

UNIVERSITY OF BEIRA INTERIOR



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**Effects of Intercooling and Regeneration in the
Performance of a Turbofan Engine**

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Abstract

The modern aviation is being questioned due to high emission of gases in the atmosphere. The introduction of heat exchangers for engines with two spools could be one of the solutions to this problem. One of the heat exchangers is the intercooler that is intended to cool the air when it leaves the low pressure compressor. After cooled air enters the high pressure compressor, causing a decrease in the compression work of the high pressure compressor. The other heat exchanger is the regenerator which is located in the hot nozzle. This exchanger, heat the air before entry in the combustion chamber. The air exits the high pressure compressor and it is heated by the exhaust gases before entering the combustion chamber. This increase in temperature causes a decrease in specific fuel consumption. These two components are already used in ground power plants and they were not used in aircraft because of the extra weight and size. The use of the heat exchangers could be justified, if the reduction in the specific fuel consumption and increase of efficiency and specific thrust are worthwhile when compared to the penalty introduced by the extra weight. In this work is compared the performance parameters of a conventional engine with the ones of three configurations intended to increase the global performance of the engine. These three configurations use intercooler, regenerator or both. The comparison is performed to show the influence of engine parameters in specific fuel consumption, specific thrust and thermal efficiency. So it shows which is the best engine configuration to be used for the lower specific fuel consumption with the same specific thrust of the conventional engine.

Keywords: heat exchangers; turbofan; intercooler; regenerator.

Resumo

A aviação moderna está a ser questionada pelas emissões de gases poluentes na atmosfera. A introdução de permutadores de calor em motores com dois veios tem sido uma das soluções para este problema. Um dos permutadores de calor é o interarrefecimento que tem o objectivo de arrefecer o ar quando sai do compressor de baixa pressão. Depois de arrefecido o ar entra no compressor de alta pressão e provoca uma diminuição no trabalho no compressor de alta pressão. Outro permutador de calor é o regenerador que fica situado no bocal de saída dos gases quentes. Este permutador de calor aquece o ar antes de entrar na câmara de combustão. O ar sai do compressor de alta pressão e vai ser aquecido pelos gases de escape. Este aumento de temperatura provoca uma diminuição no consumo específico de combustível. Estes dois componentes já são utilizados em projectos no solo, isto é, por exemplo, para a produção de energia eléctrica. Não são utilizados em aeronaves devido ao seu peso e tamanho excessivos. Para que sejam otimizados é necessário saber se a utilização destes componentes têm influência no consumo específico de combustível e na eficiência térmica sem que a tracção específica seja prejudicada. Este trabalho escolhe um motor convencional e compara-o com três configurações. Estas três configurações utilizam interarrefecimento, regeneração ou ambos. A comparação tem por base mostrar a influência dos parâmetros do motor no consumo específico de combustível, tracção específica e na eficiência térmica. E assim mostra qual a melhor configuração de motor a utilizar para os menores valores de consumo específico de combustível, com a mesma tracção específica do motor convencional.

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Nomenclature

a - Intake

b – Burner

c – Compressor

e – Efficiency

f – Fan

F/\dot{m}_0 – Specific Thrust

FPR – Fan Pressure Ratio

GE – General Electric

H – High

HPC – High Pressure Compressor

HPT – High Pressure Turbine

i – Intercooler

ICAO – International Civil Aviation Organization

IRA – Intercooler Recuperated Aero Engine

L – Low

LPC – Low Pressure Compressor

LPT – Low Pressure Turbine

LTO – Landing and Take-Off

m – Mechanic

\dot{m}_0 – Mass Flow

n – Nozzle

OPR – Overall Pressure Ratio

RFP – Request For Proposal

reg – Regenerator

SFC – Dimensionless Specific Fuel Consumption

t – Stagnation, Turbine

TET – Turbine Entry Temperature

TSFC – Thrust Specific Fuel Consumption

Hellenic letters

α – Bypass Ratio

γ – Heat Capacity Ratio

δ – Dimensionless Pressure Ratio
 ε – Cooling Mass Flow (%)
 η – Cycle Efficiency
 η_{th} – Thermal Efficiency
 θ – Dimensionless Temperature Ratio
 π – Pressure Ratio
 ρ – Density
 τ – Temperature Ratio

1. Introduction

1.1. Motivation

The environment is one thing that the Human being can't dominate, but have the power to change! The emissions of any combustion engine are co-responsible for changes in the environment. Everyday many civil and military aircraft fly the sky and every one send to the sky tones of fuel. So, if it's possible to reduce this fuel emission, the environment can become better and the quality of life can be improved.

The influence of climate change, air pollution and noise around airports motivated the International Civil Aviation Organization (ICAO) to promote some programs to find promising solutions for aircraft engines. Due to these requirements, civil aviation engines need to have low specific fuel consumption and high reliability, so it is very important to research new engine concepts.

The importance of the reduction of fuel consumption is mainly for two reasons: the necessity to save fuel, and the need to reduce the air pollution.

1.2. Objectives

The objectives of this thesis are to find a conventional engine, respecting the requirements imposed, and compare it with other three new configurations. These three cycles have the same base line and the main objective is to carry out if the new working cycles are viable solutions for fuel saving with reduction of specific fuel consumption.

1.3. Thesis structure

The thesis is structured in the following chapter:

- Chapter 2: Concept' s background

In this chapter is made a short introduction to the various engine configurations. It is divided into two sections, one that shows a study related to the engine with two spools, with intercooler and regenerator. The other section is a numerical study of the main parameters of an engine with heat recovery.

- Chapter 3: Concept's requirements

For the study of the engine are defined the requirements in this chapter. It is also show a real engine as reference. This engine is the reference basis of the requirements for the different engine configurations studied.

- Chapter 4: Conventional cycle

Through the requirements defined on Chapter 3, is made a design of a conventional engine and a parametric analysis, from which are obtained the values of the design parameters (conventional engine with two spools).

- Chapter 5: Novel cycle comparison

This chapter is the most important chapter because it is where is made the design of the three engine configurations. It also made a comparison between an engine with intercooler, regenerator or both, and a conventional engine. This chapter shows the difference in specific fuel consumption among the four types of engines.

- Chapter 6: Conclusion

This chapter is devoted to conclusions from the comparative study between these different engine configurations and shows which is the engine with less specific fuel consumption.

- Chapter 7: Future work

In this chapter is shown some further thought relate with this theme.

2. Concept's background

Evolution of flight requirements demanded along time new engine concepts for aeronautical utilization. Emissions of gaseous pollutants have been a relevant issue to nowadays society and this is one of the key parameters to improve the existing for long distance aircraft engines. In Europe and United States there are substantial research programs aimed at reducing CO_2 and NO_x emissions. The goals of some of these programs tend to be related to the ICAO Landing and Take-Off (LTO) cycle.

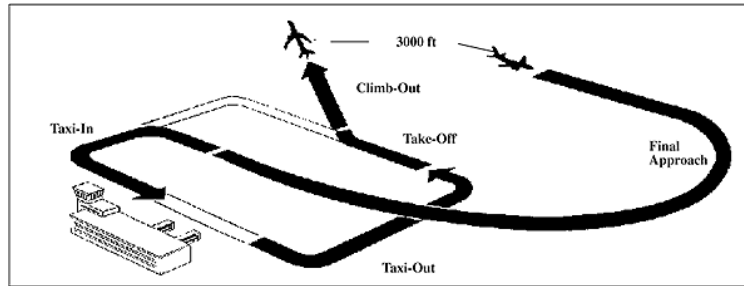


Figure 1: The ICAO landing and take-off cycle (LTO). [25]

The effect of these emissions on air quality in the vicinity of airports became a matter of public concern like the noise problem.

This program has led to several developments. Nowadays, modern technologies in civil aviation are restricted to highly optimized turbofan engines. Research findings led to the consideration of changing the conventional engine cycle. In one of the novel cycles is introduced an intercooler and a regenerator. This change of the conventional cycle provide high thermal efficiency and low specific fuel consumption.

This novel cycle is not new! It is new for aeronautical applications but it already exists in industrial and navy applications. The hardware of this cycle is not ready to implement on aero engines because weight and size problems. In the ground the extra weight and extra size is not a problem but in the aircraft are always prohibitive.

A new type of engine is in development. It is an engine with intercooler and regeneration, called IRA (Intercooler Recuperated Aero Engine). The thermodynamic cycle of this new engine is presented in Figure 2.

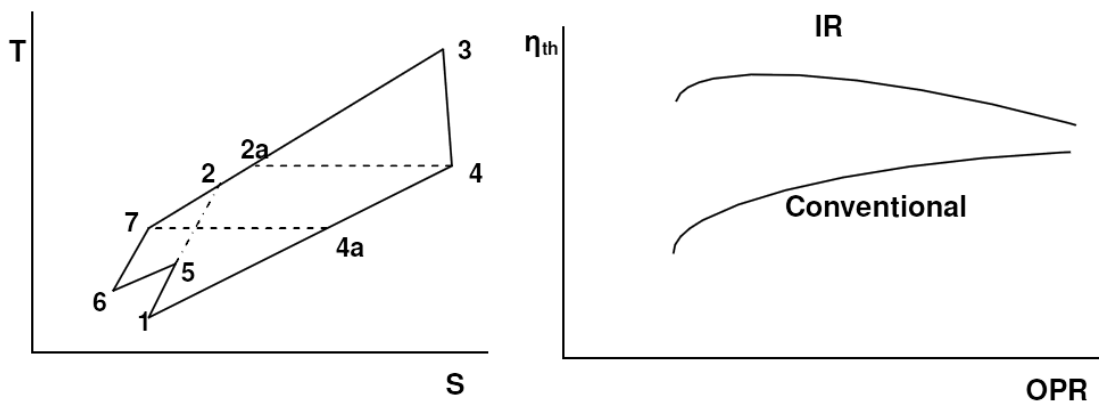


Figure 2: a) IRA cycle with two heat transfer processes and b) IRA vs Conventional. [32]

In this cycle the intercooling is made cooling the LPC outlet flow by heat exchange with part of the bypass flow. This would increase the fuel flow so that the turbine entry temperature remains high. It is needed to reduce this increase of fuel flow, so it is used a heat exchanger. This component recovers heat from the exhaust to preheat the air flow from the HPC before the combustor chamber inlet. It is important the utilization of both heat exchangers in order to increase the core specific power and keep the SFC low. The benefices proposed by this cycle are very attractive, however the heat exchanger is not yet fully researched and knowledge about its efficiency and behavior are still required.

Another modification that can be done to the conventional cycle, also in order to reduce CO₂ and NO_x emissions, is using only the regenerator. On the Figure 3 it is shown the simple cycle with a regenerator.

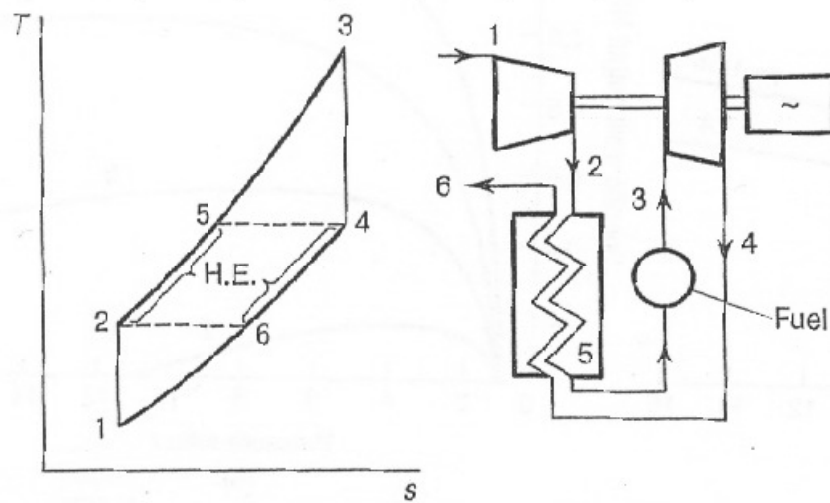


Figure 3: Simple cycle with heat-exchange. ^[2]

Like the IRA cycle, the regenerator, increase the combustion air temperature before the combustor chamber inlet after exit from HPC.

