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Engenharia

Influence of Regeneration in the Performance of a Propfan Engine

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To my parents Elisabete e Joaquim and my brother Miguel

Resumo

A indústria da aviação é um elemento essencial na sociedade de hoje em dia, e como tal, não pode ignorar as preocupações públicas sobre o aquecimento global e as questões ambientais, e sobre a economia global e o preço dos combustíveis. O actual pensamento "verde" e as novas políticas de protecção ambiental promoveram a criação de alguns projectos aeronáuticos amigos do ambiente. Estes projectos são destinados à criação de novas e melhores soluções procurando reduzir a pegada ambiental da indústria da aviação. Estas considerações envolvem o desenvolvimento de novos conceitos de aeronaves com menores emissões poluentes e consumo de combustível.

Assim sendo, este estudo visa analisar a viabilidade de um motor propfan incorporado com um regenerador de calor. De acordo com vários autores, os motores propfan são mais eficientes que os actuais *turbofans* e a introdução de regeneradores de calor em turbinas de gás reduz o seu consumo específico de combustível. Assim sendo, a combinação de ambos pode ser uma solução viável para uma redução ainda maior do consumo específico nos actuais motores.

O principal propósito desta tese é analisar se este novo conceito de motor poderá ser um substituto mais amigo do ambiente dos actuais *turbofans*. Este estudo consiste na comparação de três diferentes configurações de motores: um actual turbofan; um *propfan* convencional e um propfan incorporado com regenerador de calor. A análise é feita de modo a perceber a influência dos parâmetros do motor no consumo específico de combustível e na tracção específica. O uso do regenerador de calor pode ser justificado se a redução do consumo específico de combustível e o aumento da tracção específica valerem a pena, tendo em conta o peso extra do regenerador.

Palavras-chave

Motor propfan; Regenerador de calor; consumo específico de combustível; Desempenho;

Abstract

The aviation industry is an essential element of today's global society and thus cannot ignore the public concern about the global warming and the environmental issues as well as the global economy and fuel prices. The actual green thinking and the new policies to protect the environment promoted the creation of some aeronautical environmentally friendly projects. They are meant to create new and cleaner solutions looking for a way to reduce the environmental footprint of aviation industry. These considerations involve the development of new aircraft concepts with lower pollutant emissions and fuel consumption.

Consequently, this study aims to analyze the viability of a propfan engine with the introduction of a heat regenerator. According to several authors, the propfan engines are more efficient than the current turbofans and the introduction of heat regenerators in the gas turbines engines reduces its specific fuel consumption. Therefore, the combination of both propfan engines and heat regenerators may be a viable solution to reduce the specific fuel consumption in the current engines even further.

The main purpose of this research Thesis is to analyze if this new engine concept could be a "greener" substitute to the current turbofans. This work consists in the comparison of three different engine configurations: a current turbofan; a conventional propfan and a regenerated propfan engine. The analysis is performed to show the influence of engine parameters in specific fuel consumption and specific thrust. The use of the heat regenerator could be justified if the reduction of the SFC and the increase of specific thrust are worthwhile considering the extra weight of the heat exchanger.

Keywords

Propfan engine; Heat regenerator; Specific fuel consumption; Performance;

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Nomenclature

Variables

$\dot{m}$	Mass flow rate
B	Bypass ratio
Cp	Specific heat capacity at constant pressure
ESFC	Equivalent Specific Fuel Consumption
ESHP	Equivalent Shaft Horsepower
F	Thrust
f	Fuel to air mass flow ratio
$F/\ m_o$	Specific thrust
FPR	Fan Pressure Ratio
h	Height; enthalpy
M	Mach number
OPR	Overall Pressure Ratio
P	Pressure
$Q_{,hv}$	Lower Heating Value of the fuel
R	Gas constant
SFC	Specific Fuel Consumption
SHP	Shaft Horsepower
T	Temperature
TSFC	Thrust Specific Fuel Consumption
U	Flight speed

Acronyms

ARP	Aerospace Recommended Practice
GE	General Electric
HBPR	High Bypass Ratio
HPC	High Pressure Compressor
HPT	High Pressure Turbine
IRA	Intercooled Recuperated Engine
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
RFP	Request For Proposal

SAGE	Sustainable And Green Engines
TET	Turbine Entry Temperature
UDF	Unducted fan

Subscripts

a	Air; admission/ inlet
b	Burner
c	Overall; compressor; cold
e	Exhaust
f	Fan; fuel
ft	Free turbine
h	Hot
m	Mechanical
n	Nozzle
Prop	Propeller
reg	Regenerator
t	Stagnation; turbine
th	Thermal
g	Gearbox

Greek Symbols

α	Utilization Coefficient
ρ	Density
η	Efficiency
Δ	Finite variation
π	Pressure ratio
γ	Specific heat ratio
τ	Temperature ratio; Enthalpy ratio

1. Introduction

1.1 Motivation

The need to protect the environment as well as the urgent need to reduce non-renewable resources use, such as fossil fuels, have been increasingly part of our daily lives. Being the planes large fuel consumers and pollutant emitters to the atmosphere, it would be desirable the introduction of a new model of aeronautical engine. This new engine should minimize those emissions without compromising the aircraft thrust and weight.

Gas turbines like propfan engines have been the focus of interest due to their good performance capabilities. Having regard to environmental requirements and fuel economy, this study intends to analyze how far the incorporation of a heat regenerator into an engine like this might prove a beneficial and viable solution.

1.2 Objectives

This study was made with the main goals of designing and analyzing a propfan engine with a regenerator incorporated. The design of the engine will have the requirements of a current turbofan. The aim is to verify if this new engine concept could be a viable solution to "substitute" the current turbofans, having the same thrust power with less fuel consumption.

1.3 Contextualization

Current concerns of society have a great influence in any type of technology development, and therefore, aeronautical engines are no exception. Issues like environmental impact and fuel economy led to a harder study regarding the propfan engines.

This sort of engines has already been studied since the eighties of previous century, although they were not into large scale production. Nowadays, they are regaining interest and results of several studies already considered them very promising and waging worthy in the near future. *(Nakamura, Kajikawa, and Suzuki, 2012)*.

The development and application of this sort of engines in a near future depends essentially on the fuel crises that we're passing through and the present green thinking that restricts the pollutant emissions of fuel burn to the atmosphere.

The propfans are very efficient engines. When compared to the turbofans they have a significant reduction of fuel consumption, and therefore of pollutant emissions, which can reach up to 30%. *(Daly K, 1989; Yunos, 2011)*. This high efficiency, combined to fluctuations in oil prices in the last years and to the environmental concerns, renewed the interest in these engines. *(Schimming, 2003)*. It is therefore desirable to study several design configurations of a propfan engine. One possible concept is the introduction of a heat regenerator, which theoretically reduces the specific fuel consumption.

1.4 Thesis structure

The first chapter of this dissertation consists in the motivation, followed by this work objective and also its contextualization.

The second chapter presents a literature review, with some related relevant studies and some propfan engine developments, also considered as a source of future research. In this chapter, is also presented some environmentally friendly programs which are currently ongoing and pursue the development of new propfan concepts.

The third chapter is concerning the concepts background. In this chapter are presented some key concepts about the functioning of the propfan engines as well as its configurations. The difference between a regenerated and a conventional cycle is shown.

The fourth chapter describes the engine design requirements and the assumptions made in the calculations. In this chapter is presented the three engine configurations analyzed and the respective mathematical model used in each case.

The results obtained and the comparison within three configurations is presented in chapter 5. The analysis of the most efficient concept is discussed.

The last chapter presents the main conclusions of this Thesis research and some further thought for future work, respectively.

2. Literature Review

2.1 Relevant Studies

Both very high bypass ratio turbofans and open rotor engines are being studied in order to understand if they might become the next step in the aviation industry. *Mazzawy, 2010,* has made a study named “Next Generation of Transport Engines – Very High Bypass Ratio Turbofans vs Open Rotor Engines”.

In his study, Mazzawy says that for both fuel saving and for noise reduction the key is to improve the fundamental propulsive efficiency, and that are two ways of doing it: increase the current bypass ratio level of turbofans or eliminate the duct and use open rotors. He says that in either option, the fan pressure ratio has direct influence on the velocity of the air propelled by the engine. His results prove for two different flight Mach numbers, 0.3 and 0.85, that the fan pressure ratio reduction improves the propulsive efficiency.

Mazzawy also studied the performance of an open rotor and a HBR turbofan, confronting the major performance issue of each engine. For the turbofan with very high bypass ratio it’s the installed weight and drag associated with the large duct. For the open rotor engine, it’s the performance loss at flight speeds higher than current cruise speeds. The open rotor engine is also noisier than the turbofan due to the turbofan ability to incorporate acoustic treatment in the fan duct. The fan duct also protects the turbofan engine from fan tip losses associated with direct exposure.

In this study, Robert Mazzawy considered two engines of similar technology and thrust size. A very high bypass ratio turbofan incorporated with a gearbox, and with a compact variable pitch mechanism. The fan pressure ratio was 1.3 and the bypass ratio in the range of 12 to 13. The comparable open rotor engine had an effective bypass ratio level in excess of 20. These engines were compared on the fuel burn improvement, relatively with a current turbofan with a fan pressure ratio of 1.67 and a bypass ratio of 6.

The results proved the expected. For short cruise segments, until a flight Mach number of 0.7, the open rotor engine proves to be better, but for extended high speed flights the very high bypass ratio turbofan excels. Comparing with the current turbofan engine, at low speeds the open rotor has a fuel burn improvement that can reach almost 35%. At flight Mach numbers around 0.8, the fuel burn improvement of the very high bypass ratio engine is about 10%.

The integration of heat exchangers into the aero engine cycle can meet the growing demand for environmentally friendly gas turbine engines with lower emissions and improved specific fuel consumption. To prove that *Andriani and Ghezzi, 2004,* made a study regarding the "Heat Exchanger Influence on off-design Performances of Regenerative Jet Engines". They developed a thermodynamic numerical code in order to determinate the thermodynamic characteristics of a jet engine with regeneration, specially the behavior of off-design performances of the heat exchanger. The numerical code computes the working cycle of a jet engine for different operative conditions and simulates the introduction of the regenerator phase in the cycle. The main engine parameters that were analyzed were the performance, consumption and efficiency as functions of the flight Mach number.

To simulate the off-design behavior of the turbojet engine, Andriani and Ghezzi had to choose the engine's design point: Altitude of 10000 m, turbine inlet temperature of 1400 K, regenerator efficiency of 0.6 and fight Mach number of 0.8. It was also taken into account a variable pressure drop through the regenerator of 5%. The specific heats of air and combustion products were determined as function of temperature, moisture and molecular weight of the reactants.

The results showed that with the increase of the flight Mach number, the mass flow rate ratio increases and the efficiency of the regeneration decreases. This analysis also showed that the turbine pressure ratio cannot be considered constant during the operations, but variable with the efficiency of the regeneration. The method used to estimate the variation of efficiency during off-design operation was $N_{tu} - \varepsilon$, and it has shown that the main factor influencing the regeneration efficiency was the mass flow rate, supposing the overall thermal conductance as constant.

Another study regarding heat exchangers was made by *Boggia and Rüd, 2005,* called "Intercooled Recuperated Aero Engine". Their research concerned a conventional turbofan engine, with integrated intercooler and regenerator with bypass ratio of 5.2. It is focused on the thermodynamic cycle and technological innovations needed for the heat exchangers introduction. They optimized the conventional turbofan for long range applications, and two alternative versions with different fan diameters, 92 in and 109.9 in, were proposed. They compared a conventional engine with the ones using just regeneration or intercooling and both.

The studied Intercooled Recuperated Aero Engine (IRA) had a specific configuration: it was an advanced high bypass ratio three shaft geared turbofan; had an advanced technology fan, reduction gearbox on the low pressure shaft, axial-radial intermediate pressure compressor, flat plate intercooler, radial HPC, variable geometry turbine system, exhaust heat exchanger and piping system, and a three nozzle system.

Boggia and Rüd concluded that the use of the intercooler provides a substantially increase in the amount of recuperated heat and performance of the engine. The IRA engine showed the best performance compared with the regenerated engine and the conventional one. The intercooled and regenerated engine cycles have higher efficiencies with lower overall pressure ratio values, comparing with the conventional engine, which provide a lower NOx emission level and a weight reduction in the turbomachinery core. The specific fuel consumption has a reduction of 16% and 18.7% with the use of 92 in and 109.9 in diameter blades respectively, compared with the conventional engine. The NOx emissions would be about 60% lower using the 109.9in diameter blades than the corresponding ICAO legislation limit.

Despite the mentioned benefits, there are additional expensive components and increased complexity in the IRA construction. The high thermo-mechanical stress in the hot section, the design complexity of the variable geometry system in the turbine section and the development of constructive solutions to reduce the overall engine weight, are some of the critical points, for a successful implementation of this new engine concept.

Another study, about the IRA engine was carried out by *Gong H. and Wang Z., 2011*, "Effects of Intercooling and Recuperation on Turbofan Engine Performance". They created an overall performance simulation model for the engine and analyzed the effects of regeneration and intercooling on both thermodynamic cycle and performance parameters. As it happened in the Boggia and Rüd study, in this one the IRA engine was also compared with a conventional turbofan. The conventinal turbofan was a two spool unmixed flow engine, and it served as a base to the simulation model of the IRA. The simulation has confirmed the results obtained in the previous research of Boggia and Rüd.

Lebre and Brójo, 2010, also presented a study regarding "Effects of Intercooling and Regeneration in the Performance of a Turbofan engine". Their work intended to show the influence of engine parameters in specific fuel consumption, specific thrust and thermal efficiency. For this research they compared the performance parameters of a conventional engine with the ones using an intercooler, a regenerator and both.

The results obtained about the effects of the heat exchangers showed that the intercooled engine has higher specific fuel consumption and lower thermal efficiency than the conventional one. The engine with both intercooler and regenerator also revealed a lower specific fuel consumption and higher thermal efficiency relative to the conventional engine, which agrees with the previous studies.

In the performance parameter this study achieved different results from the others. In this research, although the results had close values to the engine with intercooler and regenerator, the engine with only regenerator showed to be the configuration with the best performance. Even though it creates a pressure drop at the nozzle exit, it presented lower values of specific fuel consumption and higher values of thermal efficiency compared to the engine with both heat exchangers.

