmer, V., 'High temperature heat exchangers for recuperated rotorcraft powerplants,' *Applied Thermal Engineering* 2019; 154: 548-561.
2. Zhang, C. and Gümmer, V., 'The Potential of helicopter turboshaft engines incorporating highly effective recuperators under various flight conditions,' *Aerospace Science and Technology* 2019;88:84-94.
3. Zhang, C. and Gümmer, V., 'Performance assessment of recuperated rotorcraft powerplants: Trade-off between fuel economy and weight penalty for both tubular and primary surface recuperators,' *Applied Thermal Engineering*, 2020;164:114443.
4. Zhang, C. and Gümmer, V., 'Multi-objective optimization and system evaluation of recuperated helicopter turboshaft engines,' *Energy*, Paper number: EGY-D-19-04453. (accepted)

7.2 Peer-reviewed conference publications

1. Zhang,C., et al., 'Evaluation of the fuel saving potential regarding recuperated helicopter flight conditions,' *Proceedings of ASME Turbo Expo* 2018, Oslo, Norway, GT2018-75637.
2. Zhang, C. and Gümmer, V., 'Optimization design analysis of primary surface recuperator for rotorcraft powerplant applications,' *Proceedings of ASME Turbo Expo* 2019, GT2019-90842.

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Appendix

A. Helicopter Bo105 data

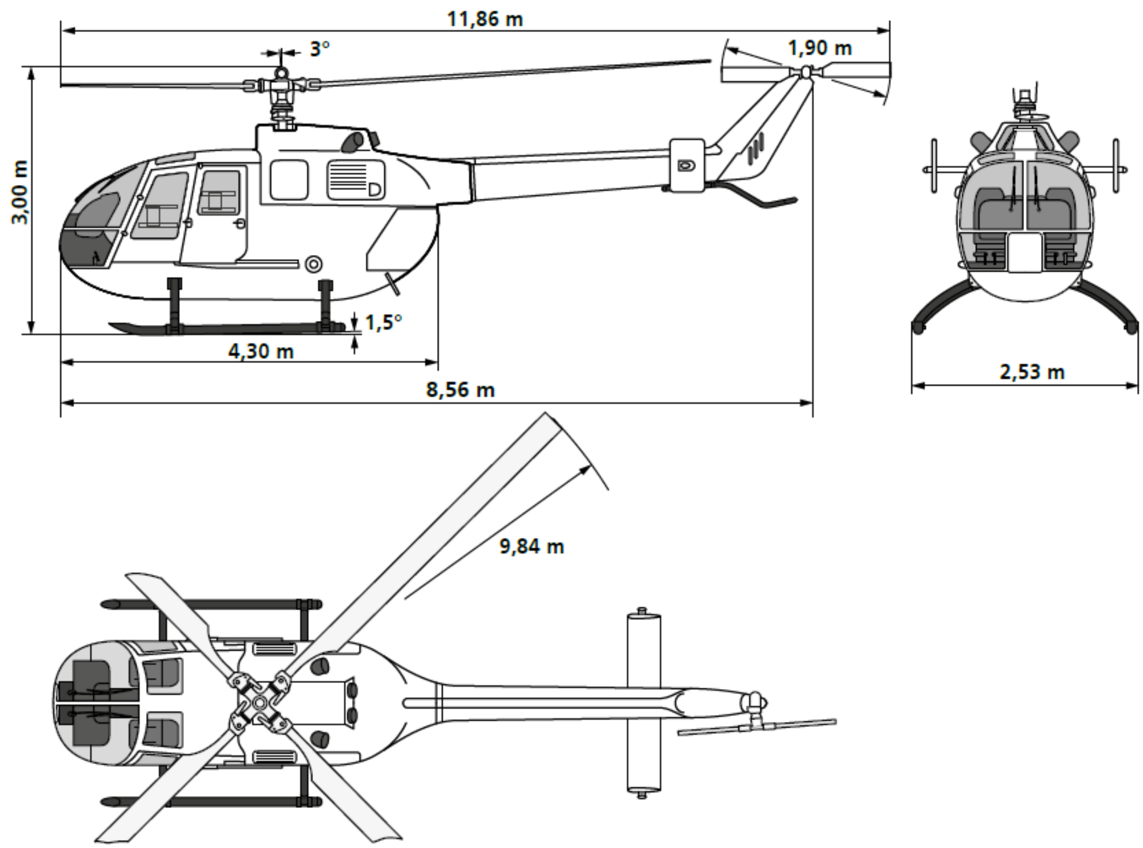
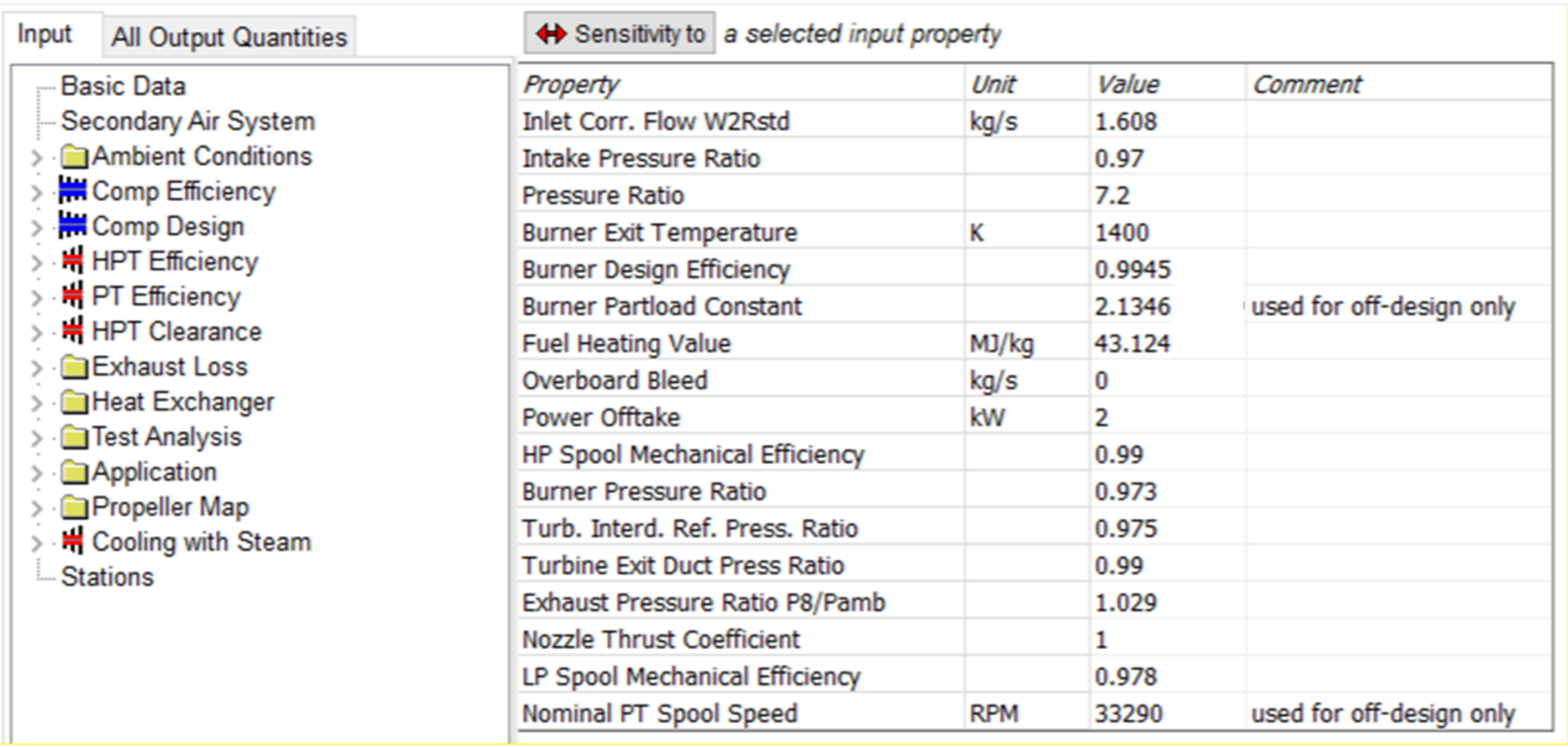