Several researches have been carried out on the use of a regenerator alone in a gas turbine, as shown, for example, in ref 30. The regenerator is located in the exhaust and recovers heat from the hot exhaust gas stream in order to heat up the high pressure compressed air before entering the combustor. With this it requires less fuel to achieve the fixed TET. Recuperated cycles are widely used in ground gas turbines in order to increase the thermal efficiency and so to decrease the SFC. Regenerators are not yet used in aero gas turbines due to their significantly high weight and size. However their introduction might have good results regarding fuel consumption and emission levels.

2.1. Literature Review

The study of turbofan engines is nowadays being directed to a very specific type of cycle: a cycle with intercooler and regeneration. The studies that have been developed until now are all related to an engine with three spools. The below article refers to a type of engine a bit different, with only two spools. In this type of engine

there are three compressors but only two turbines. The fan and the low pressure compressor are operated by low pressure turbine. The high-pressure compressor is operated by the high pressure turbine.

R. Andriani and U. Ghezzi with the article “*Performance Analysis of High ByPass Jet Engine with Intercooling and Regeneration*” ^[19] do a parametric study of a turbofan engine at high bypass ratio. The objective of this work is to put in evidence the advantages, in terms of power increase and fuel consumption reduction, of the introduction of regeneration and intercooling in a turbofan engine with high by-pass ratio. In their work, some simplifications in the engine operations have been done: no air bleeding for auxiliary or cooling system, perfect gas behaviors for the working fluids, no auxiliary power extracted from the turbine. The scheme of a turbofan engine with intercooling and regeneration is shown in Figure 4 a) and the thermodynamic cycle in Figure 4 b).

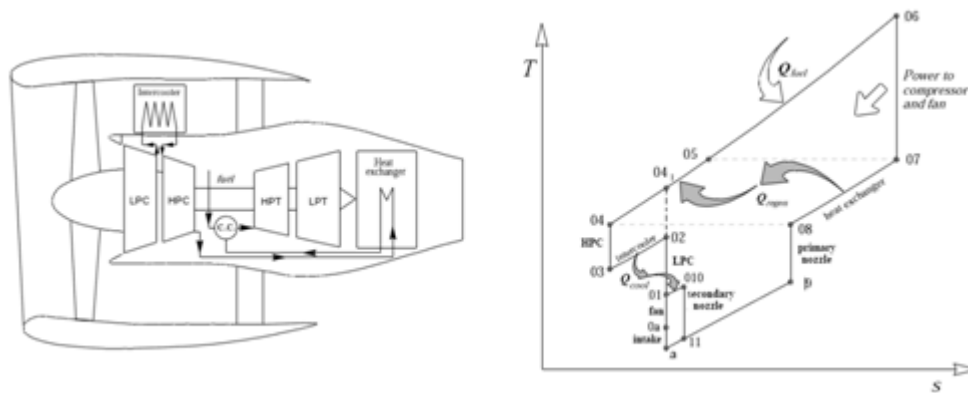


Figure 4: a) Scheme of a turbofan engine with intercooling and regeneration and b) Thermodynamic cycle. ^[19]

This work has been done considering an altitude of 10000 meters with flight Mach number of 0.85; TET is in one case 1300 K and in the other 1500 K; three values of bypass ratio (BPR): 3, 6 and 9; fan pressure ratio was kept constant in all cases at 1.70; efficiency of intercooling and regeneration: 0.6; the pressure drop has been maintained constant at 5%; the cycles computed are real and not ideal and the component efficiencies were selected and kept constants.

The conditions were kept constants at cruise condition, being TET and BPR changed. The curves are plotted as function of the compressor overall pressure ratio. The graphics represented on the Figure 5 present the behavior of a conventional turbofan engine and one in which intercooling and regeneration.

The results of this parametric study show that the introduction of the intercooler and regenerator only has good effects when TET and OPR are high. However if the level of TET is very high, especially at high altitude, can introduce mechanical problems to the high pressure turbine blades.

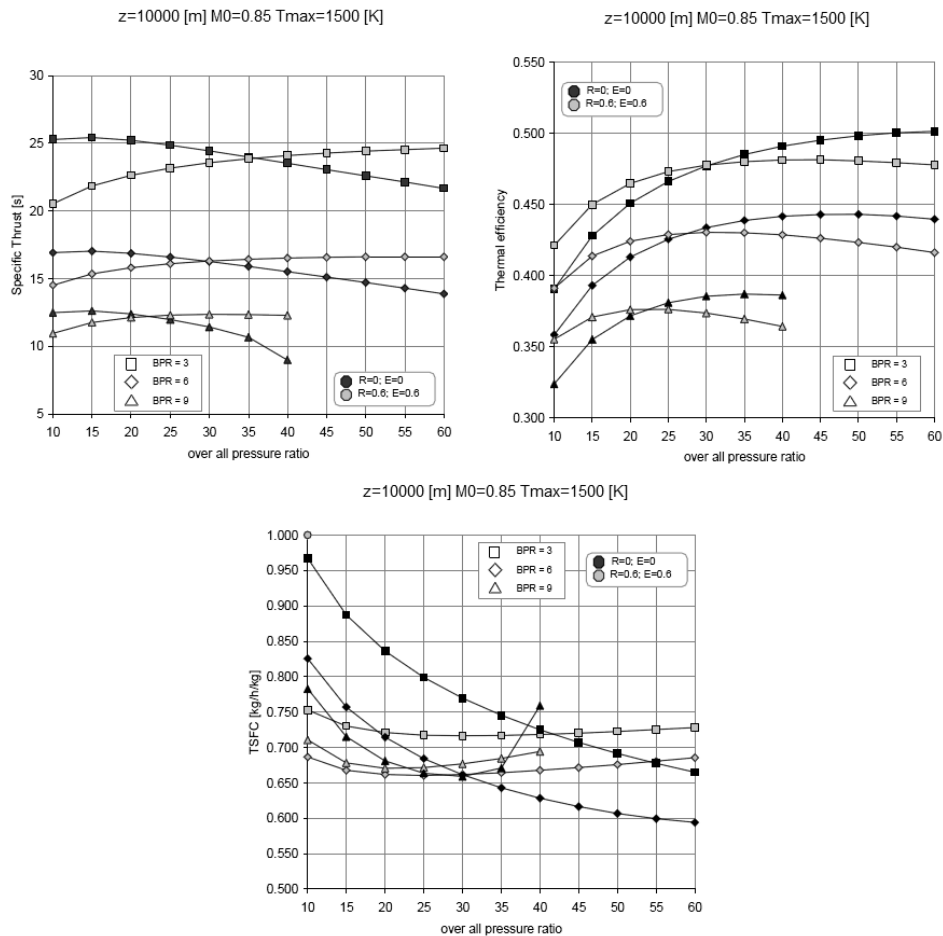


Figure 5: Specific thrust, thermal efficiency and specific fuel consumption as function of pressure ratio and BPR. [19]

Another study using regenerator was done by Cai Ruixian and Jiang Lixia, “Analysis of the recuperative gas turbine cycle with a regenerator located between turbines” [24]. A recuperative gas turbine cycle with a regenerator located between a high-pressure turbine and a low-pressure turbine. This article analyzed and compared with the simple cycle and conventional recuperative cycle in detail.

The analysis show that for the recuperative gas turbine cycle with regenerator located between turbines, the efficiency of the ideal alternative recuperative cycle can be higher than the ideal conventional recuperative gas turbine cycle with the same temperature ratio, but the specific work of former is much smaller than the latter. The maximum optimum efficiency of the practical alternative recuperative cycle is always lower than that of a conventional recuperative cycle, and the optimum pressure ratio for the higher efficiency of an alternative recuperative cycle is always higher than that of a conventional recuperative cycle. The alternative recuperated cycle does not exhibit the highest efficiency and thus the alternative cycle with a regenerator between the turbines still requires further improvements to become more attractive.

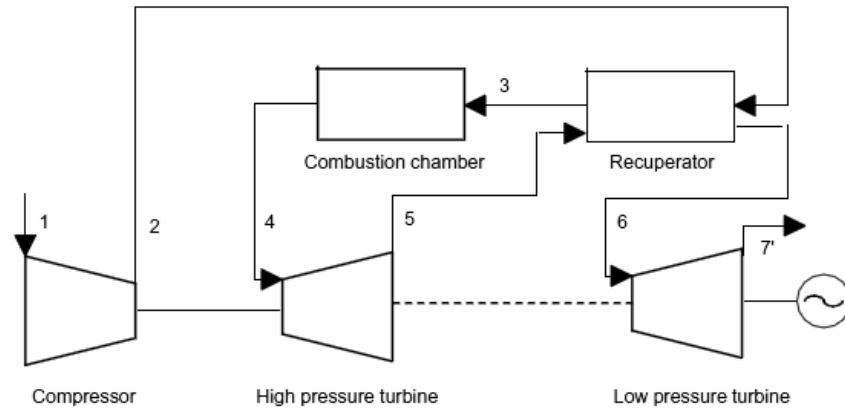


Figure 6: Alternative recuperative gas turbine cycle. ^[24]

2.2. Relevant Studies

R. Andriani and U. Ghezzi with the article “*Numerical Analysis of Main Performances of Gas Turbine Engines With Heat Recovery*” ^[16] made a numerical analysis of the performance of gas turbine engines with heat recovery. A high bypass turbofan engine with the characteristics shown in the Table 1 was studied.

Table 1: Compressor characteristics as deduced by reference engine thermal cycle. ^[16]

	N. stages	Pressure ratio	Polytropic efficiency
Fan	1	1.71	0.831
LPC	4	1.61	0.868
HPC	11	11.34	0.872

In Figure 7 is reported the engine scheme that has been considered for the calculations and the values of pressure and temperature at each station as they have been computed by the numerical code.

Once tested the code and seen that the results are in good agreement with the given data, the code was used to simulate the behaviors of the engine in different conditions. The heat exchanger is added recovering heat from the exhaust and preheating air from the compressor as shown in Figure 8. The operating conditions of the engines are: altitude of 10000 meters and flight Mach number of 0.8.

“The conventional case is the marked as $R=0$ while the two regenerative cases are respectively $R=0.5$ and $R=0.7$, where R is the efficiency of regeneration of the heat exchanger.”