In 2008 another study regarding “Regeneration and intercooling in gas turbine engines for propulsion systems” was carried out by *Andriani, Gamma and Ghezzi, 2008*. This study is similar to the previous ones but now regarding turboprop engines instead of turbofans. In this study *Andriani, Gamma and Ghezzi* developed a zero dimensions thermodynamic code, written in FORTRAN 77, to analyze in terms of performance and efficiency three different turboprop engine configurations. They compared a conventional turboprop engine, the reference one, with one using both intercooler and regenerator and other using only regenerator. The choice of turboprop engines was due to their smaller mass flow rate respect the jet engines, which can provide the use of smaller and lighter heat exchangers. And because of the slight power provided by the exhaust gases respect the propulsion power provided by the propeller.

To compute the thermal cycle of the engines, the authors of the study had to make some assumptions: no air bleeding for auxiliary or cooling system; no auxiliary power extracted from the turbine and perfect gas conditions. The parameters analyzed were the output power per unit of mass flow rate; the specific fuel consumption and the thermal efficiency of the cycles. They were analyzed as function of the pressure ratio. The numerical simulation was made considering the same operating conditions for the three engines: altitude of 6000 m, flight Mach number of 0.65 and turbine inlet temperature of 1300 K.

The results obtained for the parameters studied showed that generally, the turboprop with both intercooler and regenerator has better results compared with the other two configurations. The engine with only regeneration, unlike the other turboprop configurations doesn’t allow to exchange heat at pressure ratios higher than 18.

Regarding the output power per unit mass flow rate, at cruise conditions, the conventional engine has the highest specific power values but only until a pressure ratio of 7. Over that pressure ratio, the intercooled and regenerated engine revealed to be better, having its maximum specific power about 10 per cent higher than the conventional turboprop. The engine with only regenerator has the lowest values for specific power.

Concerning the specific fuel consumption, the engine with both heat exchangers has the best results until a pressure ratio value of 21. There, it equals its value to the conventional turboprop. For higher values of pressure ratio, the conventional engine shows better values of specific fuel consumption. The engine with only regenerator has a similar behavior to that, with both heat exchangers until a pressure ratio of 9. Above that, its specific fuel consumption starts to increase slightly.

In relation to thermal efficiency, the engine with both intercooler and regenerator is, again, the one with best results. Like in the specific fuel consumption analysis, it equals its value of thermal efficiency to the conventional turboprop at a pressure ratio of 21. Over this value the conventional engine shows better results. Again, the turboprop with only regeneration has a behavior similar to the engine with both heat exchangers but with slightly lower values, although considerably higher respecting the reference one.

Ghenaiet and Boulekraa, 2009, made a study regarding the design of turboprop engines: “Optimum Design of Turboprop Engines Using Genetic Algorithm”. Their work concerns the optimization of the design parameters of three different turboprop engines configurations in order to match the power requirements of a propeller-driven L100-30 aircraft, powered by four Allison 501-D22-A turboprop engines. The three turboprop engines configurations analyzed in their paper were: a single spool fixed turbine, a single spool free turbine and a twin spool fixed turbine. The optimization of the propulsion cycle is based not only in the power requirements but also in the technology constraints.

The first analysis Ghenaiet A. and Boulekraa did in their research was a parametric study in on-desing (cruise flight) and off-design (takeoff) conditions. For on-design analysis they considered M = 0.475 and h = 8535.4 m whereas for off-design M = 0.1, at sea level on a hot day.

The on-design analysis made in this paper is very similar to the one of the present work. Although the engines are different, the calculation method for a propfan is almost the same as the one for a turboprop once they both have external propellers.

The on-design results showed a good agreement with the reference engine: for a single spool fixed turbine it revealed less power produced at a high turbine expansion temperature ratio (TTR) and more power recovered with less fuel consumption; the compressor pressure ratio (CPR) for the maximum total specific power showed a value very similar to the reference.

In what concerns the off-design study, the takeoff parameters were estimated iteratively based on the conservation of work and mass flow. The authors assumed chocked flow conditions at turbine nozzle guide vanes and unchocked conditions at the exhaust nozzle. The off-design results were also in good agreement with the reference engine.

To optimize the propulsion cycle, Ghenaiet A. and Boulekraa used PIKAIA, a general purpose function optimization FORTRAN-77 subroutine based on a genetic algorithm (GA), together with the Pareto Principle. Comparing the three optimized propfan engines designs, the configuration with a twin spool fixed turbine showed the best performance. From the point of view of design for this turboprop configuration, when operating at the design turbine inlet temperatures: 1203K and 1342K, can be used a two stages LPC. The high pressure compressor may be a two stages centrifugal compressor or a several stages axial compressor.

From this turboprop optimization study two design options emerged from the Pareto-front solutions: "the first is a compromise near the ideal point and the second is that of maximum takeoff power. Computations showed the superiority of such a GA in rapidly optimizing and preserving the diversity of non-dominated individuals, as well as the quality of Pareto fronts."

2.2 Main Developments

The developments of propfan engines started in the early eighties, during the war between Iran and Iraq. This war caused a great increase in the oil prices which forced a rapid development in aviation. As usual, the biggest developments happen in times where it is needed great alternatives in a short time. It was known that to create a fuel burn more efficient engine it was necessary one driven by a propeller. However, this engine must have the performance of a turbofan engine and must be able to achieve its flight Mach numbers. From the result of efforts made, was born a new advanced open rotor propeller engine.

The first propfan engine developed was created by General Electric[1] and became known as GE 36 unducted fan (UDF). This aft fan model consisted of two external counter rotating rotors which had variable pitch. They were directly coupled to the counter rotating turbines which eliminated the need of a gearbox. The propellers blades were made of composite materials in order to satisfy the strength and stiffness requirements of the thin and curved blades imposed by the high velocities intended to be achieved. *(Variations of Jet Engines, 2009).*

This completely innovator engine concept was tested on a Boeing 727 and presented at Farnborough airshow in Paris, 1988. *(The Localizer A Blog for Aviation, 2011)*. This new conception of unducted fan was developed based on a F404 military turbofan engine. The main change was the withdrew of the fans. This provided a significant increase in the engine's propulsive efficiency. Unlike what happened with the turboprops this engine could reach Mach numbers of 0.75 and therefore compete with turbofans.

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[1] "General Electric Company (GE) is a diversified technology and financial services company. The products and services of the Company range from aircraft engines, power generation, water processing, and household appliances to medical imaging, business and consumer financing and industrial products." (*General Electric Company, 2012).*

The GE 36 UDF was the most radical feature of the proposed Boeing 7J7. This was supposed to be the successor of the Boeing 727. But if the reason of the GE engine development was the rise in the oil prices, the reason why it didn't succeed was its declining. Although his tests had been a success, the new GE engine had problems regarding noise and cabin vibrations. So it was necessary to make some improvements. Accordingly, and with oil again at low cost, there was no reason to spend money changing the existing turbofans into this new engine concept, being the research stopped there. *(The Localizer A Blog for Aviation, 2011)*.

Similarly to what happened to the propfan developed by GE, was also a prototype developed by Pratt & Whitney[2] in partnership with Allison[3], which has not passed the experimental stage. The 578-DX engine had also problems with noise and the low fuel prices were again the factors that stopped this project.

The main difference between this and the previous engine was the incorporation of a gearbox connected to the blades of the counter rotating low pressure turbine. This gearbox provided a higher turbine speed in relation to the aircraft propellers, which reduced the noise produced. *(Daly K, 1989)*.

Probably, the only propfan engine that is still in service is Progress D-27. This is a three shaft engine with a counter rotating propeller in a tractor configuration and it was developed by Ivchenko-Progress[4].It is rated at a maximum power of 14000 hp.

Russia and Ukraine established cooperation in 2009 in order to develop the military cargo aircraft Antonov An-70. This aircraft is powered by four of these D-27 propfan engines. The An-70 project is part of the State program in the area of arms and defense order until 2020 and the Russians intend to order about sixty of these aircrafts. The extensive preparation works to put aircraft and engines into series production have been fulfilled already. *(Ivchenko Progress, 2007)*.

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[2] "Pratt & Whitney is a U.S. - based aerospace manufacturer with global service operations. It is a subsidiary of United Technologies Corporation (UTC). Pratt & Whitney's aircraft engines are widely used in both civil aviation (especially airlines) and military aviation." (*Pratt & Whitney, 2013)*

[3] "The Allison Engine Company was an American aircraft engine manufacturer. In 1929 the company was purchased by the Fisher brothers. Fisher sold the company to General Motors, who owned it for most of its history. The company was acquired by Rolls-Royce plc in 1995 to become a subsidiary, Rolls-Royce *Corporation." (Allison Engine Company, 2013)*.

[4] "SE IVCHENKO-PROGRESS activities are design, manufacture, test, development, certification, putting into series production and overhaul of gas turbine engines both of aviation and industrial application." *(Ivchenko Progress, 2007)*.

Antonov An-180 and Yakovlev Yak-46 are two aircrafts that were supposed to be powered by D-27, but they were never built. *(El-Sayed, 2008)*. It is expected that Progress D-27 becomes the base platform for future propfan engines. *(Kravchenko I., Russian Aviation, 2012)*.

Figure 1: Illustration of the propfan engines referred in the bibliographic review:

a) General Electric *GE36 (The Localiser A Blog for Aviation, 2011)*; b) Pratt & Whitney/Allison 578-DX *(Spotting PAE)*; and c) Progress D-27. *(Ivchenko Progress, 2007)*

2.3 "Green" Programs in current development

Currently there are some programs in development in order to create new engine concepts and breakthrough technologies to make the aviation industry more environmentally friendly. These "green" projects intend to meet until 2020, the European environmental targets for aero engines set by ACARE[5]. *(Min, Jeong, Ha, & Kim, 2009)*. Some of these programs include open rotors as a new bet for fuel economy and aircraft performance.

Clean Sky is an example of these programs that was born in 2008 and it's a seven year program. It is a joint technology initiative, a Public Private Partnership between the European Commission and the Aeronautical Industry. It aims to significantly increase airplanes environmental performance, making them less noisy and more fuel efficient, in order to achieve the Single European Sky environmental objectives. This program is made up of 6 Integrated Technology Demonstrators which intend to develop a set of flying demonstrators to validate the advanced technologies under study *(Airspace America, 2008)*. These 6 SAGES (Sustainable And Green Engines) will integrate technologies for open rotors and heat exchangers such as intercoolers: SAGE 1, Geared Open Rotor Demonstrator and SAGE 2, Direct Drive Open Rotor Demonstrator. *(Parker, 2011; Clean Sky)*. Rolls-Royce[6], Snecma[7], MTU[8] and Volvo Aero[9] are examples of some companies that are leading these SAGEs. *(Airspace America, 2008)*. The overall objective is to achieve less 20% of fuel burn compared to modern engines in service at 2000. *(Avellán, 2011)*.

Another program, DREAM, is Rolls Royce lead, and its purpose is to demonstrate new open rotor engine concepts. It's a European program that begun in 2008 in order to improve the understanding of noise and other performance characteristics of open rotors. This DREAM program tests open rotors with both gearbox and free turbines driving counter rotating propellers. This technology is intended to go beyond the ACARE goals in specific fuel

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[5] "Advisory Council for Aviation Research and innovation in Europe and provides a network for strategic research in aeronautics and air transport so that aviation satisfies the needs of society and secures global leadership for Europe in this important sector." *(ACARE)*

[6] "Rolls-Royce is a global company, providing integrated power solutions for customers in civil and defence aerospace, marine and energy markets." *(Rolls-Royce plc, 2013)*.

[7] *Société Nationale d'Étude et de Construction de Moteurs d'Aviation*. Is part of the international group Safran, and is one of the world's leading manufacturers of aircraft and rocket engines. *(Safran Snecma, 2010)*.

[8] "MTU Aero Engines is Germany's leading engine manufacturer. It engages in the development, manufacture, marketing and support of commercial and military aircraft engines in all thrust and power categories and industrial gas turbines." *(MTU Aero Engines)*.

[9] Volvo Aero Corporation develops and manufactures engine components for commercial and military aircrafts and rockets. *(Volvo Aero Corporation Company Information)*.

consumption. The successfully developed technology in DREAM will go into the Clean Sky program. The Clean Sky technology is designed to reach and go beyond the environmental targets set by ACARE. *(Parker, 2011; Avellán, 2011)*.

3. Concepts' background

The propfan engine concept, or, as well called, ultra high bypass ratio engine (HBPR) or turbopropfan, is born from the turboprop and the turbofan concepts. A propfan is a modified turbofan engine with advanced propellers. *(Yunos, 2011).* The fan is placed outside the engine nacelle on the same axis as the compressor blades. Its functioning is very similar to a turbofan with the principal difference in the use of external fan blades. That is why propfan engines are also known as unducted fans or open rotor jet engines. This concept is intended to offer the speed and performance of a turbofan combined with the fuel economy of a turboprop. Although the external fan provides high efficiency it is also the cause of propfan's greatest limitation, the noise. *(El-Sayed, 2008).* Figure 2 presents a schematic diagram of a propfan engine.

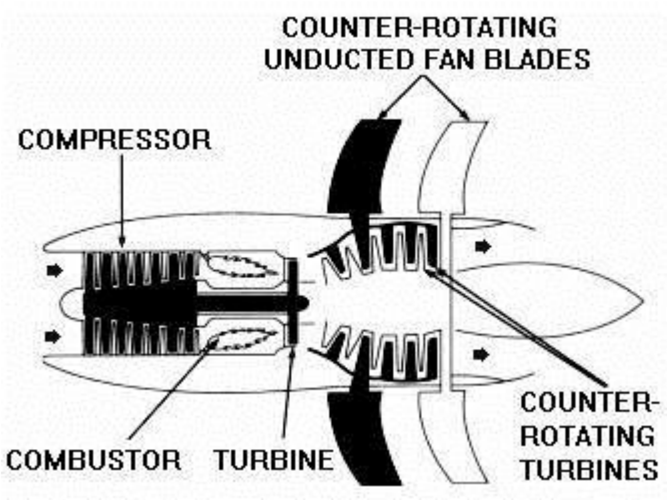

Figure 2: Propfan engine schematic diagram. (*The Ultra High Bypass Engine, 2008).*

3.1 Bypass ratio importance

One of the main reasons for the increase of the engine's propulsive efficiency is the high bypass ratio (HBPR). The bypass ratio concept involves the flow split into two streams and describes the ratio between the mass of cold air that passes through the fan disk and bypasses the engine core (un-combusted air), to the hot air passing through the core entering into the combustion system (combusted air). *(Roskam and Lan, 1997).* When the bypass ratio is high, only a small fraction of the air that passes through the propeller enters the compressor. *(Sweetman B, 2005).*

If the bypass ratio increases, the specific fuel consumption (SFC) decreases. This is because the turbine produces more energy than that needed by the compressor, being the remaining transferred to the propeller that raises its speed of air at the inlet, and produces mechanical energy. Which means that for high bypass ratios, the largest part of the thrust comes from the propeller and not from the hot gases exhaustion. *(Variations of Jet Engines, 2009).*

However, there is a limit to how much the bypass ratio of an engine can be increased, because after that limit the economy on fuel burn is not worth the extra weight and drag of the fan system. Using the open rotor engines there is no such problem, and the bypass ratio achieved is infinite. *(Parker, 2011; Mair and Birdsall, 1992).*

3.2 Different propfan configurations

Although propfans are not produced in large scale for commercial application, they have already been studied and several different configurations were prototyped.