Figure A.1: Helicopter Bo105 main dimensions

B. Allison 250-C20B simulation model



Property	*Unit*	*Value*	*Comment*
Inlet Corr. Flow W2Rstd	kg/s	1.608	
Intake Pressure Ratio		0.97	
Pressure Ratio		7.2	
Burner Exit Temperature	K	1400	
Burner Design Efficiency		0.9945	
Burner Partload Constant		2.1346	used for off-design only
Fuel Heating Value	MJ/kg	43.124	
Overboard Bleed	kg/s	0	
Power Offtake	kW	2	
HP Spool Mechanical Efficiency		0.99	
Burner Pressure Ratio		0.973	
Turb. Interd. Ref. Press. Ratio		0.975	
Turbine Exit Duct Press Ratio		0.99	
Exhaust Pressure Ratio P8/Pamb		1.029	
Nozzle Thrust Coefficient		1	
LP Spool Mechanical Efficiency		0.978	
Nominal PT Spool Speed	RPM	33290	used for off-design only

Figure B.1: Specifications for the design point in GasTurb

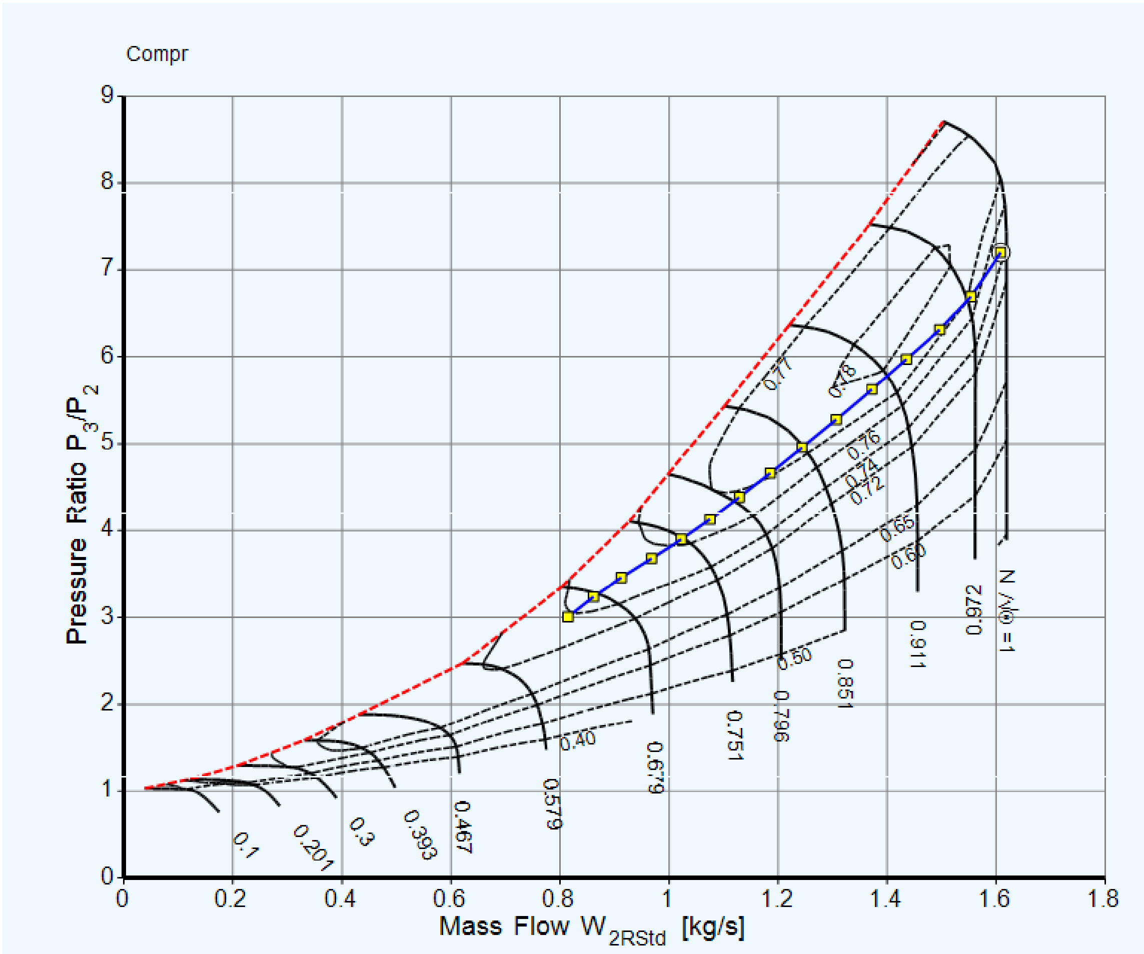


Figure B.2: Operating line in the compressor performance map

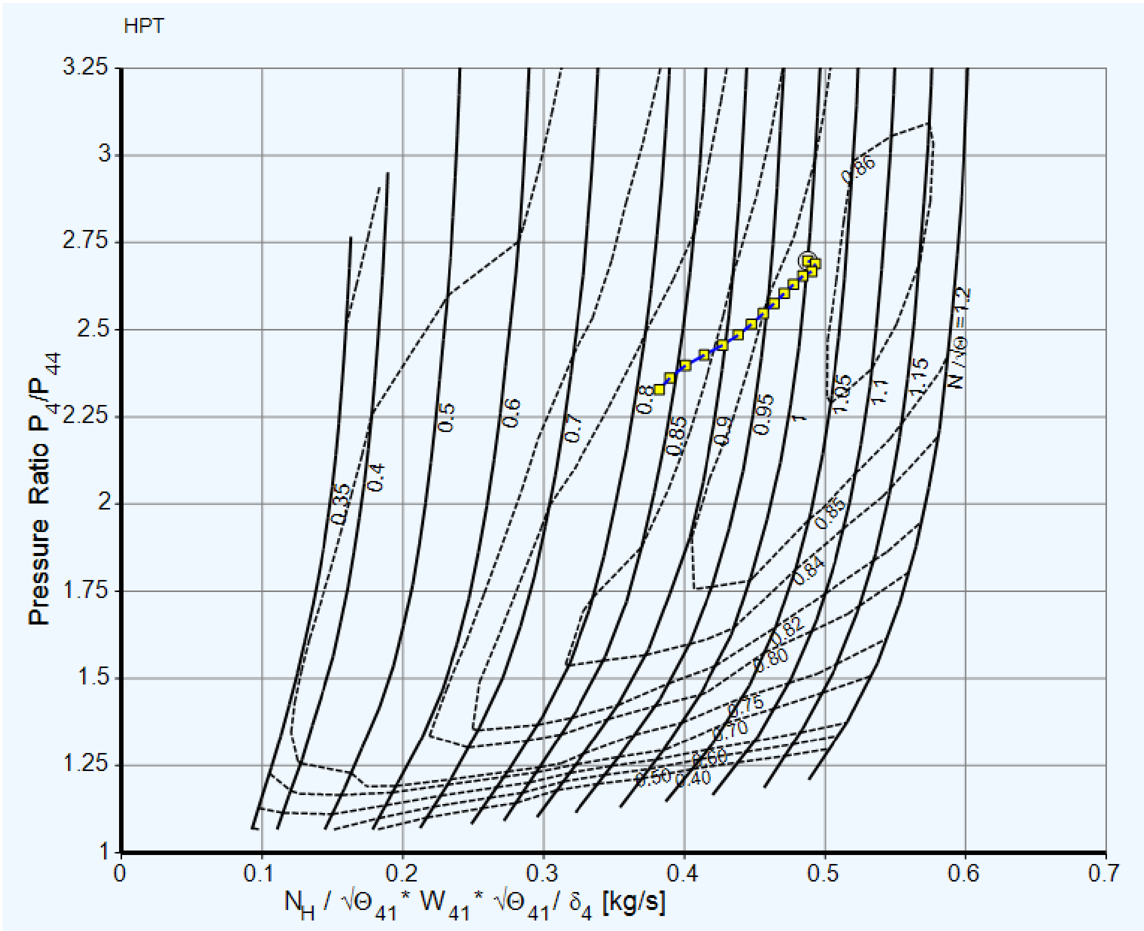


Figure B.3: Performance map for the high-pressure turbine

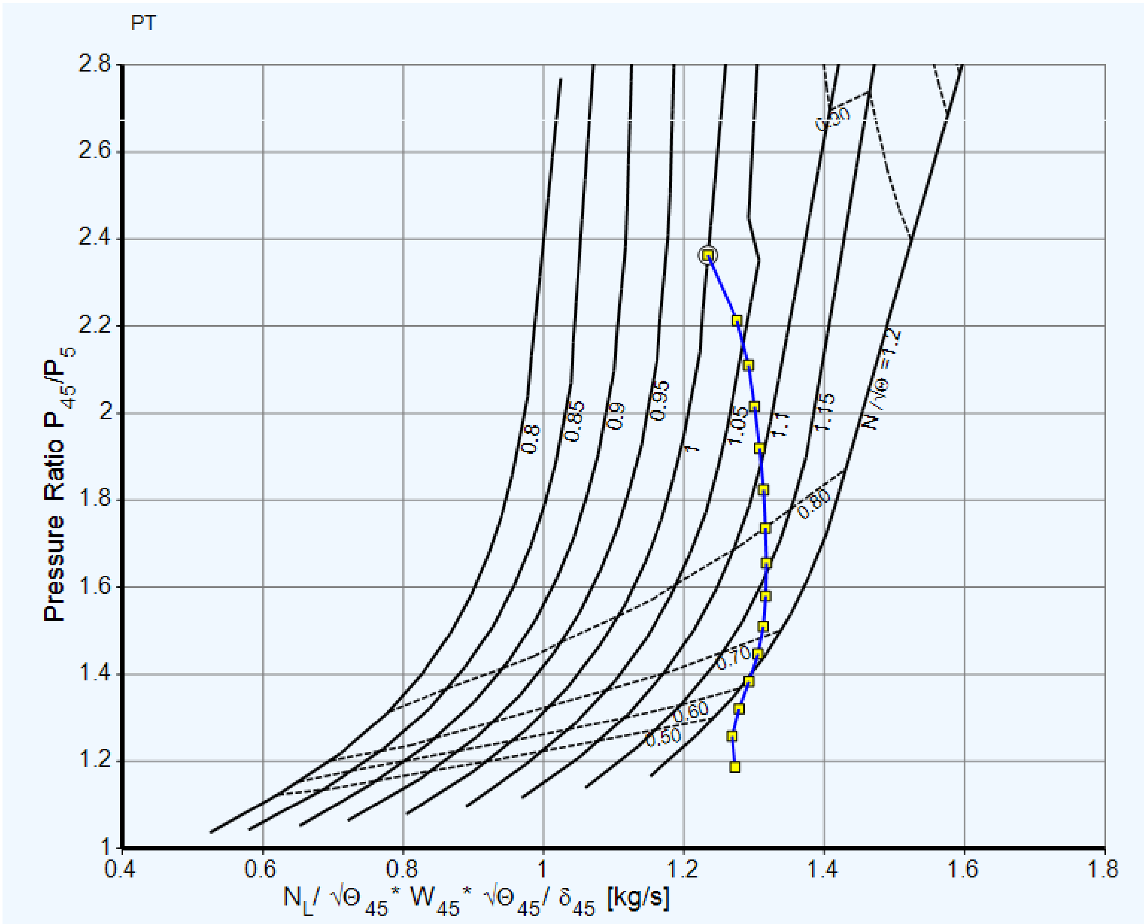


Figure B.4: Performance map for the low-pressure turbine