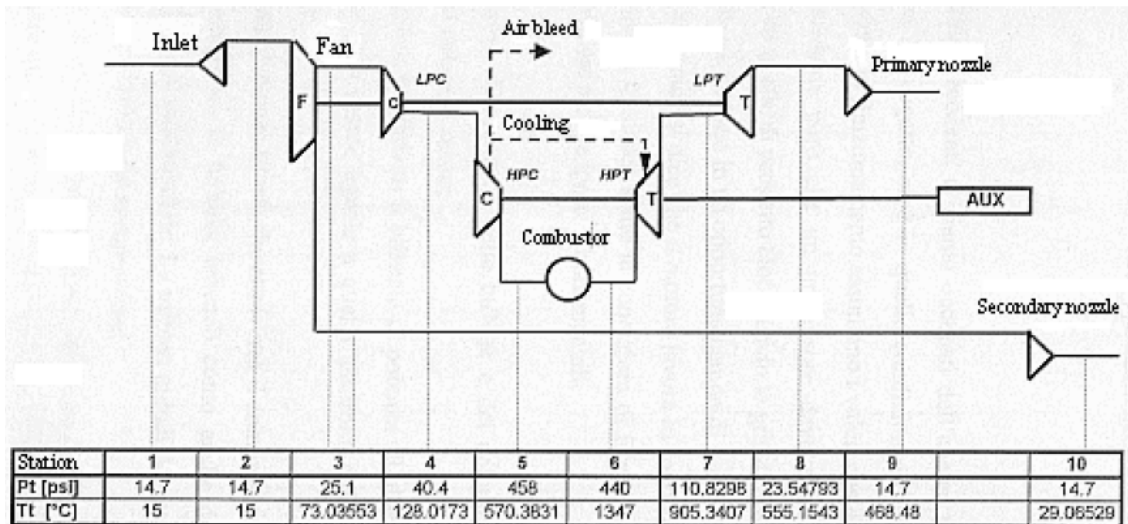


Figure 7 Engine blocks scheme and pressure and temperature computed by the code at different stations. [16]

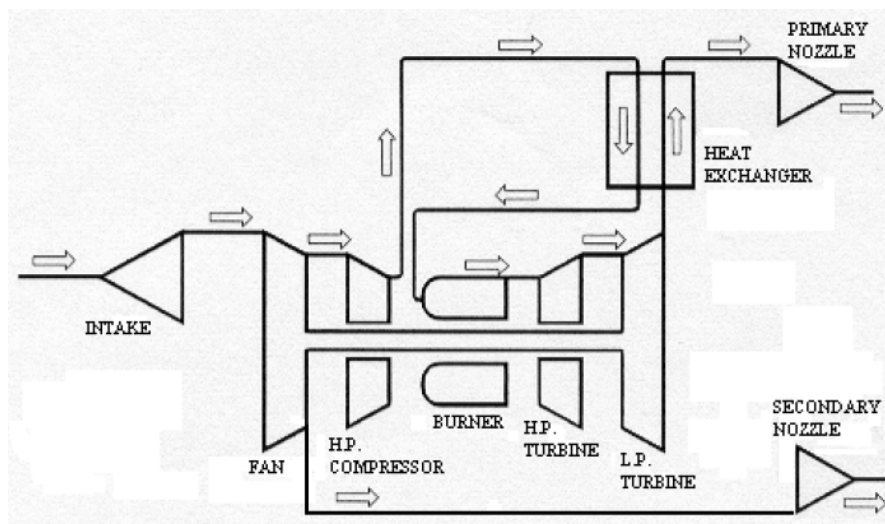


Figure 8: Scheme of a turbofan engine with regeneration. [16]

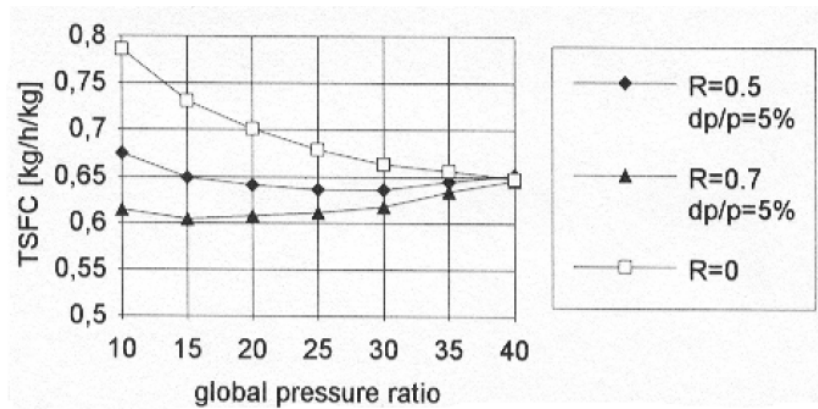


Figure 9: Traction specific fuel consumption for a conventional turbofan and two regenerated turbofan engines at 10000 m altitude and 0.8 flight Mach number. [16]

The recuperated engine shows a reduction in TSFC, but also a reduction in performance at the same time. Thus, Andriani and Ghezzi, recommend improving the performance by the use of an intercooler. The TSFC is reduced with an increase in output power at the same time.

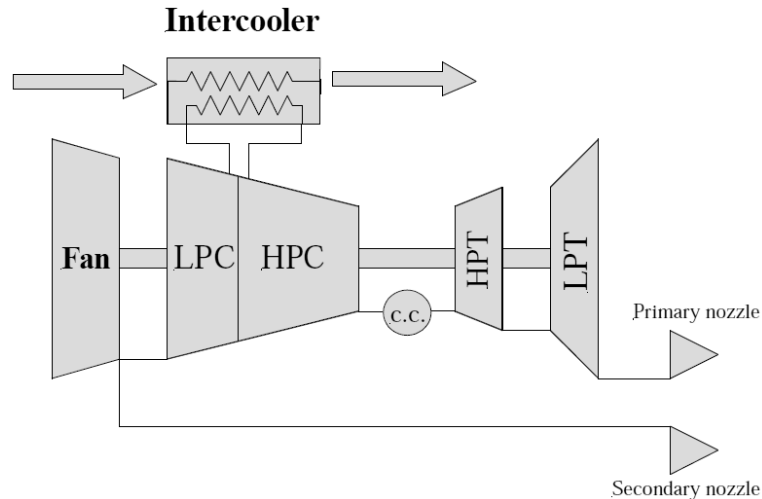


Figure 10: Engine scheme with the intercooler placed between the LPC and HPC. [16]

In the conventional engine is added an intercooler as shown in Figure 10 “Since the compressor absorbs less power, it becomes available in the nozzle a greater enthalpy drop for thrust.” [16].

“The cooling fluid is external air. Through the intercooler we have considered a pressure drop of 3% and an efficiency of 90%, defined as the ratio between the actual amount of heat transferred from working fluid to cooling air and the maximum that could be transferred in the same operating conditions.” [16].

The behavior of specific thrust and specific fuel consumption in the case of turbofan engine with intercooling is depicted in the Figure 11.

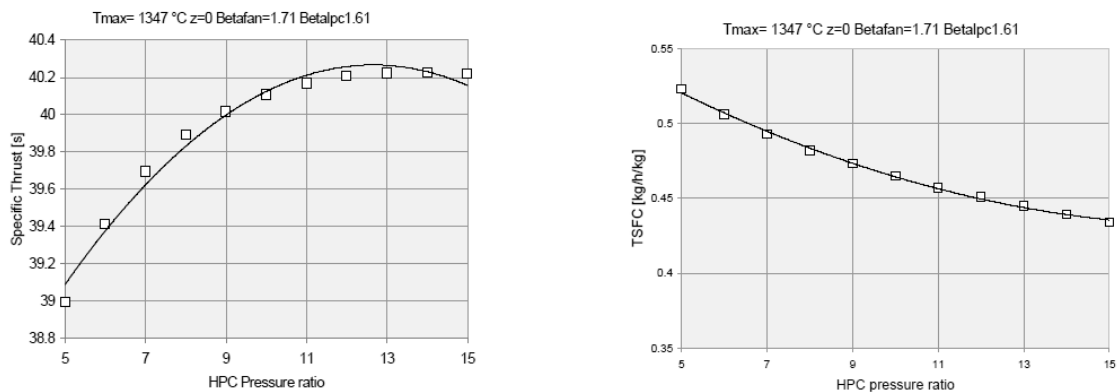


Figure 11: Specific thrust and thrust specific fuel consumption as function of high pressure compressor ratio. [16]

2.3. Conclusions

With the results presented, can be concluded that the use of the regenerator or its combination with an intercooler, result in a fuel consumption reduction. The approach used to research these novel cycles, is to take values of reference and compare performance results, such as, specific consumption, thermal efficiency and specific thrust. In this thesis, the procedure to obtain the results is a little different. The aim is not to compare results with the values assumed initially, but to obtain reference values such as, Bypass Ratio, OPR, FPR, etc., for each type of configuration. Thus the path taken in this thesis is to perform the parametric calculations for the same specific thrust and flight altitude to obtain the different reference values for each of the different cycles.

3. Concept's requirements

At the beginning of any study is necessary to know theoretical limitations in order to guarantee that the theoretical study is very close to the real one. In this section, in addition to the simplifying assumptions is also referred the scheme and the nomenclature of the engine, according to the Aerospace Recommend Practice. To know the objectives of an aircraft/engine system is needed a requirements document such as a Request For Proposal (RFP). Thus it is shown in this section the requirements for the study of engines with regenerator or intercooled recuperative engines.

3.1. Station Numbering

The station numbering is important to identify the different locations in the engine. The Figure 12 shows the generalized conventional engine and Figure 13 the blocks diagram of components.

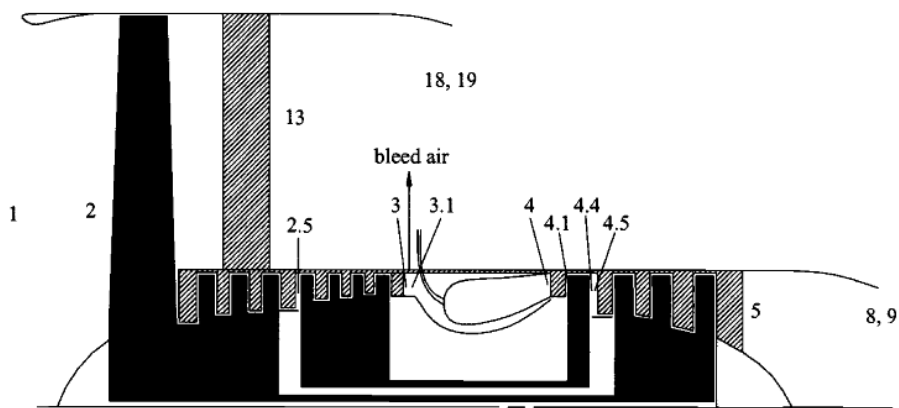


Figure 12: Schematic diagram of a high-bypass-ratio conventional turbofan. ^[1]

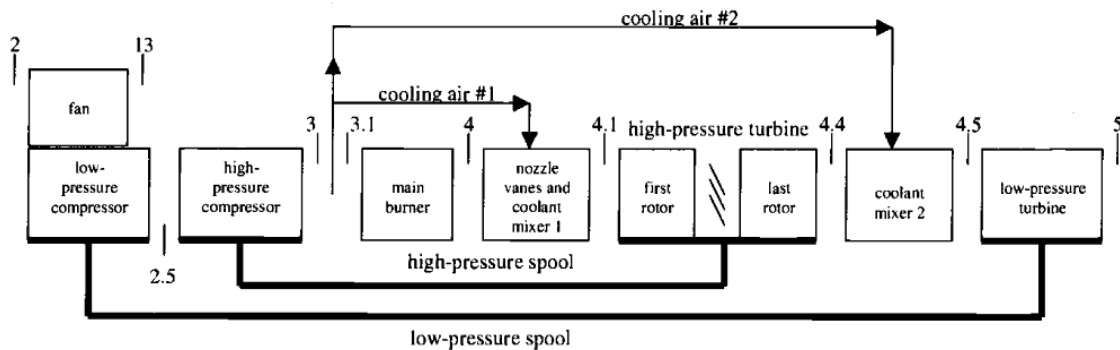


Figure 13: Reference station – turbine cooling airflows. ^[1]

The station numbering should be made in accordance with Aerospace Recommend Practice, as presented in Table 2.