There are two concepts regarding the engine propeller position: a single rotor with a frontal propeller, or twin counter rotating rotors. This last configuration is the most common amongst the propfans. It involves the applications of two concentric rotors on the same centerline driven by the same prime mover which through a gearbox cause each propeller to rotate in a direction opposite the other. This concept is used in order to recover the residual swirl downstream of the front rotor. It can provide an increase of 6 to 8% of propulsive efficiency when compared with a single rotor concept. *(Peters, 2010; Mair and Birdsall, 1992).*

Like the turbofan engines, the propfans can also have tractor or pusher configurations. The pusher concept, similar to the aft fan, is more appropriated to propfan engines. Being the noise, the propfans greatest restraint, moving the propellers to the rear of the aircraft minimizes this effect. *(Cohen, Rogers and Saravanamuttoo, 2001).*

3.3 Propeller Blades

Propfan engines were designed as alternatives to turbofans. A propfan is nothing but a turbofan with an unshielded propeller, which provides the engine the needed thrust to achieve higher velocities with lower fuel consumption. Even though propfan engines are based on the turboprops, their propeller design has to fulfill different requirements. In this case the propeller has to be dimensioned in order to reach high velocities and even have greater efficiency. *(Roskam and Lan, 1997)*.

The main purpose of the aeronautical engines propellers is the conversion of the mechanical or shaft power to thrust power. The total thrust of the aircraft is the sum of the thrust produced by the propeller and the one from the hot gases exhaustion. These engines propellers become more efficient with increasing thrust.

The engine's propeller is a prime reliable component, which raises the need of good analytical and designing tools. There are two implicit theories when we speak of propellers: the actuator disk theory and the blade element theory. The combination of both results in a more accurate analysis and design.

In the actuator disk theory the rotor is considered to act like a solid disk with infinitesimal thickness and an infinite number of blades, each with an infinite aspect ratio. The actuator disk induces a speed increase in its section in order to generate the required thrust. A static pressure discontinuity is created across the disk section. With the blade element theory it is possible to determinate the forces and the momentums applied to the rotor. The blades are divided in several elements and each one of them is studied individually. It is needed to integrate from hub to tip across all blade elements to study the behavior of the entire rotor. Thereby is obtained the total forces values and through them it is possible to design the propeller. *(Mattingly, Heiser, Pratt, 2002)*.

The propeller blades of a propfan engine are different from the tuboprop ones. Although both engines have external propellers, propfan engines must operate at higher flight speeds. Higher flight speeds involve a higher disk loading, and therefore the blades must be adapted to a higher rotation and must have a specific design. Propfan blades are shorter than the conventional turboprop ones so that its tips do not get into a supersonic flow. However, smaller blades reduce the thrust, so the number of blades increase. Typically propfan engines have between 6 and 12 blades. (*Jackson, 2009; Ehrich F., EncyclopÆdia Britannica)*. Even at high subsonic speeds the efficiency of the propeller is maintained because of the blades shape. They are curved and with swept-back leading edges at the blade tip to prevent shockwaves formation. Most of the propfan engines have also a counter rotating configuration which provides them higher propulsive efficiency and disk loading than the conventional propellers. *(Schimming, 2003; Ehrich F., EncyclopÆdia Britannica)*.

3.4 Engine cycle

3.4.1 Conventional cycle

Aeronautical engines are designed to create the thrust power required for an aircraft flight. Although there are several types of gas turbines configurations the majority of them are based on the same working principles. The gas turbines operation mode can be thermodynamically described by the cycle represented in figure 3.

Propfan engines, like the other gas turbine engines use air as its working fluid to generate thrust force. All four phases of engine operation occur simultaneously at different engine stages.

The air at atmospheric conditions is driven by the compressor, and so the admission takes place between stages 1 and 2. Due to the ram effect, both temperature and pressure increase slightly. Then, in the compressor, the air undergoes an isentropic compression and both temperature and pressure increase until they reach a level needed for the combustion (stages 2-3). Theoretically, until this stage, the entropy remains constant and the process is still reversible. Now, the air enters the combustion chamber (3). In the combustion chamber and after fuel mixing, the combustion occurs and the temperature rises. Because combustion process is an irreversible process the entropy increases substantively (stages 3-4). Immediately after the combustion gases flow to the turbine, where the gases suffer an isentropic expansion and both temperature and pressure decreases. The turbine produces the energy required for the compressor and for the external propeller driving (stages 4-5). During the last stage (exhaust nozzle), the hot gases expand back to atmospheric pressure. The thrust is produced by those hot gases discharge to atmosphere which provides a propulsive jet (stages 5-6).

Although thermodynamically, in a cycle the last stage of the last process is the first stage of the first process, in reality, the released exhaust gases do not return onto the intake and therefore a gas turbine works in an open cycle. In spite of that, the stages 1 and 6 are at the atmospheric pressure. Therefore, in order to complete the cycle we can assume that all process stages from 1 to 6 are a constant pressure process. *(Rolls- Royce, 1992; Learn Engineering [TV]).*

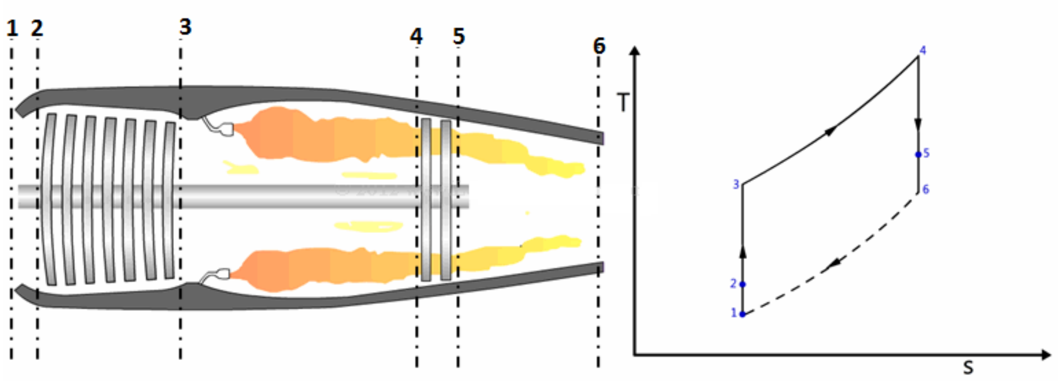

Figure 3: Working cycle of a conventional engine. ***(Learn Engineering*** ^{TV}***).***

3.4.2 Regenerated cycle

In this study is intended to verify the influence of the heat regenerator in the propfan propulsive efficiency and specific fuel consumption. More complex thermodynamic cycles, using heat exchangers to recover exhaust heat will be required in order to provide a significant step change in performance and reduction of toxic emissions. *(Mcdonald and Wilsont, 1996).*

The air temperature at the compressor outlet is lower than the gases leaving the turbine. Considering that, the objective sought with the incorporation of this heat exchanger is to use some of the energy of the exhaust gases in order to heat the air after the compressor outlet and before the combustion chamber entrance (see Figures 4 and 5). Therefore, the thermal efficiency is increased since some of the exhaust gases energy rejected before, is thus re-utilized. Furthermore, the regenerator causes a reduction in fuel consumption because a smaller amount of fuel will be required to heat the air coming from the compressor. The incorporation of this heat regenerator in a gas turbine and its thermodynamic cycle are pictured in figure 5. *(Bahrami M., Brayton Cycle; Brayton Cycle_3).*

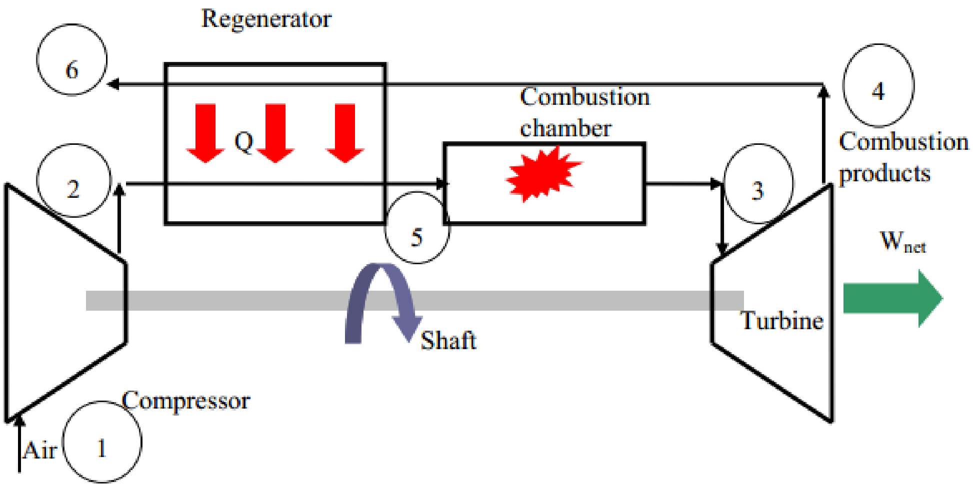

Figure 4: Schematic of a gas turbine engine with regenerator. *(Bahrami M., Brayton Cycle).*

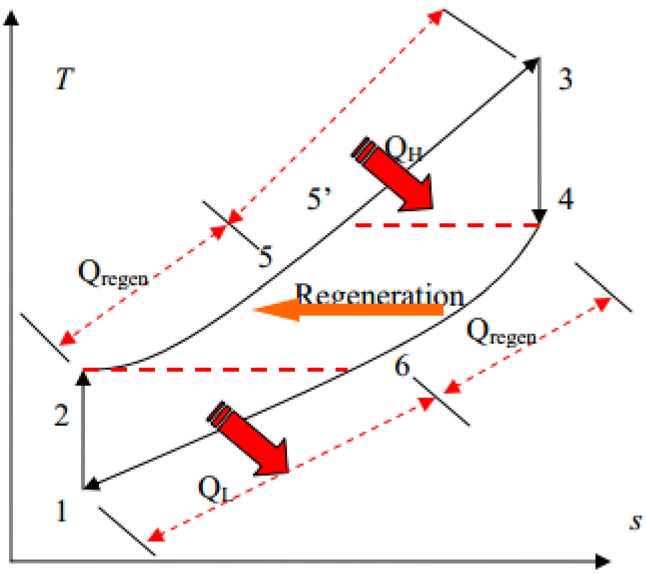

Figure 5: Working cycle of a regenerated engine. *(Bahrami M., Brayton Cycle).*

4. Engine Requirements

4.1 Engine Selection

The first step in the design is the development of a *Request for Proposal* (RFP), which is a document describing the desired performance and that includes the requirements to fulfill. *(Mattingly, Heiser, Pratt, 2002)*.

After knowing the required specifications, the next step following is the design process. Figure 6 is an example of the general design sequence in gas turbine engines design. It is a schematic diagram that represents a preliminary propulsion design process, on which this study is based on. *(Cohen, Rogers and Saravanamuttoo, 2001)*.

In this work there is no such document as the RFP, and so, the project conditions are developed taking into account an existing engine with similar characteristics to the one intended. The base engine of this study is a high bypass turbofan. It was chosen to use a turbofan as reference because it is the most alike engine to the propfan. The aim is to take the best velocity and performance level of this engine and make it work in the new engine design. The requirements considered are the ones of the turbofan CFM56-3B-2[10] engine. It is a two shaft engine with a high bypass ratio and it powers commercial aircrafts like Boing 737-300 and 737-400. *(CFM)*. Its specifications were considered very close to the pretended and they are described in Table 1:

Table 1: CFM-3-B2 engine characteristics. *(Meier N., Civil Turbojet/Turbofan Specifications, 2005; Brady C., The 737 Technical Site, 1999).*

Thrust: between 20 100 and 22 100 [lbf]	Thrust cruise: 5 040 [lbf]
Airflow (static): 683 [lb/s]	Cruise speed: 0,80 [M]
Type of Compressor: 3 LPC and 1stage fan; 9 stage HPC	Cruise altitude: 35 000 [ft.]
Type of Turbine: 1 stage HPT and a 4 stage LPT	Engine dry weight: 4 301 [lb.]
OPR (static): 24,3	Engine length: 93,1 [in]
BPR (static): 5,9	Engine diameter: 63,0 [in]
Turbine entry temperature: 1642 [K]	Fan diameter: 60,0 [in]

[10] "CFM56-3 is designed for Boeing 737-300/-400/-500 series aircraft, with static thrust ratings from 18,500 to 23,500 lbf. A "cropped fan" derivative of the -2, the -3 engine has a smaller fan diameter at 60 in but retains the original basic engine layout CFM56." *(CFM)*.

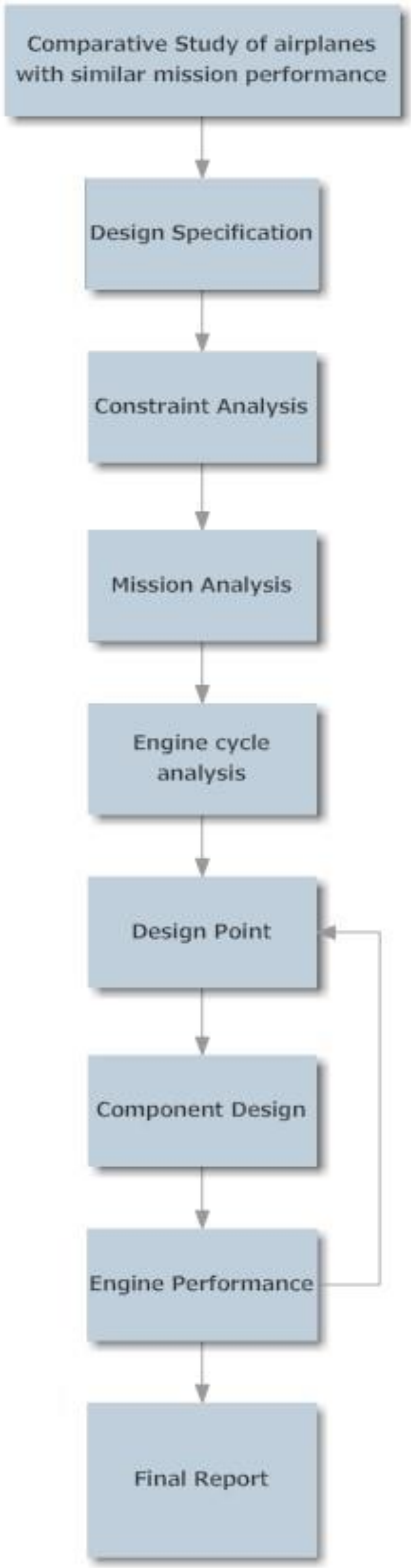

Figure 6: Gas turbines design procedure. *(Mattingly, Heiser, Pratt, 2002).*

4.2 Assumptions

In order to make the calculations and the analysis of the different engine configurations, there are some required assumptions to be made, such as follows:

- Engine operation condition: standard day;
- Steady flow;
- One-dimensional flow;
- Perfect gas behavior of the fluid, with constant molecular weight;
- Both low and high pressure turbines do not provide any mechanical power for accessories, P TOL = 0 and P TOH =0;
- The amount of bleed air is not considered;
- Polytropic compression and expansion;
- Two values for Cp and for γ were considered. Cp_c = 1005 J/kg.K and γ_c = 1.4 before the combustion chamber and Cp_t 1148 J/kg.K and γ_t = 1.333 after the combustion chamber;
- Turbine entry temperature constant: TET = 1642 K;
- The values that were kept constants and the efficiencies of components are presented in Table 2:

Table 2: Components efficiencies and pressure ratios. *(Lebre and Brójo, 2010; Jackson, 2009; El-Sayed, 2008).*

Component	Symbol	Value
Propeller efficiency	η_{prop}	0,8
Fan pressure ratio	π_f	1,71
Gearbox efficiency	η_g	0,8
Low pressure compressor polytropic efficiency	η_{Lc}	0,9
High pressure compressor polytropic efficiency	η_{Hc}	0,9
Burner efficiency	η_b	0,995
Burner pressure ratio	π_b	0,96
Low pressure turbine polytropic efficiency	η_{Lt}	0,91
High pressure turbine polytropic efficiency	η_{Ht}	0,89
Free turbines overall efficiency	η_{ft}	0.91
Mechanical efficiency	η_m	0,995
Nozzle efficiency	η_n	0,9
Nozzle total pressure ratio	π_n	0,99
Regenerator efficiency	η_{reg}	0,8
Regenerator total pressure ratio	π_{reg}	0,95

4.3. Conventional Propfan Engine

In order to analyze a regenerated propfan engine it is first necessary to make the same study on a conventional propfan. Thus it is possible to verify if the regenerator has any influence on the engine's performance.

Before the calculations it is important to know the engine's components location. Therefore this section shows a conventional propfan engine scheme and its station numbering, before the mathematical model used to analyze it.

4.3.1 Station Numbering

Unlike the turbofans the propfan analyzed here has two counter rotating external propellers in a pusher configuration. Therefore, it has no bypass ratio. It is a two shaft engine with two extra free turbines that drive the propellers. Figure 7 is a schematic representation of a conventional propfan engine. Figure 8 is a representation of the components block diagram.

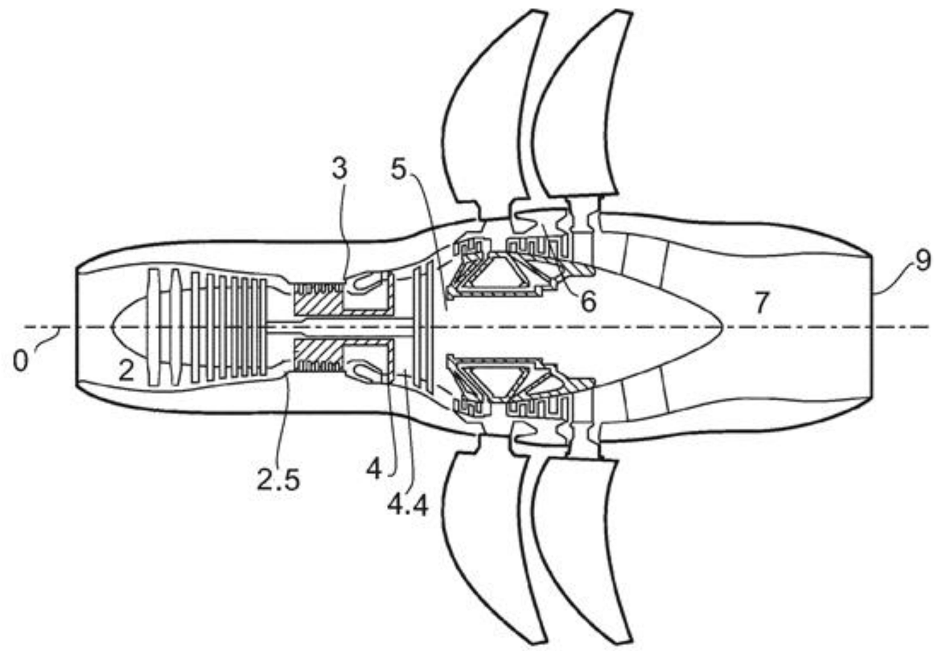

Figure 7: Schematic diagram of a conventional propfan engine. *(European Patent Application, 2012).*

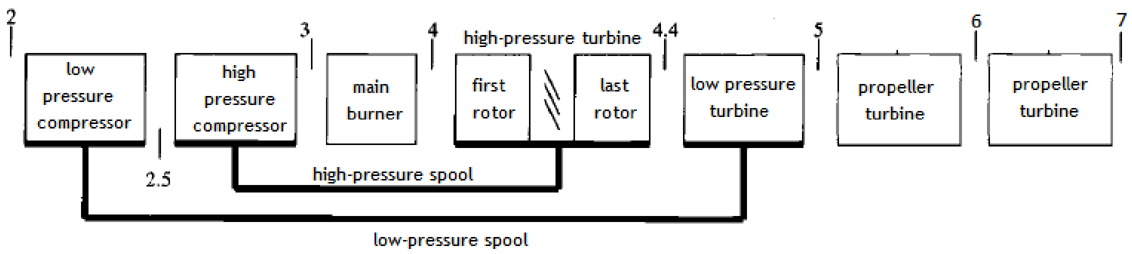

Figure 8: Components reference stations of a conventional propfan engine. *(Mattingly, Heiser, Pratt, 2002).*

The station numbering of the engines should be made in accordance with Aerospace Recommended Practice (*ARP*) 755A, to make it easier to identify the components locations in different engines. *(Mattingly, Heiser, Pratt, 2002).* The station numbers that will be used throughout this study are presented in Table 3:

Table 3: Station numbering. *(Mattingly, Heiser, Pratt, 2002).*

Station	Location
0	Far upstream or freestream
1	Inlet or diffusor entry
2	Low pressure compressor entry
13	Fan exit
2,5	Low pressure compressor exit High pressure compressor entry
3	High pressure compressor exit Burner entry
4	Burner exit High pressure turbine entry
4,4	High pressure turbine exit Low pressure turbine entry
5	Low pressure turbine exit First free turbine entry

6	First free turbine exit
	Last free turbine entry
7	Last free turbine exit
	Core exhaust nozzle entry
9	Core exhaust nozzle exit
19	Bypass exhaust nozzle exit

4.3.2 Mathematical Model

The calculations for a conventional propfan engine are meant to provide values for engine parameters that affect the engine performance. The calculations are based on the mathematical models presented in *Aircraft Engine Design* and *Aircraft and Gas Turbine Engines, (Mattingly, Heiser, & Pratt, 2002; El-Sayed, 2008)*. The engines are analyzed in on-design conditions (cruise flight: M = 0.8 and h = 10668 m).

The performance parameters that will be analyzed are the specific thrust and the specific fuel consumption. The propfan engine calculations were made using the turboprop formulas with the difference that the propfan engine has two propellers driven by two free turbines. For turboprop engines the fuel consumption is identified by the equivalent specific fuel consumption (ESFC).

The thrust of the propfan is generated both from the propellers and the exhaust gases. The last one is also called core thrust. The total thrust of the engine is the sum of both core and propeller components. The value of the total thrust of the propfan is imposed. As the aim is to design an engine with the same thrust as the current turbofan CFM-3-B2, the value of the thrust has to be the same. The total specific thrust equation, as well as both the propellers and exhaust gases contributions to it are:

$$\frac{F_{prop}}{\dot{m}_a} = \frac{\eta_{prop} \times \eta_g \times \eta_m \times C_{pt} \times (T_{05} - T_{07})}{U} \tag{1}$$

$$\frac{F_{core}}{\dot{m}_a} = (U_{09} - U_a) + \frac{R \times T_{09}}{P_{09} \times U_{09}} \times (P_{09} - P_a) \tag{2}$$

$$\frac{F}{\dot{m}_a} = \frac{F_{total}}{\dot{m}_a} = \frac{F_{prop}}{\dot{m}_a} + \frac{F_{core}}{\dot{m}_a} \tag{3}$$

Where:

$\frac{F_{prop}}{\dot{m}_a}, \frac{F_{core}}{\dot{m}_a}$	Specific thrust of the propeller and the core respectively;
$\frac{F}{\dot{m}_a}, \frac{F_{total}}{\dot{m}_a}$	Total specific thrust power;
$\eta_{prop}, \eta_g, \eta_m$	Propeller, gearbox and mechanical efficiencies respectively;
C_{pt}	Specific heat capacity at constant pressure for burned gas;
T_{05}, T_{07}, T_{09}	Temperature at stages 05, 07 and 09 respectively;
U	Flight speed;
U_a, U_{09}	Speed at admission and at stage 09 respectively;
R	Gas constant;
P_a, P_{09}	Pressure at admission and stage 09 respectively;

To calculate the pressure and the temperature at stage 07, after the free turbines, there are some considerations:

- The two free turbines that drive the propellers are considered as a whole, and their global efficiency is considered the same as the low pressure turbine;

- It is considered a utilization coefficient, α and an enthalpy drop, Δh. The value for the utilization coefficient is assumed as the optimum, which means that the total traction has its optimum value. Thus, from stage 05 to stage 07 there is a full expansion to the ambient pressure, induced by the free turbines that drive the propellers and nozzle. The representation of the successive expansion processes in the free power turbines and nozzle is presented in figure 9.

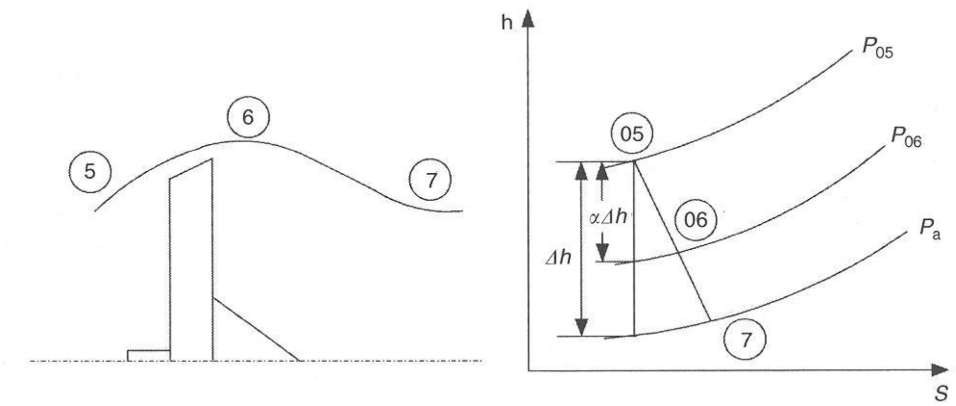

Figure 9: Expansion in the turbine and nozzle of a double-spool turboprop engine. *(El-Sayed, 2008).*

The equations to determinate the optimum α and *Δh* are the following:

$$\Delta h_{5-7} = Cp_t \, T_{05} \times \left[1 - \left(\frac{P_a}{P_{05}}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{4}$$

$$\alpha_{optimum} = 1 - \frac{U^2}{2\,\Delta h_{5-7}} \times \left[\frac{\eta_n}{{\eta_{prop}}^2 \times {\eta_g}^2 \times {\eta_{ft}}^2 \times {\eta_m}^2}\right] \tag{5}$$

Where:

Δh_{5-7}	Enthalpy variation from the stage 05 to 07;
P_{05}	Pressure at stage 05;
γ	Specific heat ratio;
$\alpha_{optimum}$	Optimum work coefficient;
$\eta_n, \eta_{ft}, \eta_m$	Nozzle, free turbines and mechanical efficiencies respectively;

The Equivalent Specific Fuel Consumption is given by:

$$ESFC = \frac{\dot{m}_f}{ESPH} \tag{6}$$

ESHP is the Equivalent Shaft Horsepower. For a propfan engine during flight, the ESHP is equal to the shaft horsepower plus the exhaust jet thrust power:

$$ESHP = shp + \frac{F_{core} \times U}{745.7 \times \eta_{prop}} \tag{7}$$

$$shp = \frac{F_{prop} \times U}{745.7 \times \eta_{prop}} \tag{8}$$

Where:

$ESFC$	Equivalent Specific Fuel Consumption;
$\dot{m}_f$	Fuel mass flow;

$ESHP$	Equivalent Shaft Horsepower;
shp	Shaft horse power;
F_{core}, F_{prop}	Thrust provided by core and propellers respectively;

4.4 Propfan Engine with Regeneration

According to several authors, a conventional propfan configuration has already lower specific fuel consumption than a current turbofan. The integration of a heat regenerator on a gas turbine engine is expected to reduce further its specific fuel consumption. Thus, considering the same heat regenerator incorporated on a propfan engine, even further reductions may be expected, with prospects of reaching also the same performance.

4.4.1 Configuration

The heat regenerator purpose is to transfer the heat from the exhaust gases to the air leaving the high pressure compressor, before entering the combustion chamber. This happens in order to reduce the combustion chamber's required fuel. To be able to transfer the energy from the exhaust gases, the regenerator is placed on the engine's exhaust nozzle. In figure 10 is a schematic representation of a propfan engine with heat regenerator, followed by its components block diagram of (Fig. 11).