Table 2: Station numbering. ^[1]

Station	Location
0	Far upstream or freestream
1	Inlet or diffuser entry
2	Inlet or diffuser entry, fan entry
13	Fan exit
2.5	Low-pressure compressor exit
	High-pressure compressor entry
3	High-pressure compressor exit
	Burner entry
	Nozzle vanes entry
4	Modeled coolant mixer 1 entry
	High-pressure turbine entry for π_{tH} definition
	Nozzle vanes exit
4.1	Coolant mixer 1 exit
	High-pressure turbine entry for π_{tH} definition
4.4	High-pressure turbine exit
	Modeled coolant mixer entry
4.5	Coolant mixer 2 exit
	Low-pressure turbine entry
5	Low-pressure turbine exit
7	Core exhaust nozzle entry
9	Core exhaust nozzle exit
17	Bypass exhaust nozzle entry
19	Bypass exhaust nozzle exit

The ratio of total (isentropic stagnation) pressures π and total (adiabatic stagnation) temperatures τ are the following,

$$\pi_i = \frac{\text{total pressure leaving component } i}{\text{total pressure entering component } i}$$

$$\tau_i = \frac{\text{total temperature leaving component } i}{\text{total temperature entering component } i}$$

3.2. Assumptions

Before proceeding with the analysis, the assumptions to be employed in this thesis are summarized as follows:

- The flow is steady;
- The flow is one-dimensional at the entry and exit of each component and at each axial station;
- The fluid behaves as a perfect gas with constant molecular weight across the diffuser, fan, compressor, turbine, nozzle, and connecting ducts;
- Calorically perfect gas c_p and γ are assigned one set of values from station 0 through stations 3.1 and 19 (denoted as $c_{p_c}=1005$ J/kgK and $\gamma_c=1.4$), a second set of values from station 4 through 9 (denoted as $c_{p_t}=1148$ J/kgK and $\gamma_t=1.33$);
- Engine Operation Condition: Standard day;
- The total pressure ratio of the diffuser or inlet, the nozzles and the burner were kept constant:

$$\pi_d = 0.99$$

$$\pi_{nf} = 0.99$$

$$\pi_b = 0.96$$

- The fan and low-pressure compressor are driven by the low-pressure turbine, but can't provide mechanical power for accessories, $P_{TOL}=0$;
- The high-pressure compressor receives air directly from the low-pressure compressor and is driven by the high-pressure turbine, but can't provide mechanical power for accessories, $P_{TOH}=0$;
- Fuel heating was kept constant: $h_{PR} = 4.28 \times 10^7$ J/kg
- Percent of cooling mass flow air, removed between stations 3 and 3.1, and is given by ^[1]:

$$\varepsilon_1 = \varepsilon_2 = \frac{T_{t4\max} - 1400}{8000} \quad \text{for } T_{t4\max} > 1400\text{K}$$

$$\varepsilon_1 = \varepsilon_2 = 0 \quad \text{for } T_{t4\max} < 1400\text{K}$$

- No air bleed for auxiliary system;
- The flow in the bypass duct (from station 13 to 19) is isentropic;
- The effect of cooling on turbine efficiency is accounted for by a reduction of e_{tH} due to $\dot{m}_{cool 1}$ and $\dot{m}_{cool 2}$;
- The turbine entry temperature was kept constant: TET = 1500K;
- The efficiencies of components used are presented in Table 3.

Table 3: Efficiency of components ^[1]

Component	Value
Intake efficiency (ea)	0.99
Fan polytropic efficiency (ef)	0.89
Low pressure compressor polytropic efficiency (ecL)	0.9

High pressure compressor polytropic efficiency (ecH)	0.9
Burner efficiency (eb)	0.995
High pressure turbine polytropic efficiency (etH)	0.89
Low pressure turbine polytropic efficiency (etL)	0.91
Primary nozzle adiabatic efficiency (enf)	0.9
Secondary nozzle adiabatic efficiency (en)	0.9
Mechanical efficiency (em)	0.995
Intercooler efficiency (ei) ^[19]	0.6
Regenerator efficiency (ereg) ^[19]	0.6

- The total pressure ratio of Intercooler and Regenerator:

$$\pi_{\text{int}} = \pi_{\text{reg}} = 0.95 \text{ (drop = 5\%)}$$

- The regenerator leads to a decrease of thrust in the hot nozzle (based in Ref. 27):

$$\pi_{\text{Nzreg}} = 0.95 \text{ (drop = 5\%)}$$

3.3. Engine requirements

When designing an aircraft, it is necessary to start with its requirements. These requirements are written on a document, commonly called RFP. This document has all the descriptions of the desired aircraft performance. In this thesis does not exist the RFP and so, to perform the parametric calculations, one must have some base values for the requirements. These requirements were based on an engine with the characteristics considered as close to the one to be studied in this thesis (CF6-80A2). The CF6-80A2 engine (see Fig. 14) is an engine build by GE and used on Boeing 767-200/-200ER/-300, having the following characteristics [34]:

Physical Information	Power Specifications
- Fan/Compressor Stages: 1F/3LPC/14HPC	- Specific Fuel Consumption at Sea Level: 0,355 – 0,357
- Low-Pressure Turbine/High-Pressure Turbine Stages: 4/2	- Max. Power at Sea Level (Lb.): 50.000
- Fan Diameter (Inches): 86,4	- Specific Fuel Consumption at Cruise: 0,623
- Length (Inches): 167	- Max. Power Cruise (Lb.): 11.000
- Dry Weight (Lb.): 8.760 – 8.776	- Overall Pressure ratio at Maximum Power: 27,3 – 28,4
- Airflow static (lb/s): 1460	- Bypass Ratio: 4,59 – 4,66
	- Cruise Speed(M): 0,8
	- Cruise Altitude (ft): 35.000

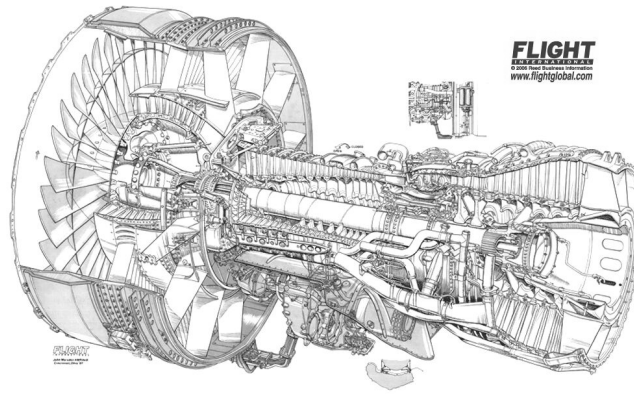


Figure 14: CF6-80A2 engine. ^[33]

With this reference engine, the requirements for the engine to study in this thesis (Conventional, Intercooled, Regenerative and Intercooled Recuperative) are the show in Table 4.

Table 4: Requirements for the engines.

	Sea Level	Cruise
Height [m]	0	10668
Thrust [kN]	250	50
Mass flow [kg/s]	650	-
Mach	-	0,80
TET Max [K]	1500	1500

4. Conventional cycle

In this chapter is shown the conventional cycle and the calculations and graphs needed to choose the design point. The choice of the design point and the performance calculations were obtained with using Microsoft Office Excel 2007 running on a personal computer.

4.1. Conventional engine theory

Modern conventional turbofan engines can be categorized according to their application. At this point it is important to manifest the changes of variables used, corresponding to the two or three shaft configurations. With three shafts, these engines are used for long/medium-haul flights where the thrust class is about 40,000 – 100,000lbs. In the short/medium haul flights the engines are of moderate thrust class, 8,000-40,000lbs thrust, being normally used two shafts with moderate values of Overall Pressure Ratio, Turbine Entry Temperature and Bypass Ratio.

The High OPR contributes to high engine efficiency and, in turn, low SFC. However, raising the engine OPR results in heavier and more costly engines because it normally requires additional compressor or fan stages and larger turbines. In the Figure 15 is shown the steady and rapid increase in OPR for turbojets and turbofans over the past five decades. The smaller core engines, normally have lower OPRs.

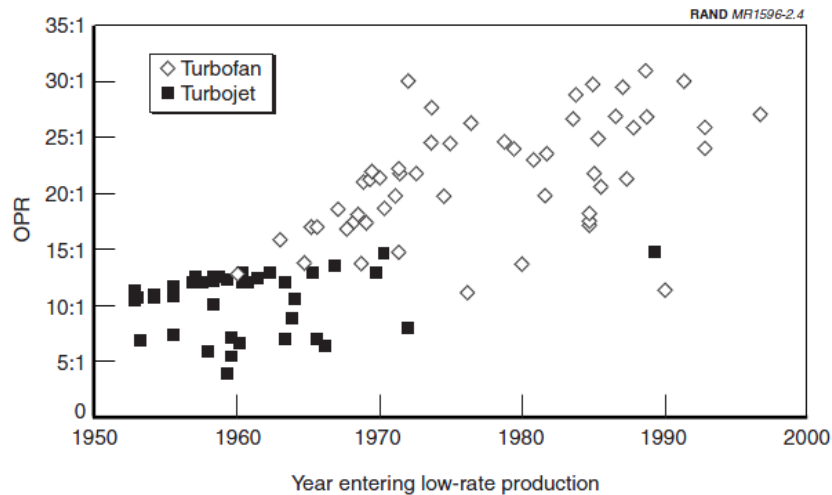


Figure 15: Turbojet and Turbofan Overall Pressure Ratio Trends. ^[11]

The SFC is often referred to as the thrust specific fuel consumption (TSFC) and is defined as the ratio of the fuel mass flow rate to the thrust. In Figure 16 can be verified the advantage in the thrust SFC offered by turbofans when compared with turbojets. The very low SFC engines indicated at the bottom of the Figure are all high BPR turbofans.

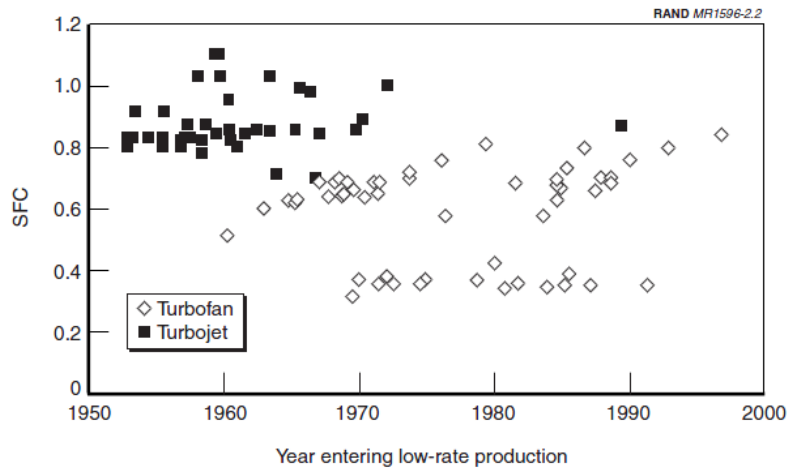


Figure 16: Turbojet and Turbofan Thrust-Specific Fuel Consumption Trends. ^[11]

Two spool engines are generally lighter and with lower manufacturing costs due to its relative simplicity. If the SFC decreases, the weight of the aircraft decreases too because the fuel necessary to do a haul is less.

The conventional engine studied in this thesis is an engine with two spools. The high pressure turbine transfers its movement to the high-pressure compressor and the low pressure turbine transfers to the low pressure compressor and the fan.

4.2. Engine Selection

The object of a parametric cycle analysis is to obtain estimates of the performance parameters (primarily specific thrust and thrust specific fuel consumption), based on the design limitations: flight conditions (the ambient pressure, temperature, and Mach number) and design choices (such as compressor pressure ratio, fan pressure ratio, bypass ratio, and theta break). The calculation of performance parameters are based on the method presented by Jack D. Mattingly and David T. Pratt of the University of Washington and William H. Heiser of the U.S. Air Force Academy in Ref 1. The initial conditions for the iterative calculations were the ones presented in Table 5.