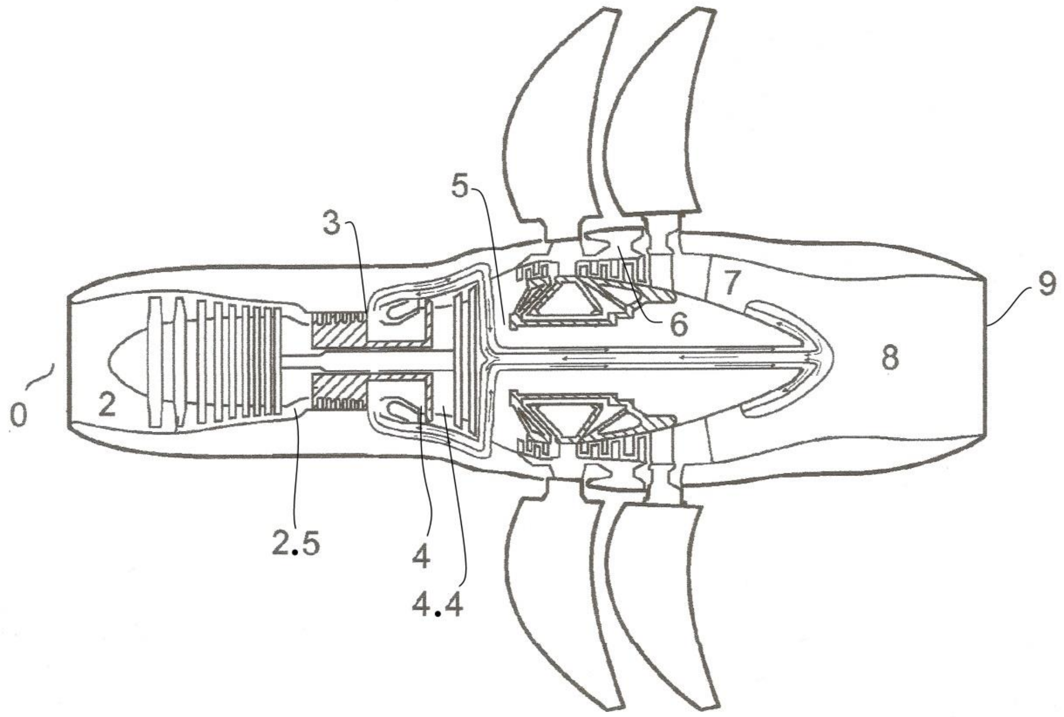

Figure 10: Schematic diagram of a regenerated propfan engine. *(Adapted from European Patent Application, 2012).*

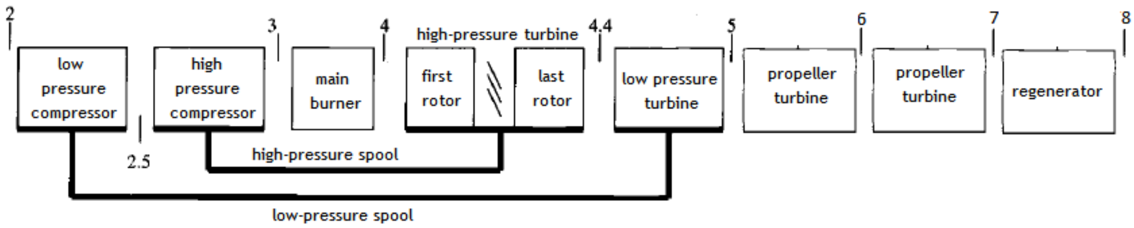

Figure 11: Components reference stations of a regenerated propfan engine. *(Mattingly, Heiser, Pratt, 2002).*

4.4.2 Mathematical Model

The mathematical model used to make the calculations of the propfan engine integrated with a heat regenerator is very similar to the one used with the conventional propfan. The main difference appears with the regenerator. In the conventional propfan, to calculate the temperature and pressure after the free turbines, and before the regenerator, α was assumed as optimum, which means a full expansion to the ambient pressure at stage

07, see figure 9. To calculate the influence of regeneration the value of α is varied from the minimum to maximum, 0 to 1. The value of α = 0, see figure 9, means that from stage 05 to stage 07, (before the regenerator) both the enthalpy and the pressure do not change. In this case there is no thrust power extracted from the propellers. When the value of α is maximum, the pressure at stage 07 is the ambient pressure and therefore the thrust power produced at the core is only the one corresponding to velocity differences between the core jet and the airplane.

The temperature and pressure change at the regenerator, stage 08, are calculated as follows:

$$T_{08} = T_{07} - \frac{\Delta h_{7-9}}{Cp_t} \tag{9}$$

$$P_{08} = P_{07} \times \pi_{reg} \tag{10}$$

$$\Delta h_{7-9} = (1-\alpha) \times \Delta h_{5-7} \times \eta_{reg} \tag{11}$$

Where:

T_{07}, T_{08}	Temperature at stages 07 and 08 respectively;
Δh_{5-7} , Δh_{7-9}	Enthalpy variation from the stage 05 to 07 and from the stage 07 to 09;
P_{07}, P_{08}	Pressure at stages 07 and 08 respectively;
π_{reg}	Regenerator total pressure ratio;
α	Work coefficient;
η_{reg}	Regenerator efficiency;

The power thrust and the equivalent specific fuel consumption of the regenerated propfan are calculated by the same method as in the conventional propfan.

4.5 Turbofan Engine

The analysis of a current turbofan is very important for this study. We need to know the performance characteristics of a turbofan in order to design an equivalent propfan. The chosen engine is a CFM-3-B2.

4.5.1 Configuration

The turbofan consists of a two shaft engine with high bypass, and its configuration is presented in figure 12. In figure 13 is shown the engine components block diagram.

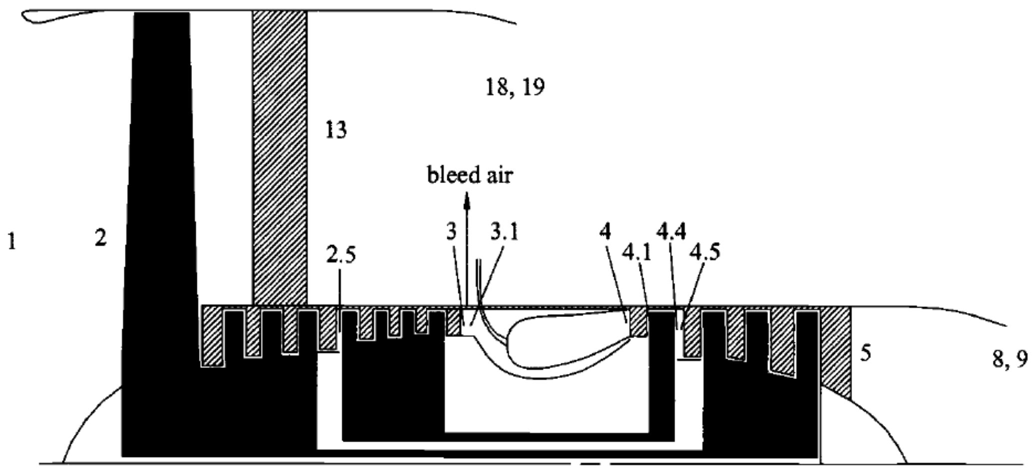

Figure 12: Schematic representation of a current turbofan engine with high bypass ratio. *(Mattingly, Heiser, Pratt, 2002).*

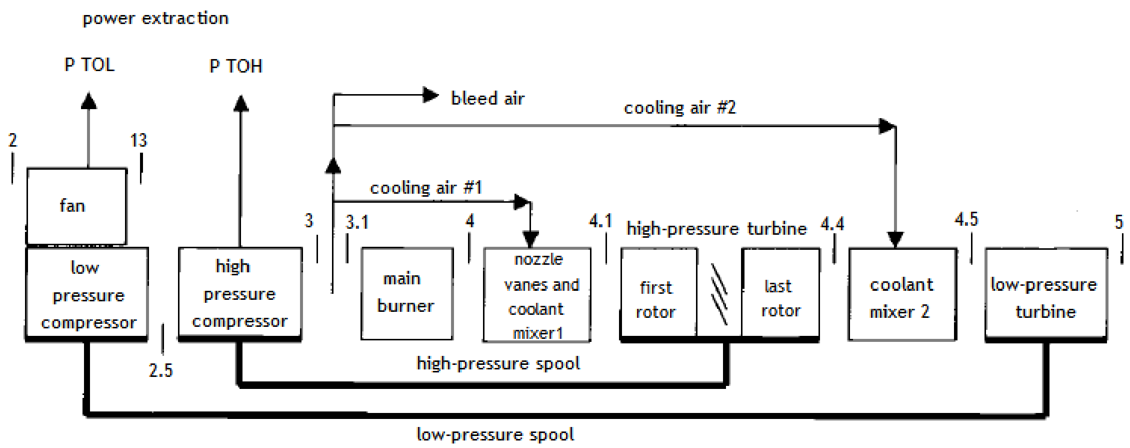

Figure 13: Blocks diagram of components of a high bypass ratio turbofan engine. *(Mattingly, Heiser, Pratt, 2002).*

4.5.2 Mathematical Model

The mathematical model used to make the calculations of the turbofan with separated exhaust streams, is also based on the models presented in *Aircraft Engine Design* and *Aircraft and Gas Turbine Engines, (Mattingly, Heiser, & Pratt, 2002; El-Sayed, 2008)*. The analysis is also made for cruise conditions: M = 0.8 and h = 10668 m.

The analyzed parameters are also the specific thrust and the specific fuel consumption in order to allow comparing the results of the three configurations. For turbofan engines the specific fuel consumption is identified by the thrust specific fuel consumption (TSFC).

The total specific thrust is the sum of the thrust from the hot gases exhaustion (F hot) and the one from the cold air of the bypass, (F cold). It is given by:

$$\frac{F}{\dot{m}_a} = \frac{F_{hot}}{\dot{m}_h} + \frac{F_{cold}}{\dot{m}_c} \tag{12}$$

$$\frac{F_{hot}}{\dot{m}_h} = \left[(U_{09} - U_a) + \frac{R \times T_{09}}{P_{09} \times U_{09}} \times (P_{09} - P_a)\right] \times \frac{\dot{m}_h}{\dot{m}_a} \tag{13}$$

$$\frac{F_{cold}}{\dot{m}_c} = \left[(U_{019} - U_a) + \frac{R \times T_{019}}{P_{019} \times U_{019}} \times (P_{019} - P_a)\right] \times \frac{\dot{m}_c}{\dot{m}_a} \tag{14}$$

Where:

$\frac{F}{\dot{m}_a}$	Total specific thrust;
$\frac{F_{hot}}{\dot{m}_h}, \frac{F_{cold}}{\dot{m}_c}$	Specific thrust produced from the hot gases exhaustion and from the cold air of the bypass, respectively;
U_a, U_{09}, U_{019}	Speed at the intake, at stage 09 and at stage 019, respectively;
R	Gas constant;
T_a, T_{09}, T_{019}	Temperature at intake, stage 09 and 019 respectively;
P_a, P_{09}, P_{019}	Pressure at intake, stage 9 and 19 respectively;

After knowing the specific thrust is then possible to calculate the engine's thrust specific fuel consumption:

$$TSFC = \frac{f_0}{F/\dot{m}_a} \quad (15)$$

$$f_0 = \frac{\dot{m}_f}{\dot{m}_a} \quad (16)$$

Where:

$TSFC$	Thrust Specific Fuel Consumption;
f_0	Overall fuel-air ratio;
$F/\dot{m}_a$	Specific thrust;
$\dot{m}_f, \dot{m}_a$	Fuel and air mass flows, respectively;

Once all the parameters formulas are known, the next step is to analyze the results and compare the three engine configurations and determine if the regenerated propfan excels the others.

5. Results

This chapter contains all the results obtained from the calculations. First, are presented the graphics regarding the propfan engines, which include the conventional engine and the regenerated propfan. The turbofan engine results are presented next, followed by a comparison between the three engine configurations.

5.1 Propfan Engines Results

The results regarding the propfan engines imply a direct comparison between the regenerated propfan and the conventional one. On both engines the range of overall pressure ratio is between 5 and 40, although only in the conventional propfan was possible to obtain values for the OPR of 40. For propfan engines the calculations were made for constant mass airflow, $\dot{m}_a$ = 17 kg/s.

Figure 14 presents the variation of the specific fuel consumption with the equivalent total specific thrust. Through this figure is possible to verify that the specific thrust increases with the increasing of α. The ESFC decreases with the increasing of both overall pressure ratio and α. This figure also shows that for each α, the ESFC may have two different values for the same specific thrust, which means that for each α there is an optimum value for the specific thrust. For values of α equals or greater than 70, it is only possible to make the calculations for an OPR until 30. Regarding this two parameters, only one regenerated propfan excels the conventional: the engine with α equal to one.

Figure 15 is a different point of view to visualize the variation of total specific thrust with ESFC, varying now with the OPR instead of α. In this figure is possible to observe a deviation next to the point of α equal to 0.7. It means that this is a transition point, where the nozzle flow changes from choked to unchoked.

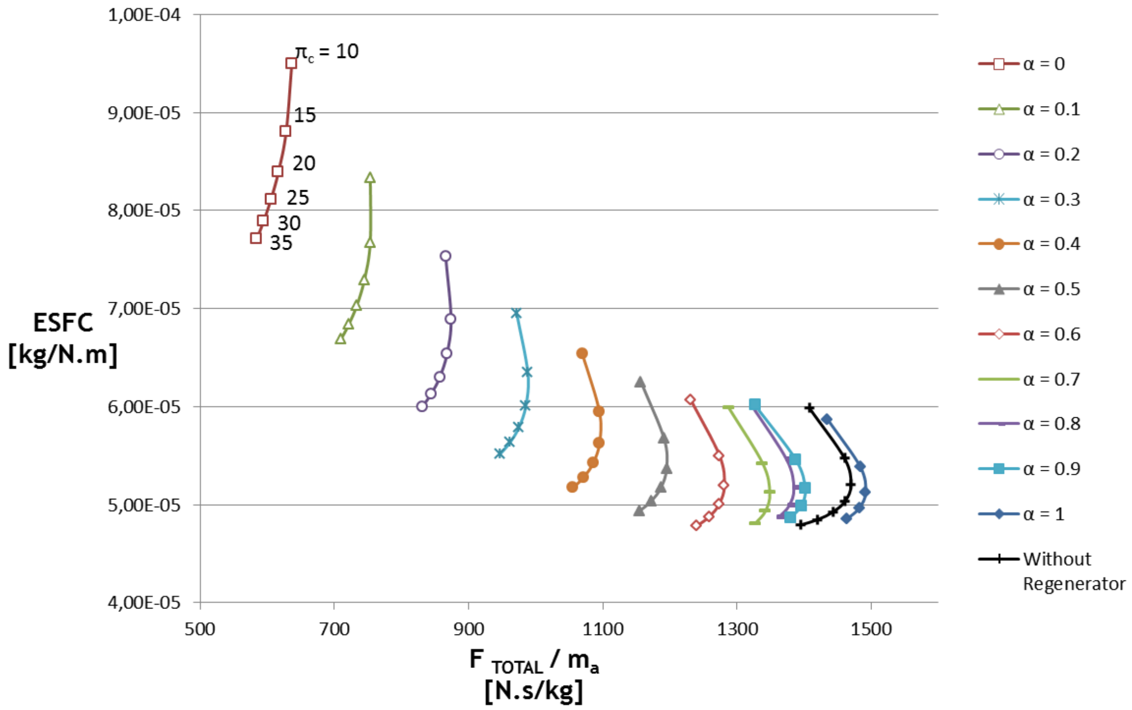

Figure 14: Equivalent Specific Fuel Consumption vs Total Specific Thrust, varying with α.

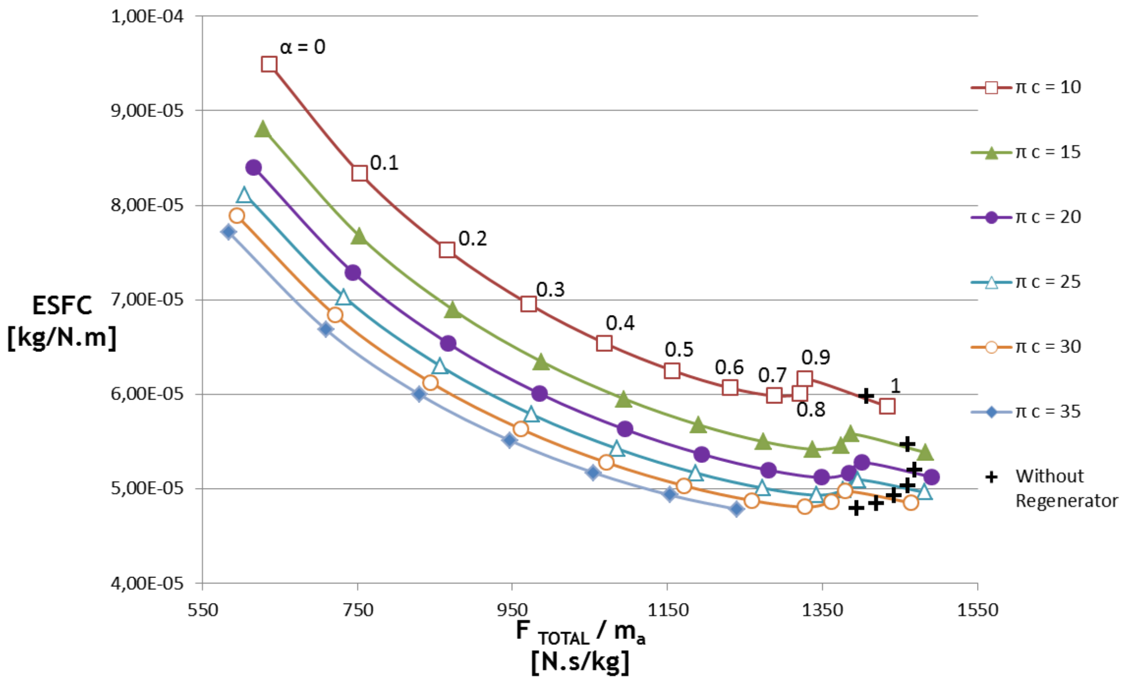

Figure 15: Equivalent Specific Fuel Consumption vs Total Specific Thrust, varying with overall pressure ratio.

The next three figures (figure 16, 17 and 18) present the OPR influence on the total specific thrust, ESFC and fuel mass flow, respectively. In figure 16 is possible to see the variation of OPR with the specific thrust, for different values of α. It shows that in a general way specific thrust decreases slightly with the increase in OPR, for OPR values above 10. Increasing the values of α causes an increase in the specific thrust. Higher values of α provide higher specific thrust coming from the propellers and less from the exhaust gases. As the propellers deliver more thrust than the exhaust gases, higher α coefficients mean higher specific thrust values. Again in this figure, it can be seen that only the regenerated engine with α equal to one excels the conventional propfan.

From figure 17 we can see that the equivalent specific fuel consumption decreases with the increase of both α overall pressure ratio. Regarding ESFC, regenerated propfans only begin to worthwhile to α close to 60%, but with a very slight reduction in ESFC comparing with the conventional engine.

Although the conventional propfan has a lower ESFC, through figure 18 can be concluded that the same does not happen for the fuel mass flow consumption. The higher values for the fuel consumption appear for the non-regenerated engine, matching the values for the regenerated engine with α equal to one. The situation that consumes less fuel is where the regenerator recovers the highest energy value, α equal to zero.

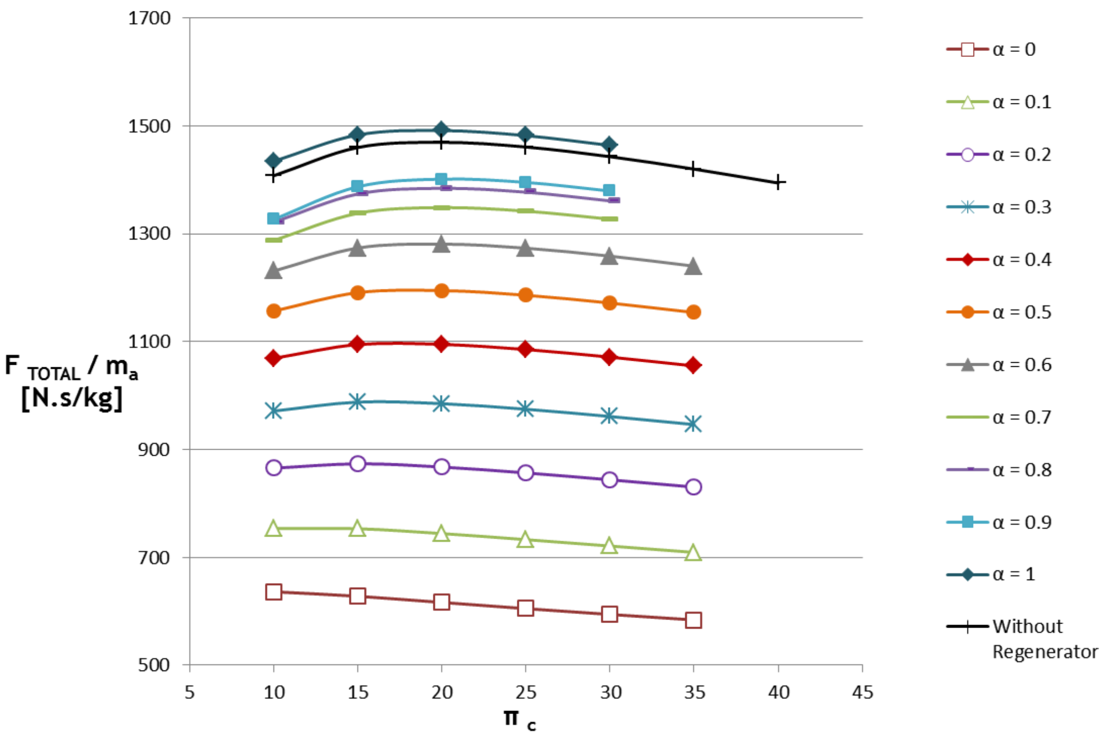

Figure 16: Total Specific Thrust vs Overall Pressure Ratio, varying with α.

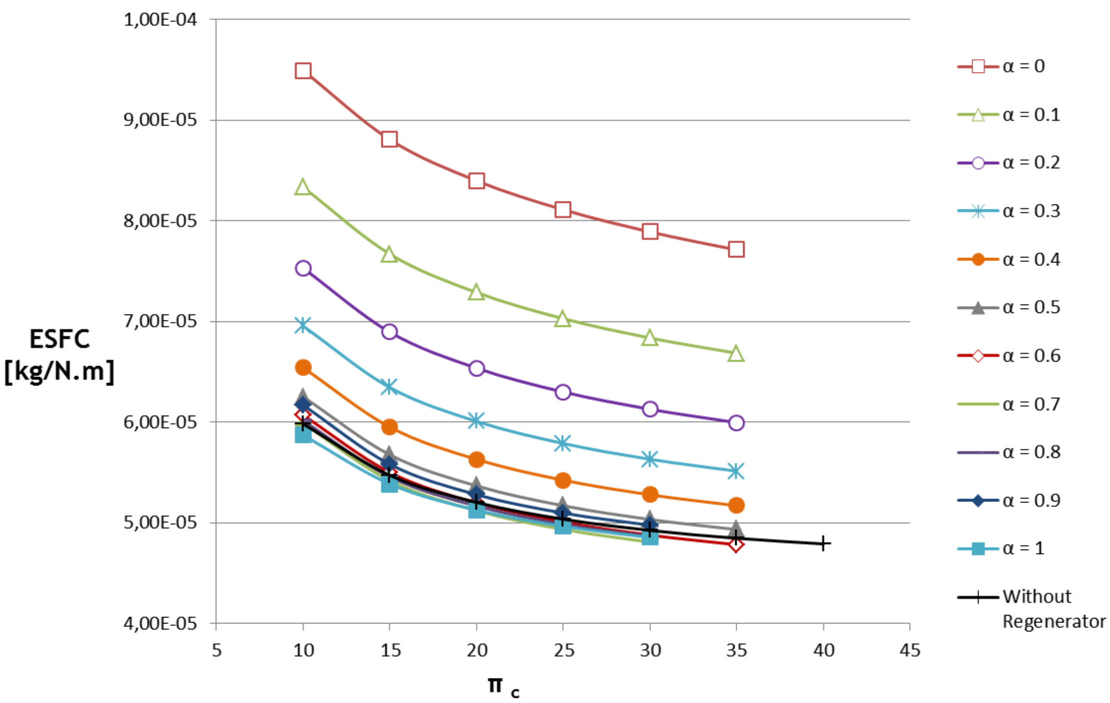

Figure 17: Equivalent Spefic Fuel Consumption vs Overall Pressure Ratio, varying with α.

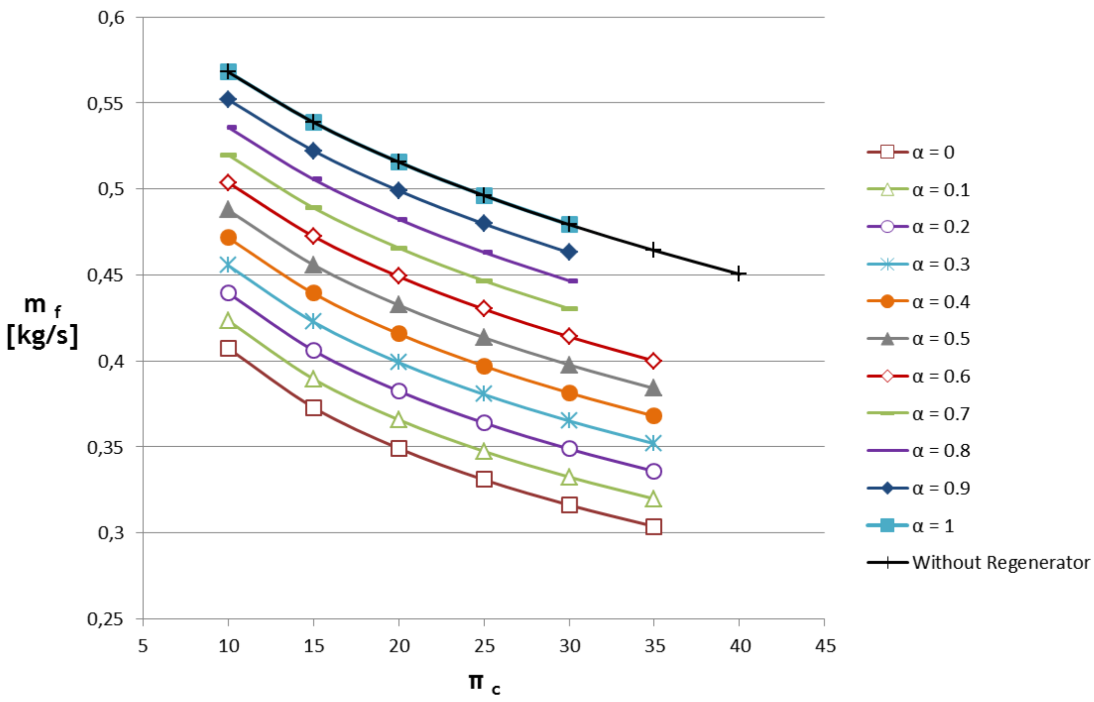

Figure 18: Fuel mass flow vs Overall Pressure Ratio, varying with α.

After the calculations with constant mass airflow, the mass airflow was changed, in order to have the same thrust power in the propfans that in the current turbofan CFM-3-B2, F = 22419.058 N. The graphic of figure 19 shows the $\dot{m}_f$ value for the optimum point of the specific thrust, calculated for each α. In this figure, to make it easier to compare, is represented the total thrust power and not the specific thrust, once the specific thrust for each value of α is different. For the required thrust, the best from all the optimum points is the $\dot{m}_f$ corresponding to an α of zero. These results correspond to the expectations because the regenerated propfan where both enthalpy and pressure do not change across the propellers is the situation where all of the energy from the hot gases is regenerated, and so the inlet of the combustion chamber has a higher temperature, which provides less fuel burn.