Table 5: Typical F/\dot{m}_0 and SFC values. ^[1]

Engine type	Compressor pressure ratio (π_c)	Fan pressure ratio (π_f)	Bypass ratio (α)	T_{t7} , °R	T_{t4} , °R	F/\dot{m}_0 , lbf/lbm/s	S , 1/h
Turbojet no A/B	10–20	—	—	—	2000	54–58	1.0–1.1
					3000	93–96	1.3–1.4
Turbojet with A/B	10–20	—	—	3600	2000	94–101	2.0–2.2
					3000	115–119	1.7–1.8
Turbofan low α no A/B	20–30	2–4	0.2–1	—	2000	23–47	0.85–1.0
					3000	53–84	0.96–1.5
Turbofan low α with A/B	8–30	2–4	0.2–1	3600	2000	75–98	2.1–2.7
	10–30				3000	102–116	1.7–2.0
Turbofan high α no A/B	30–40	1.4–1.6	5–7.5	—	2000	5.5–12	0.76–0.97
		1.4–4	5–10		3000	13–27	0.67–1.03

4.2.1. Engine Calculations

To determine the primary measures of the engine's overall performance it is necessary to know the thrust. For a turbofan engine with separate exhausts streams it is given by:

$$F = (\dot{m}V_9 + \dot{m}_{19}V_{19} - \dot{m}_0V_0) + A_9(P_9 - P_0) + A_{19}(P_{19} - P_0) \quad (1)$$

which can be rearranged into its nondimensional form, thrust per unit mass flow of captured airflow (F/\dot{m}_0) or specific thrust, form as:

$$\frac{F}{\dot{m}_0 a_0} = \frac{1}{1 + \alpha} \left\{ \begin{aligned} & \left((1 + f_0(1 + \alpha) - \beta) \frac{V_9}{a_0} + \alpha \frac{V_{19}}{a_0} - (1 + \alpha) M_0 + \right. \\ & \left. + (1 + f_0(1 + \alpha) - \beta) \frac{R_9}{R_0} \frac{T_9/T_0}{V_9/a_0} \frac{(1 - P_0/P_9)}{\gamma_0} + \right. \\ & \left. + \alpha \frac{T_{19}/T_0}{V_{19}/a_0} \frac{(1 - P_0/P_{19})}{\gamma_0} \right\} \quad (2) \end{aligned} \right.$$

Like specific thrust, dimensionless thrust specific fuel consumption (SFC) is a performance parameter of primary interest and is obtain by:

$$S = \frac{f_0}{F/\dot{m}_0} \quad (3)$$

The independent design variables considered for this engine are the fan pressure ratio (π_f), the overall cycle pressure ratio (π_c), and the bypass ratio (α). The pressure ratio across the high-pressure compressor is obtained from:

$$\pi_{cH} = \pi_c / \pi_{cL} \quad (4)$$

The temperature ratios across the fan (τ_f), the low-pressure compressor (τ_{cL}), and the high-pressure compressor (τ_{cH}) are related to their pressure ratios by equations 5, 6 and 7, respectively.

$$\tau_f = \frac{T_{t13}}{T_{t2}} \quad (5)$$

$$\tau_{cL} = \frac{T_{t2.5}}{T_{t2}} \quad (6)$$

$$\tau_{cH} = \frac{T_{t3}}{T_{t2.5}} \quad (7)$$

The temperature ratios across the high-pressure turbine (τ_{tH}) and low-pressure turbine (τ_{tL}) are obtained from power balances of the high- and low-pressure spools resulting in equations 8 and 9.

$$\tau_{tH} = 1 - \frac{\tau_r \tau_{cL} (\tau_{cH} - 1) + (1 + \alpha) C_{TOH} / \eta_{mPH}}{\eta_{mH} \tau_\lambda \left\{ (1 - \beta - \varepsilon_1 - \varepsilon_2)(1 + f) + \varepsilon_1 \tau_r \tau_{cL} \tau_{cH} / \tau_\lambda \right\}} \quad (8)$$

$$\tau_{tL} = 1 - \frac{\tau_r \left\{ (\tau_{cL} - 1) + \alpha (\tau_f - 1) \right\} + (1 + \alpha) C_{TOL} / \eta_{mPL}}{\eta_{mH} \tau_\lambda \tau_{tH} \left\{ (1 - \beta - \varepsilon_1 - \varepsilon_2)(1 + f) + (\varepsilon_1 + \varepsilon_2 / \tau_{tH}) \tau_r \tau_{cL} \tau_{cH} / \tau_\lambda \right\}} \quad (9)$$

The temperature ratios across the two cooling air mixing processes (τ_{m1} and τ_{m2}) are given by equations 10 and 11.

$$\tau_{m1} = \frac{(1 - \beta - \varepsilon_1 - \varepsilon_2)(1 + f) + \varepsilon_1 \tau_r \tau_{cL} \tau_{cH} / \tau_\lambda}{(1 - \beta - \varepsilon_1 - \varepsilon_2)(1 + f) + \varepsilon_1} \quad (10)$$

$$\tau_{m2} = \frac{(1 - \beta - \varepsilon_1 - \varepsilon_2)(1 + f) + \varepsilon_1 + \varepsilon_2 \{ \tau_r \tau_{cL} \tau_{cH} / (\tau_\lambda \tau_{m1} \tau_{tH}) \}}{(1 - \beta - \varepsilon_1 - \varepsilon_2)(1 + f) + \varepsilon_1 + \varepsilon_2} \quad (11)$$

The pressure ratios across the high-pressure turbine (π_{tH}) and low-pressure turbine (π_{tL}) are related to their respective temperature ratio and polytropic efficiency by equations 12 and 13.

$$\pi_{tH} = \left(\frac{P_{rt4.4}}{P_{rt4.1}} \right)^{1/\varepsilon_{tH}} \quad (12)$$

$$\pi_{tL} = \left(\frac{P_{rt5}}{P_{rt4.5}} \right)^{1/\varepsilon_{tL}} \quad (13)$$

The fuel-air ratio (f) is given by equation 14.

$$f = \frac{\tau_\lambda - \tau_r \tau_{cL} \tau_{cH}}{h_{PR} \eta_b / h_0 - \tau_\lambda} \quad (14)$$

Thus, the only unknowns for the obtention of the specific thrust (see equation 2), are the pressure ratios, $P0/P9$ and $P0/P19$. This turbofan engine is modeled as having fixed convergent nozzles for both the core and bypass air streams. Thus, the exit pressure is equal to the ambient pressure for unchoked nozzle operation and the exit pressure is greater than the ambient pressure when the nozzle flow is choked.

As the mass flow rate, at engine entry, changes with the Mach number, the temperature, and the pressure, the "corrected mass flow rate" used in this analysis is defined as:

$$\dot{m}_0 = \dot{m}_{cruise} = \dot{m}_{SL} \delta_{cruise} / \sqrt{\theta_{cruise}} \quad (15)$$

The dimensionless pressure and temperature are represented by δ and θ , respectively. This corrected mass flow rate has to be calculated because, in the requirements, the mass flow it is given at sea level.

4.2.2. Engine Analysis

Through the requirements described in section 3.3 of this thesis was possible to obtain different graphics in order to choose the values of the parameters that lead to the higher engine performance. These graphs were obtained by iterative calculations, varying the parameters to obtain the best values for choosing the on-design point of an engine. The Figures 17-21 indicate how were obtained the parameters for the on-design point of the engine project.

Through Figure 17 can be obtained an estimate of the values of bypass at the cruise altitude. We can also verify that the range of bypass values will be between 4 and 6. In what concerns the values of OPR that best suit the requirements, Figure 18 shows the variation of OPR for different bypass values.

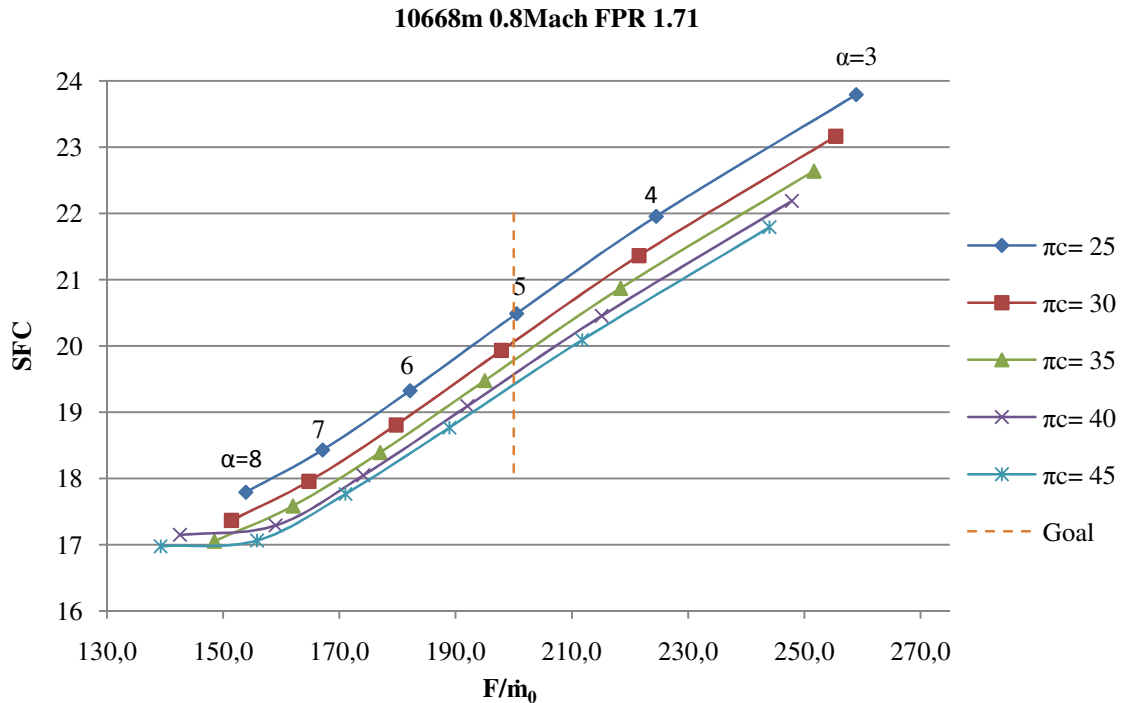


Figure 17: Specific Fuel Consumption vs Specific Thrust at cruise conditions for conventional engine

From Figure 18 can be seen that to obtain the value of 200 for the specific thrust, the value for OPR will have to be 26. This for a bypass value equal to 5 or lower because if the bypass value is greater than 5 for any value of the OPR, the requirement will never be reached. If it is smaller than five it puts itself in commitment the increase of fuel consumption as shown in the Figure 19. This graph shows the variation of specific fuel consumption with the OPR in the range of bypass values previously defined.

The choice of the fan pressure ratio, FPR, is made through a graph that shows the influence of the specific thrust with the changes in the FPR. Figure 20 shows this variation for the altitude and cruise speed and for an OPR equal to 26.

As well as in the choice of the best OPR, the value for the FPR is 1.71. This value is chosen considering the desired requirement as the lowest fuel consumption possible for a fixed bypass of 5. Figure 21 shows the effect of the fan pressure ratio in the specific fuel consumption.

These Figures shows that the consumption decreases with the increase of the FPR and the bypass. The value of FPR is optimized for the specific thrust that was required previously.