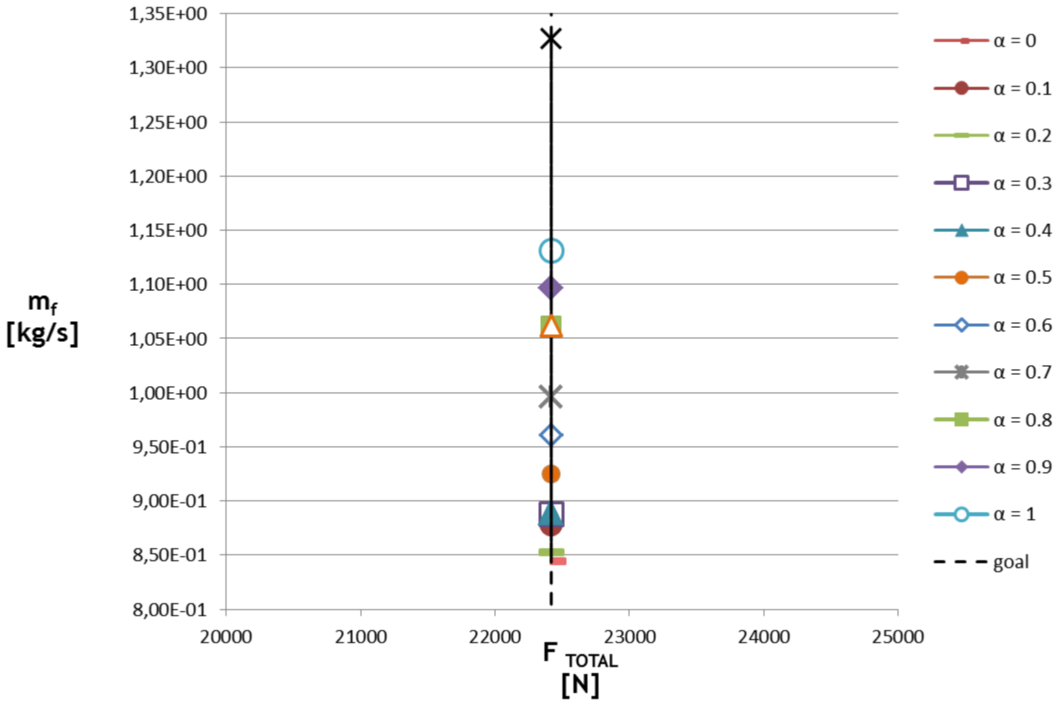

Figure 19: Values of $\dot{m}_f$ for the optimum point of specific thrust, for each α.

5.2 Turbofan Engines Results

For the turbofan engines, the calculations were made to analyze the same parameters as in the propfans, so that the results might be compared. For the turbofan engine, the bypass ratio was varied between 3 and 10, and the overall pressure ratio between 10 and 40. Like as in the propfans case, for the turbofan calculations were also considered a constant mass airflow, $\dot{m}_a$ = 135 kg/s.

Figures 20 and 21 present two different points of view for the variation of the specific thrust with the specific fuel consumption, for different values of bypass ratio and overall pressure ratio. As can be seen in figure 21, until a bypass ratio close to 8, increasing both the bypass ratio and the overall pressure ratio reduces the specific fuel consumption. Above that value the graphic trend slightly changes. That is the point where the nozzle flow changes from choked to unchoked, as also happens in propfans.

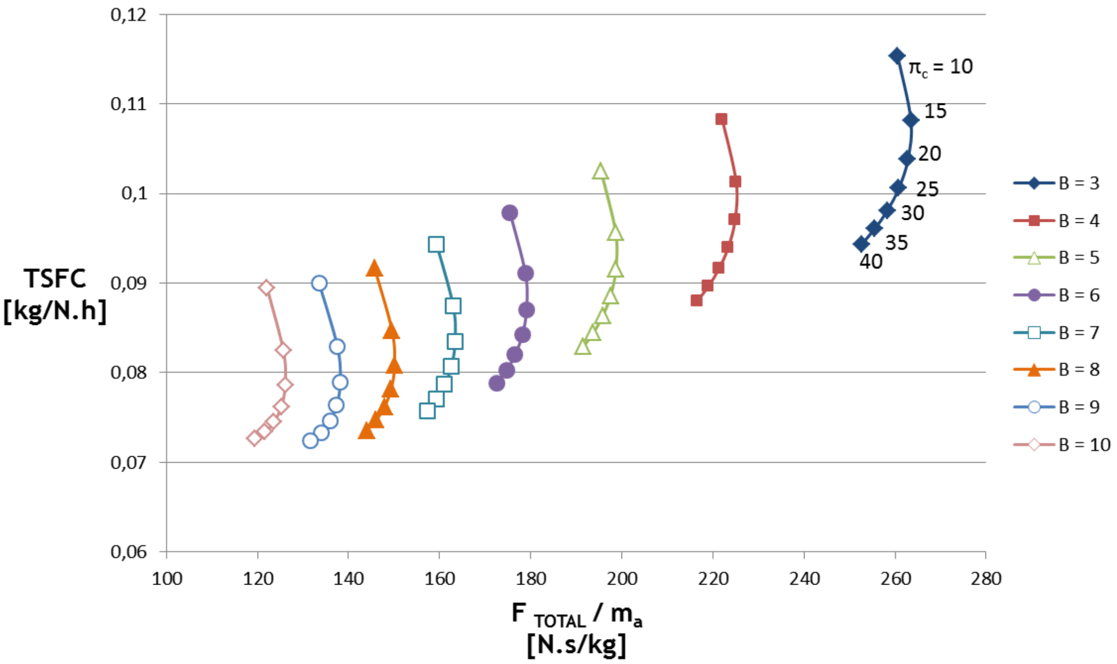

Figure 20: Thrust Specific Fuel Consumption vs Total Specific Thrust, varying with Bypass ratio.

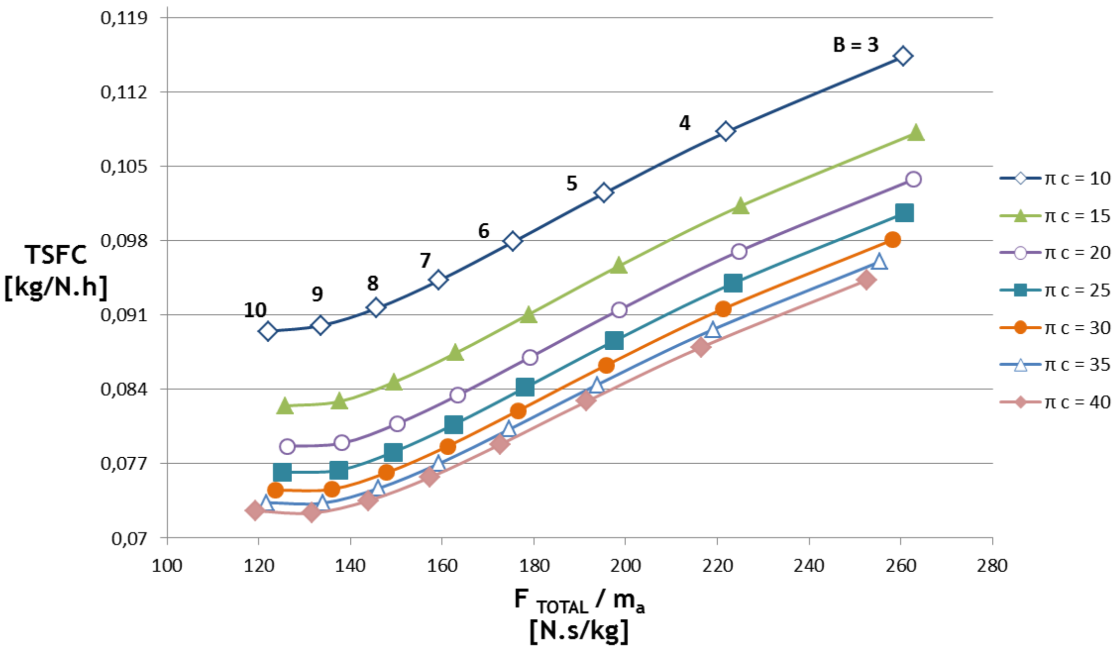

Figure 21: Thrust Specific Fuel Consumption vs Total Specific Thrust, varying with overall pressure ratio.

Figures 22 and 23 represent how the OPR influence on the total specific thrust and the thrust specific fuel consumption, respectively. From figure 22 can be observed that an increase, in the bypass ratio causes an increase in the specific thrust. According to what happens in the propfan engine, for the turbofan, the specific thrust also has an almost constant value along the different values for the OPR, decreasing just slightly. Contrarily to what happens for the specific thrust, the TSFC value decreases with the increase of both bypass and OPR (see figure 23).

In similarity with the propfan engines calculations, figure 24 shows the TSFC value for the optimum point of specific thrust, calculated for each bypass ratio. In this case, the mass airflow was also varied and the thrust kept constant, equal to the required one, F = 22419.058 N. In this figure is represented the thrust power and not the specific thrust for the same reasons already referred. It is possible to verify that the optimum point of TSFC for the required thrust is obtained with a bypass ratio of 10. For a bypass ratio of 10 the amount of air passing through the engine core is less than for the other bypasses, which causes a lower value of specific thrust but also a lower value of TSFC.

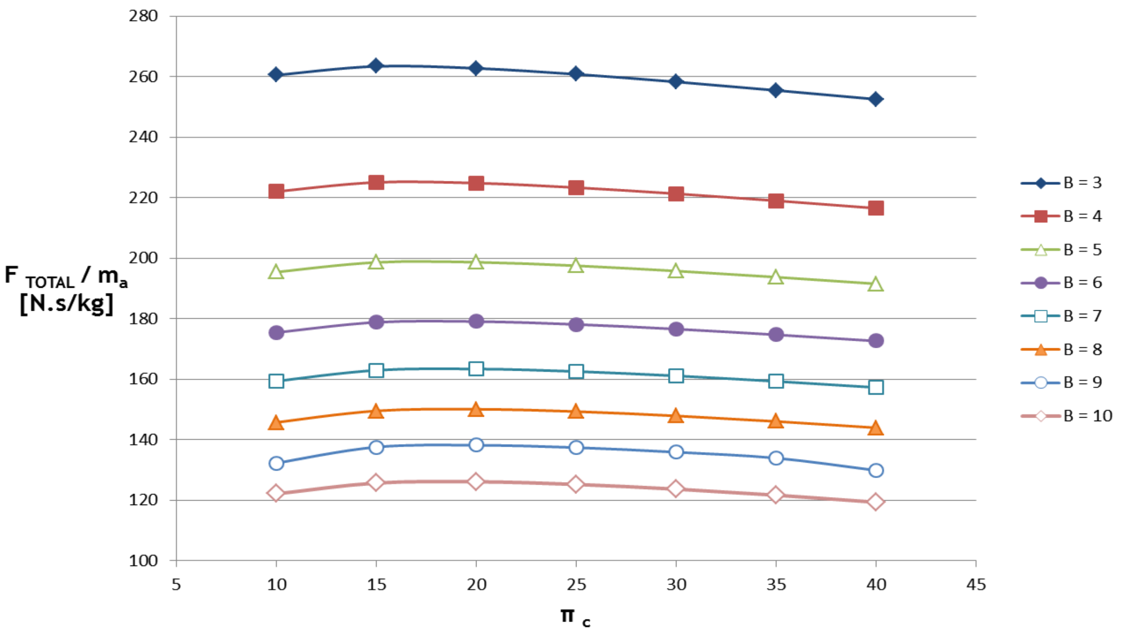

Figure 22: Total Specific Thrust vs Overall Pressure Ratio, varying with bypass ratio.

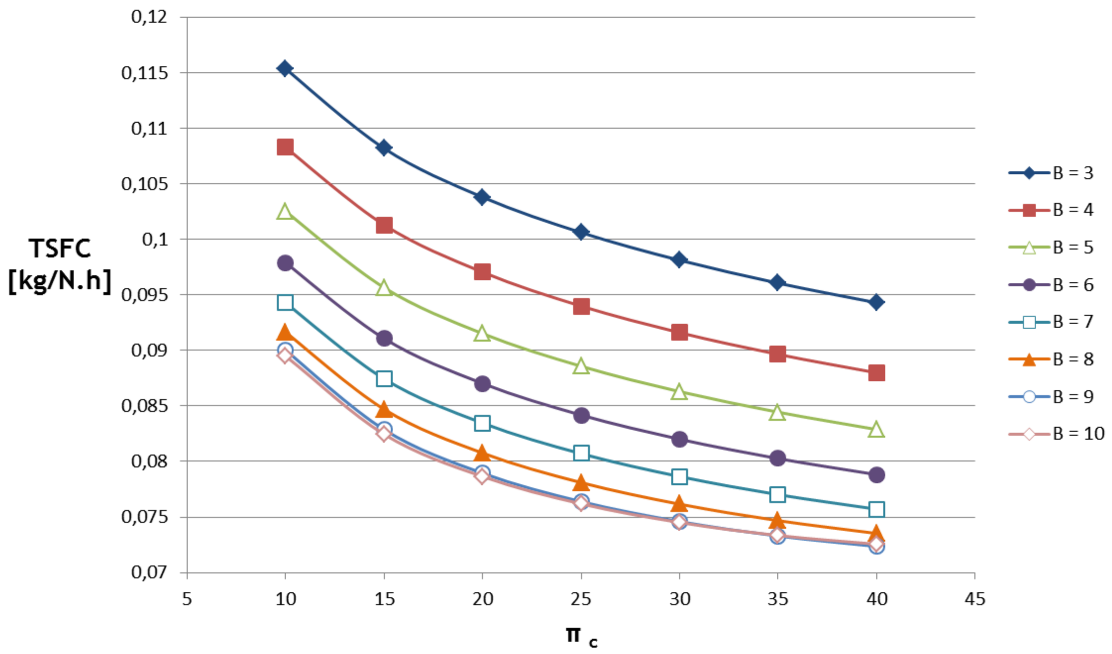

Figure 23: Thrust Specific Fuel Consumption vs Overall Pressure Ratio, varying with bypass ratio.