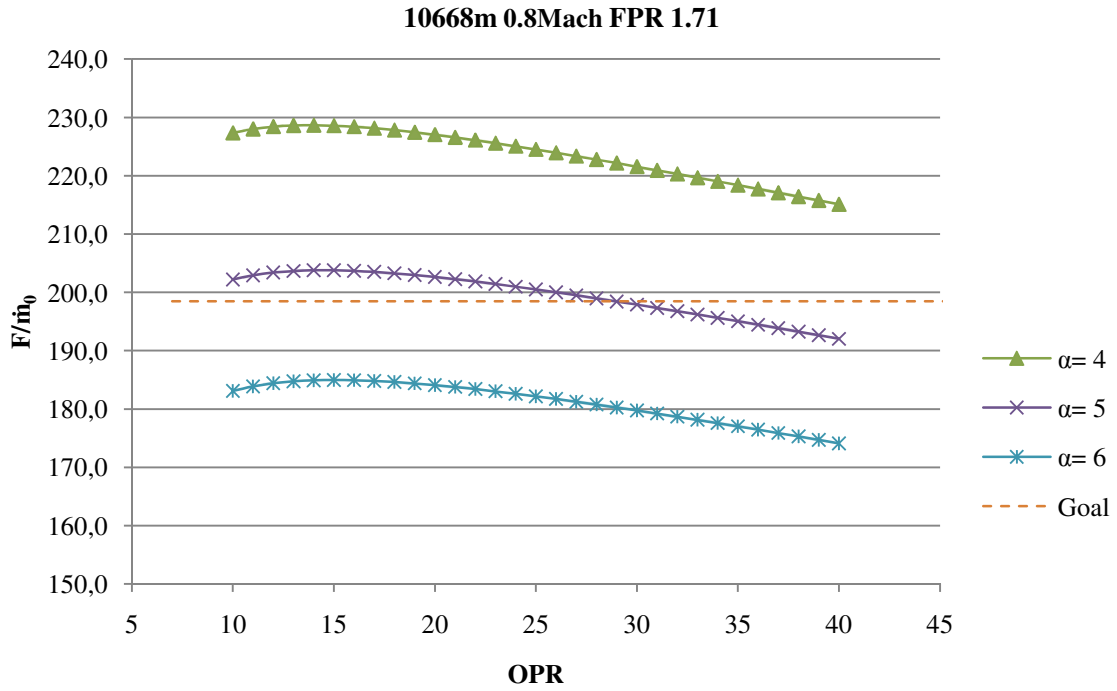


Figure 18: Specific Thrust vs Overall Pressure Ratio for a conventional engine

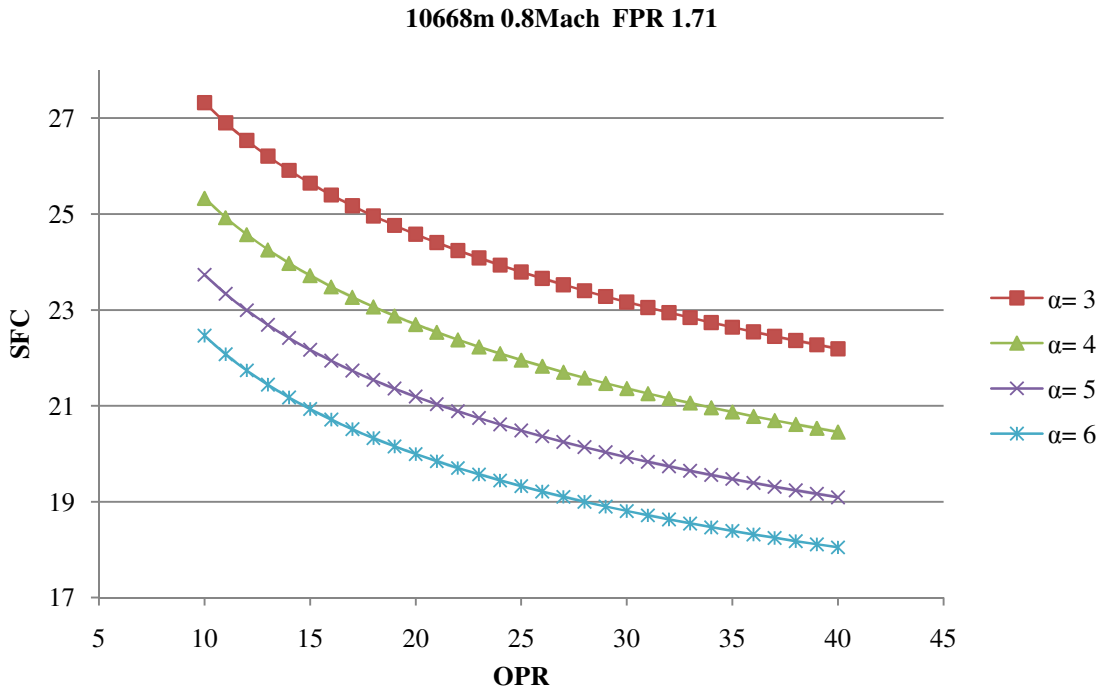


Figure 19: Specific Fuel Consumption vs Overall Pressure Ratio for conventional engine

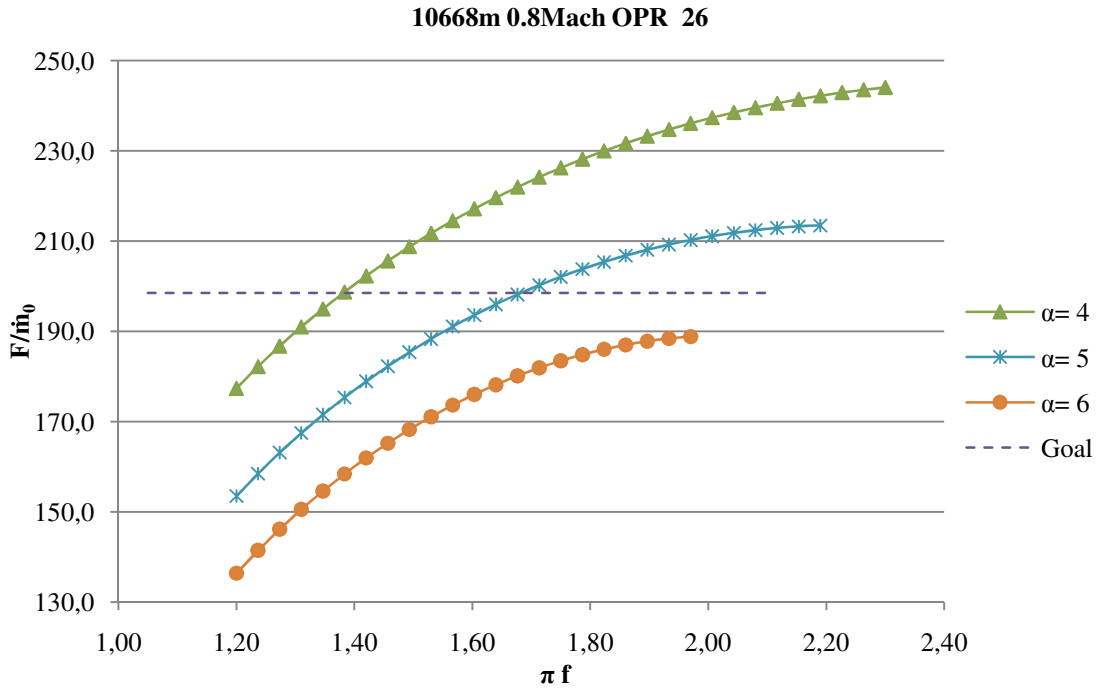


Figure 20: Specific Thrust vs Fan Pressure Ratio for a conventional engine

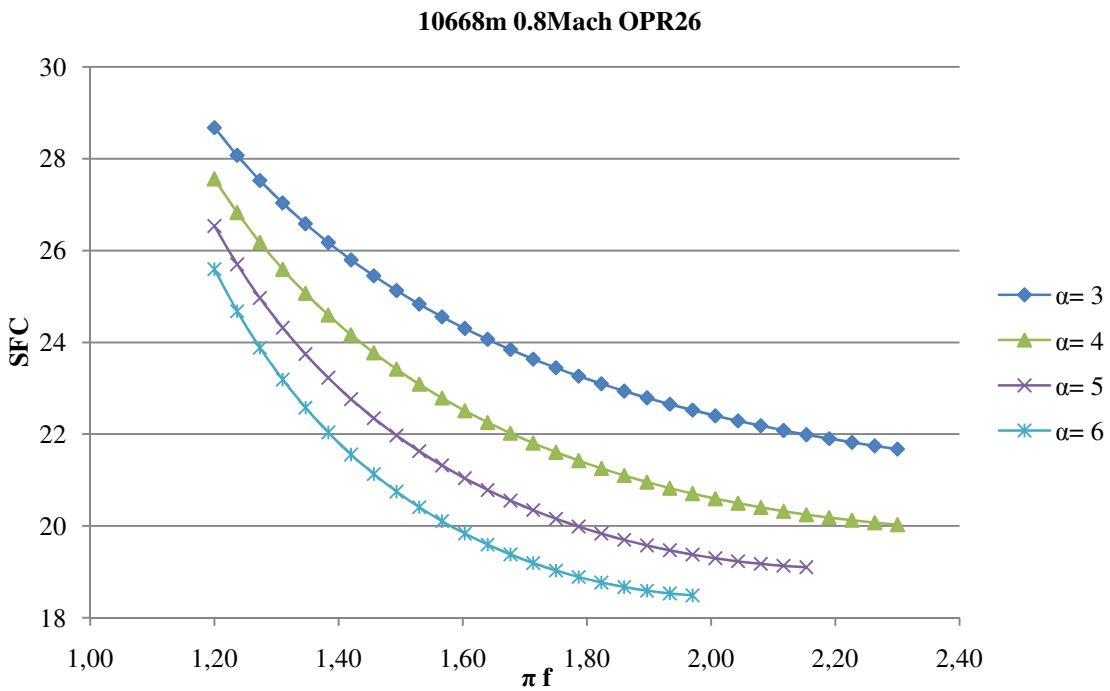


Figure 21: Specific Fuel Consumption vs Fan Pressure Ratio for a conventional engine

4.3. Results

The values obtained are not fully optimized because this would require a complete study of the engine performance, considering several altitudes and turbine inlet temperatures, and thus it would be out of the main objective. The main purpose of this study is to compare several configurations in the same working conditions and so, these results are an approximation of the actual choice of a conventional engine.

The estimated values of the performance parameters for a conventional engine, with two spools, and a specific thrust of 200, at a cruise altitude of 10668m and a Mach 0.8 are shown in the Table 6.

Table 6: Main parameters for conventional engine

Main Parameters	Value
Overall pressure ratio	26
Fan pressure ratio	1.71
Bypass ratio	5

5. Novel cycles comparison

The objective of this chapter is to show different types of cycles and calculate the parameters of performance for three configurations. One with Intercooler, another with regeneration and the last with these two components (intercooled recuperative engine). The requirements for these three different engines are the ones considered in chapter 3. In the last section is compares these three configurations with the conventional engine obtained in chapter 4.

5.1. Engine with Intercooling

Intercooling consists in cooling down the air temperature between the exit of one stage (LPC) to the inlet of the following (HPC). This way, once fixed the global compression ratio, the work needed to raise the air pressure is less than the one needed on the conventional adiabatic case. Since the compressor spends less power, it becomes available in the nozzle a greater enthalpy drop for thrust. This practice is not new, and many ground power systems adopt it to increase the output power. The hardware scheme and thermodynamic cycle are presented in Fig. 22.

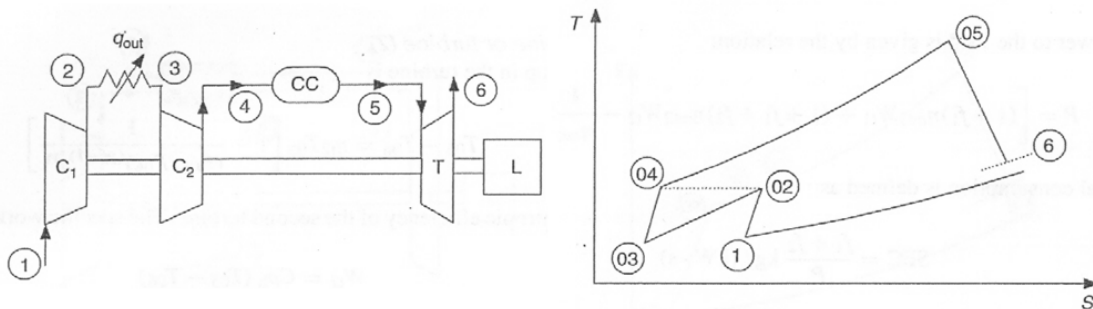


Figure 22: Single spool with intercooler and load. ^[4]

5.1.1. Configuration

The cycle with intercooler is shown in Figure 23 and 24. The intercooler is located between the low pressure compressor and the high pressure compressor. This Figure shows also the station numbering used in the calculations.

In Figure 23 is shown the location of the intercooler. This component is located between the compressors and makes the cooling between them. Compared to the conventional engine, the nomenclature used in this engine only varies at the entrance of the intercooler. Thus it is necessary to introduce a new location for the parametric calculations (2.1). It can be seen in Figure 24 that the intercooler only interferes with the flow between compressors. The cooling system is not affected by the introduction of this component

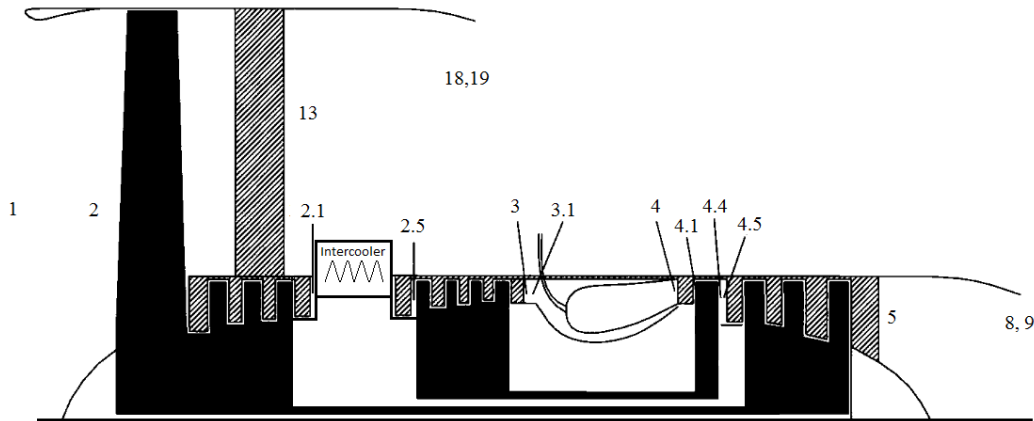


Figure 23: Scheme and reference numbering of a turbofan engine with Intercooling. [Adapted by 1]

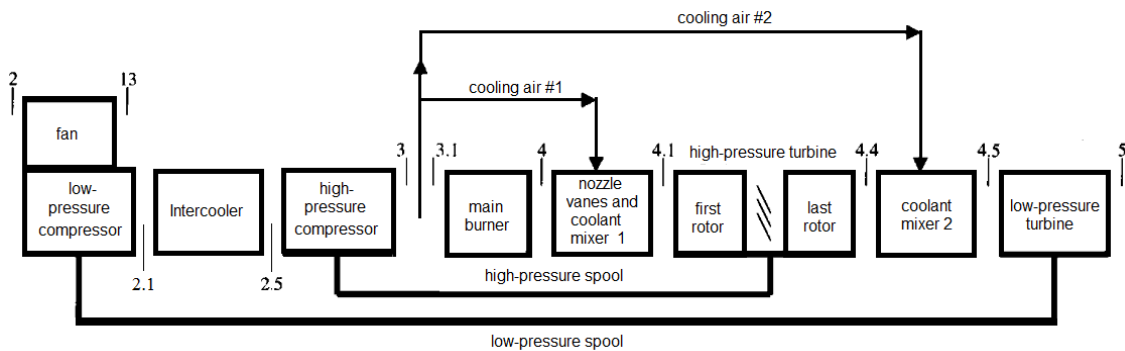


Figure 24: Reference station – turbine cooling airflows and Intercooling. [Adapted by 1]

5.1.2. Calculation method

The calculation method used is similar to the one used in the calculation of the conventional engine. Nevertheless, there is a difference, when the flow exits the low pressure compressor, there is a decrease on the temperature. After that, the air enters the high pressure compressor. Through the intercooler, the pressure drop was considered as 5% and the efficiency as 60%. These values were considered, because they were the lower ones that occurred in the initial studies of these aero engines. If these values are in reality higher, that improves overall performance of the engine.

5.1.3. Analysis and comments

The Figure 25-29 shows, in an analogous way to the conventional engine the principal parameters of an engine with intercooler. The bypass and fan pressure ratios are the same, as the conventional engine, 5 and 1.71 respectively. The difference in this engine with intercooler, is that to respect the requirements, the overall pressure ratio have to be higher than the one used in the conventional engine. This happens because

the compressor work reduces due to the intercooler. So, the value of the overall pressure ratio is 29.

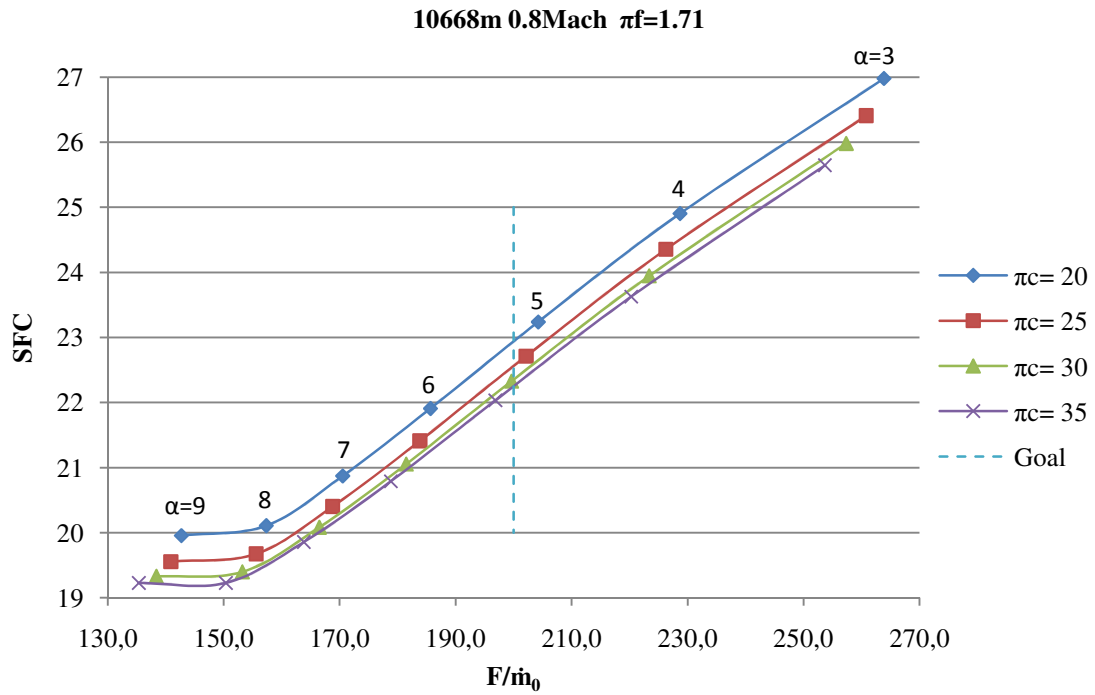


Figure 25: Specific Fuel Consumption vs Specific Thrust at cruise conditions for an engine with intercooler.

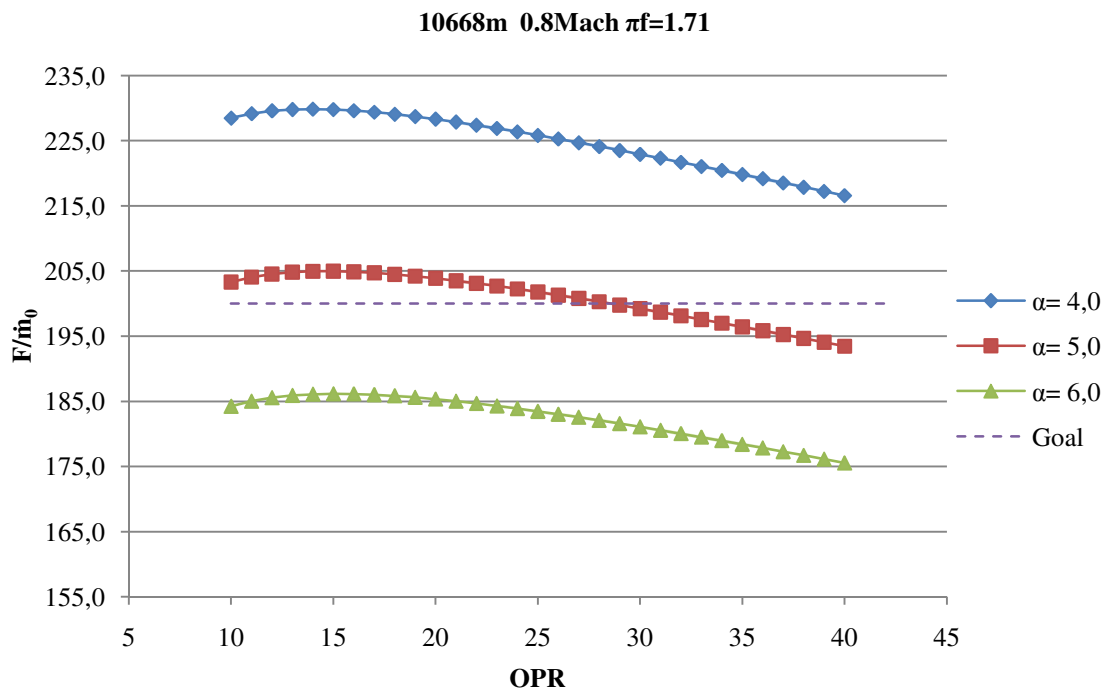


Figure 26: Specific Thrust vs Overall Pressure Ratio for engine with intercooler.

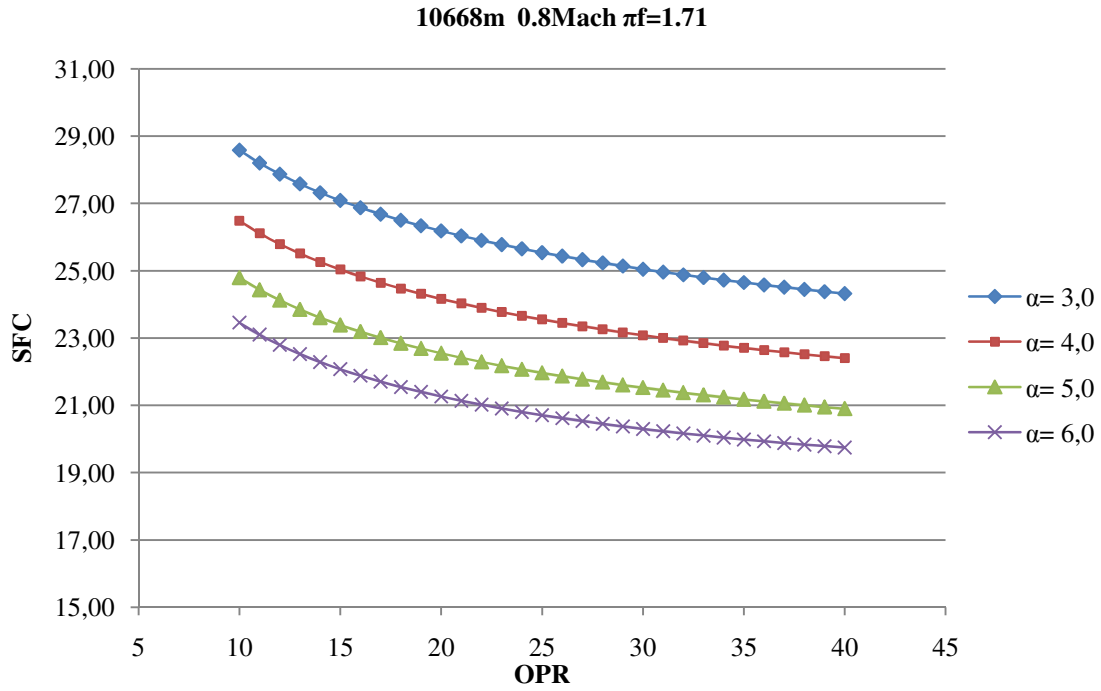


Figure 27: Specific Fuel Consumption vs Overall Pressure Ratio for an engine with intercooler.