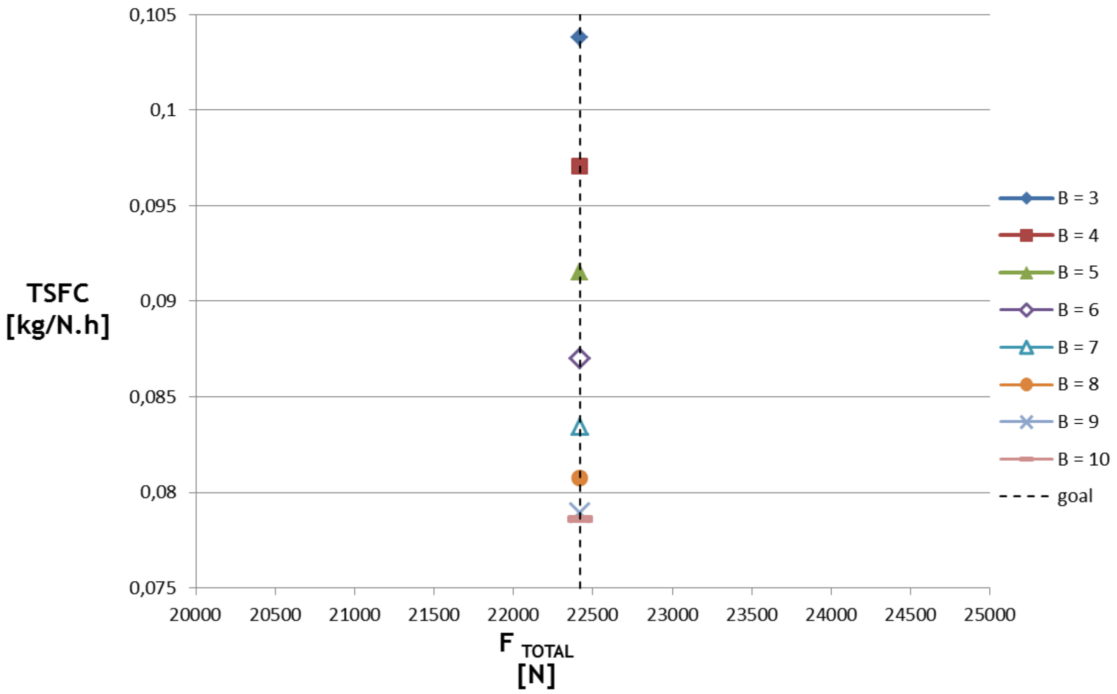

Figure 24: Values of TSFC for the optimum point of specific thrust, for each bypass ratio.

5.3 Engines Comparison

The three engines are compared regarding the specific thrust and the specific fuel consumption. The next figures are represented only for the conventional propfan engine, the current high bypass ratio turbofan and for the regenerated propfan with values of α between 0.9 and 1. The remaining propfan engines with values of α between 0 and 0.8 are not represented, once the non-regenerated propfan revealed a considerable difference in the values of every parameter. For the turbofan engines it is only shown in the comparative graphics the values for a bypass ratio of 6, because that is the real bypass ratio of the turbofan engine analyzed, and that is the one intended to compare with.

The graphic pictured in figure 25 was built considering the mass air flow constant: $\dot{m}_a$ = 135 kg/s for the turbofan engine and $\dot{m}_a$ = 17 kg/s for the propfan engines. This figure shows the variation of the specific fuel consumption with the thrust.

It shows that the current turbofan has the highest value of specific fuel consumption and the propfan with the higher value of α has the lowest, for the point of maximum thrust. In the propfan engine with α equal to one the thrust power is almost entirely produced by the propellers. Using the heat regenerator, the exhaust gases jet is practically zero because all the energy is regenerated. Thus, we conclude that the propellers provide better values of fuel consumption.

In figures 26 and 27 is shown the variation of the total specific thrust and the specific fuel consumption with the OPR, respectively. The turbofan engine specific thrust is significantly smaller than that of propfans, and its SFC is higher. Again in these figures is shown that the regenerated propfan with the major value of α has the best values of specific thrust and fuel consumption, but very close to the conventional propfan.

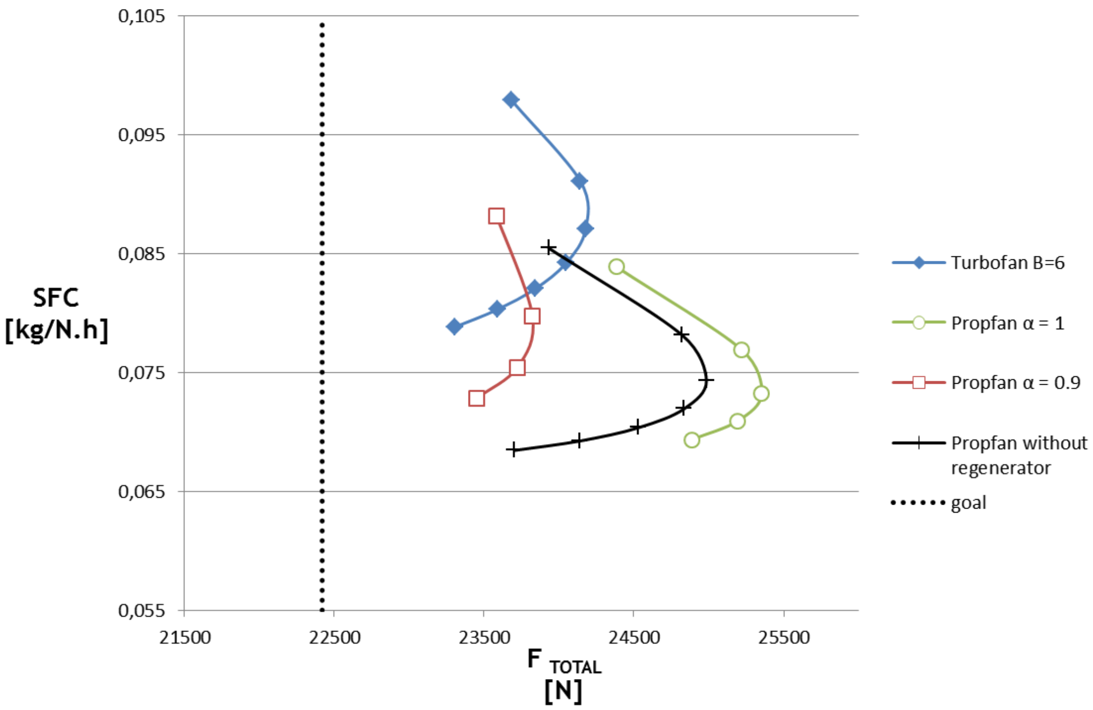

Figure 25: Specific Fuel Consumption vs Total Thrust.

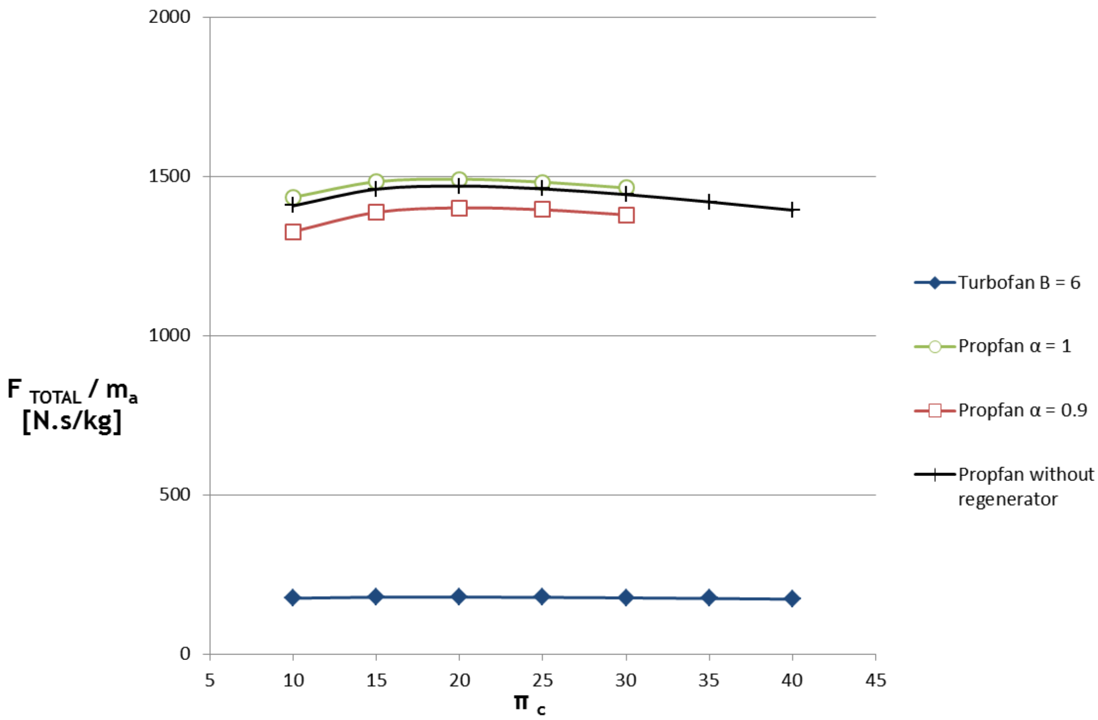

Figure 26: Specific Thrust vs Overall Pressure Ratio.

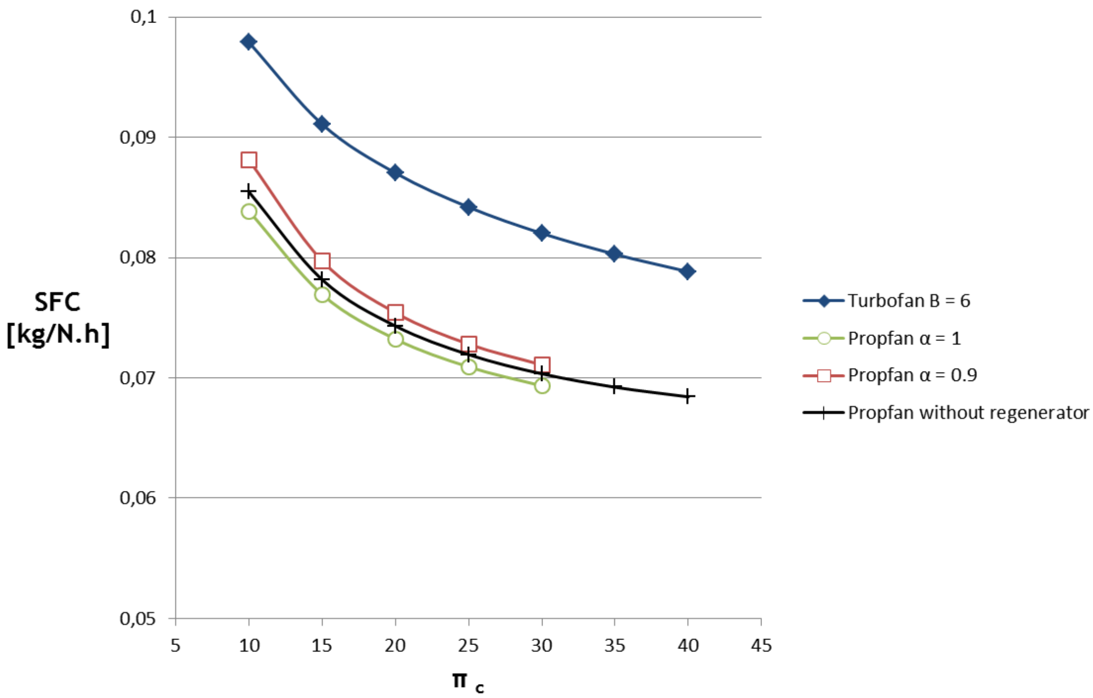

Figure 27: Specific Fuel Consumption vs Overall Pressure Ratio.

6. Conclusions and Future Work

6.1 Conclusions

The aim of this work was to study the effects of the introduction of a heat regenerator in a propfan engine. What was expected was that this new configuration of engine had better performance than the current turbofan engines. In order to prove the expectations three different configurations of engines were compared: a current high bypass turbofan, a conventional propfan and a regenerated propfan. The regenerated propfan was studied in several different situations. It was studied for different values of pressure and enthalpy at the free turbines exit and the regenerator entry. These values were defined by a utilization coefficient. For a utilization coefficient of zero, the thrust provided by the propellers is zero, and the engine's thrust is all provided from the hot gases exhaust. For a utilization coefficient of 1, the opposite happens.

The performance parameters analyzed were the specific thrust and the specific fuel consumption, and the engines were studied for on-design conditions (flight cruise). For the turbofan it was studied a range of bypass ratios from 3 to 10, and the OPR, considered for all engines, from 10 to 40.

The graphics obtained revealed that among the propfans, the regenerated engine calculated with the higher utilization coefficient has the greatest performance values in every parameter studied. Its specific thrust is the highest and its ESFC is the lowest, although its values are very close to the non-regenerated engine. This happens because the regenerated propfan with work coefficient of 1 is the situation where the thrust is almost entirely produced by the propellers. Even though its ESFC has the lower value, if we analyze in terms of fuel mass flow consumption it is one of the biggest consumers, as well as the conventional propfan. The implementation of a heat regenerator may not reduce the equivalent specific fuel consumption, but the results show that it has a great influence reducing the fuel mass flow consumption. This is proven once the regenerated engine with null work coefficient (situation where the regenerator acts perfectly) is the one with less fuel mass flow consumption.

Regarding the conventional propfan, it has better values of specific thrust and equivalent specific fuel consumption than any regenerated propfan with utilization coefficient below one. But even for the regenerated engine with utilization coefficient of one, the conventional propfan has very competitive values.

Comparing all the engine configurations, there is a considerable distance between the regenerated propfan, for a utilization coefficient of 1, and the turbofan with bypass ratio of 6, the propfan excels the turbofan. From the comparison graphics it is possible to verify a very close behavior between the regenerated propfan with utilization coefficient of 1 and the non-regenerated one. So, even without regeneration, the conventional propfan engine has better performance values than the current high bypass turbofan, as it was expected.

After this study it was possible to see the different influences of each engine configuration and design parameters in specific thrust and fuel consumption, and the conclusion is that the expectations were proven. On one hand, considering specific thrust and SFC, the integration of a heat regenerator on a propfan engine can be a viable option to achieve higher values of performance. However, the use of regenerated propfan is worthwhile only for utilization coefficient of 100%. Although this regenerated propfan has the best values, the conventional propfan engine revealed to be very competitive. On the other hand, if we consider the fuel mass flow consumption every regenerated propfan engines analyzed have considerably lower values than he conventional propfan. Once the conventional propfan has no extra weight of the heat exchanger and it is much easier to construct, another study would be necessary to verify if the regenerator is really worthwhile.

6.2 Future Work

This Thesis is about propfan engines, but it is focused only in on-design conditions. Another research could be done considering the off-design conditions (takeoff). In this research the regeneration influence is studied only for the performance and fuel consumption. Optimization of this work can be another possibility for a future work, regarding the design of the heat regenerator, its weight, size and the analysis to determinate if the added weight to the engine would be worthwhile. This study regards only the integration of a heat regenerator in a propfan engine, which allows other researchers to study the introduction of an intercooler, for example.

Propfans are gaining a renewed interest in the aviation industry and their development is seen as a promising sustainable innovation. With the actual environmentally friendly concept, ultra-high bypass ratio turbofans are an example of another promising solution that deserves to be studied.

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