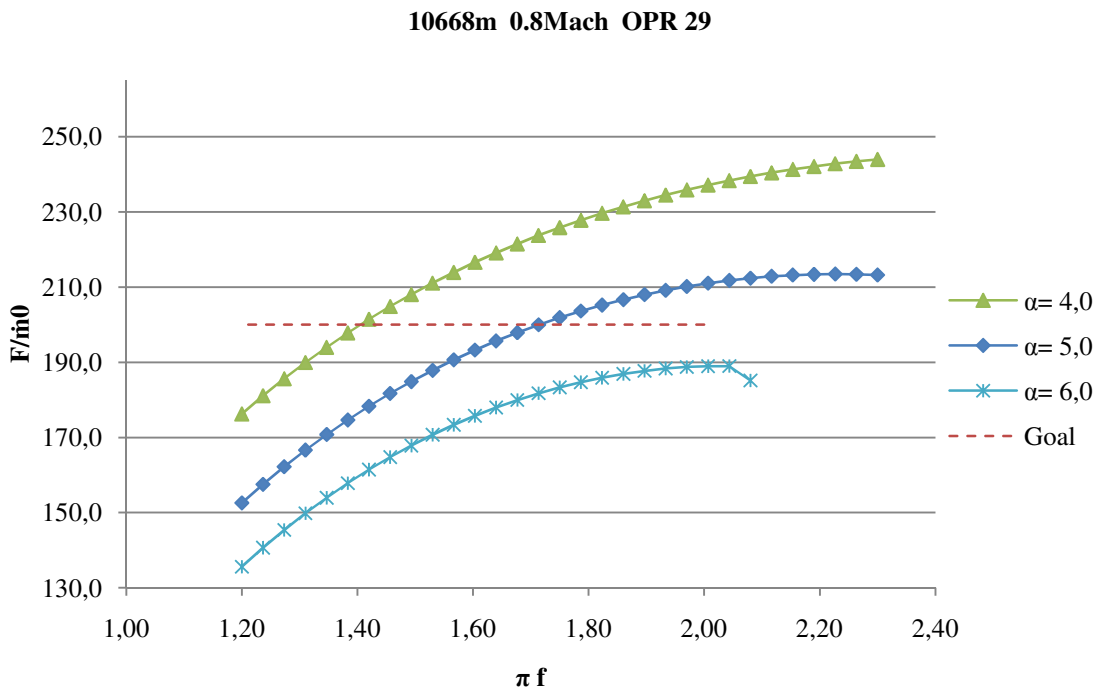


Figure 28: Specific Thrust vs Fan Pressure Ratio for an engine with intercooler.

10668m 0.8Mach OPR 29

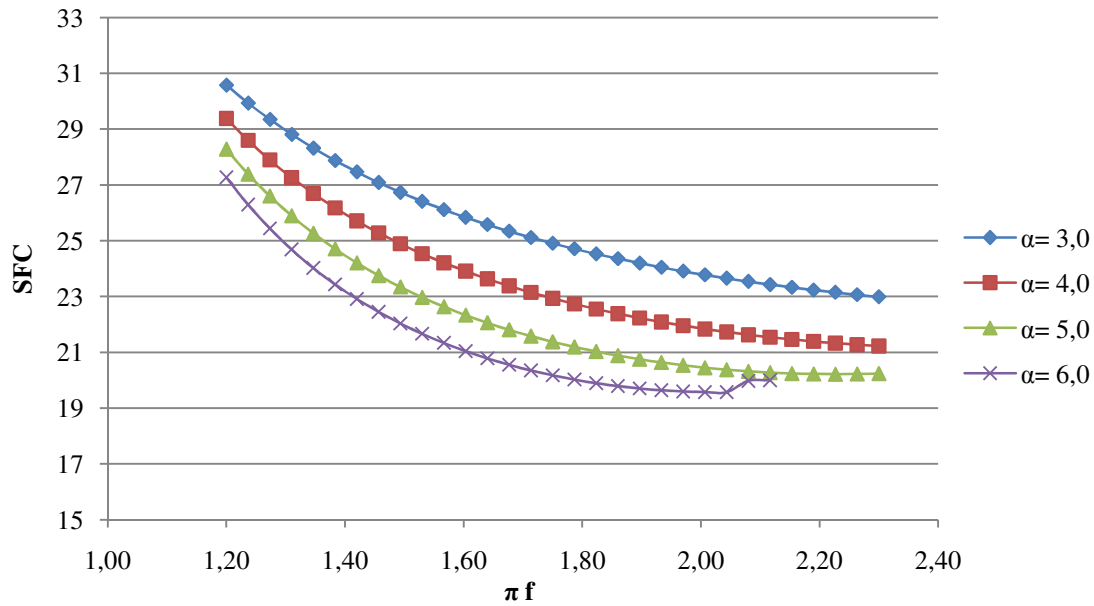


Figure 29: Specific Fuel Consumption vs Fan Pressure Ratio for an engine with intercooler.

The Table 7 shows the main parameters for an engine only with intercooling.

Table 7: Main parameters for an engine with intercooler.

Main Parameters	Value
Overall pressure ratio	29
Fan pressure ratio	1.71
Bypass ratio	5

5.2. Engine with Regeneration

In gas-turbine engines, the temperature of the exhaust gases leaving the turbine is often considerably higher than the temperature of the air leaving the compressor. Therefore, the high pressure air leaving the compressor can be heated by transferring heat to it from the hot exhaust gases in a counter-flow heat exchanger, which is also known as a *regenerator*. The cycle with that configuration is shown in Figure 30, where can be seen the hardware needed to transfer heat from the exhaust gases leaving the turbine to the air flow leaving the compressor. Using the regenerator the fuel needed to raise the temperature, of the air leaving the compressor decreases. The thermal efficiency of this cycle increases as a result of regeneration, since less fuel is used for the same work output. In Figure 31 is presented the ideal thermodynamic cycle for the same gas turbine with regeneration.

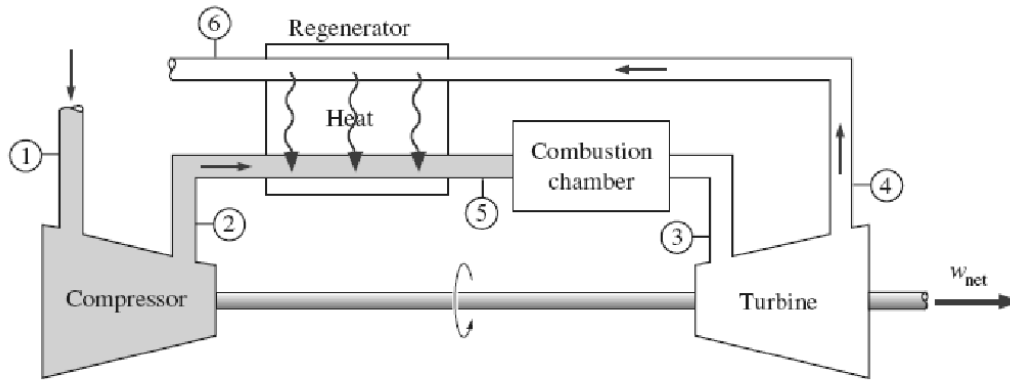


Figure 30: A gas-turbine engine with regenerator. [35]

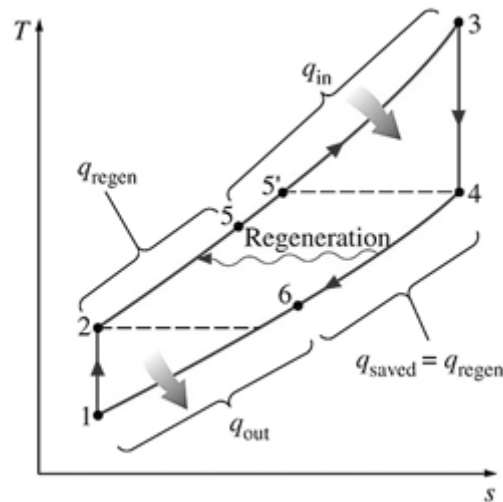


Figure 31: Thermodynamic cycle of a turbopfan engine with regeneration. [35]

5.2.1. Configuration

The engine with regenerator is shown in Figure 32-33 and the regenerator is located after the low pressure turbine and before the exit nozzle. These figures show the station numbering used for the calculations performed in the next section.

In figure 32 is shown that the flow before entering in the burner has to go through the regenerator. Thus, the flow will warm due to the temperature of exhaust gases and go back to the entrance of the burner. Between the locations 6-7 exists a pressure drop due to the use of the regenerator.

The flow required for cooling the turbine is obtained as in the previous configuration. This leaves the location 3, that is, before entering the regenerator. This happens at this location since the flow has a temperature smaller than the one it has when leaving the regenerator, in order to the purpose of the use of cooling to be accomplished. This can be seen in Figure 33.

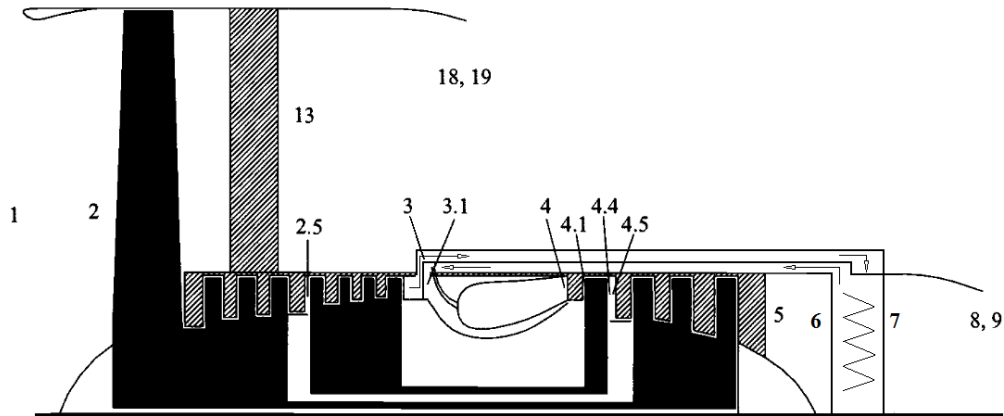


Figure 32: Scheme and reference numbering of a turbofan engine with regenerator. [Adapted by 1]

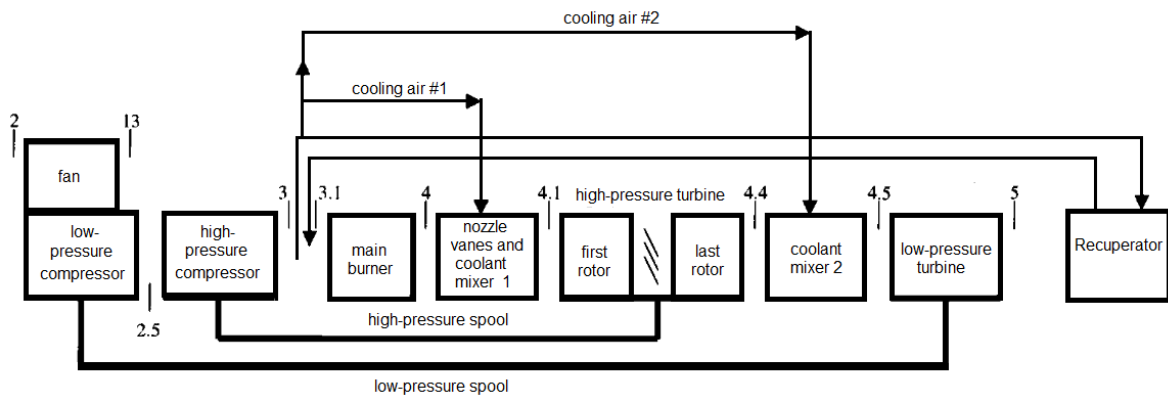


Figure 33: Reference station – turbine cooling airflows and regeneration. [Adapted by 1]

5.2.2. Calculation method

The calculation method used for the engine with only the regenerator has the same baseline as the conventional engine. The difference concerns the pressure drop before the entry on the main burner. Besides this, the temperature changes between station 3 and 3.1. Through the regenerator, the pressure drop was considered 5% and the efficiency 60%.

5.2.3. Analysis and comments

From Figure 34 is possible to verify that the curves for the various values of overall pressure ratio are opposed to those shown in Figure 17 and 25. While, in the Figure 27, the OPR increase leads to a decrease in SFC, in Figure 36 is verified the opposite. The SFC decreases with the decrease of the OPR. The OPR have a stronger influence in the SFC in this engine than on the engines study previously.

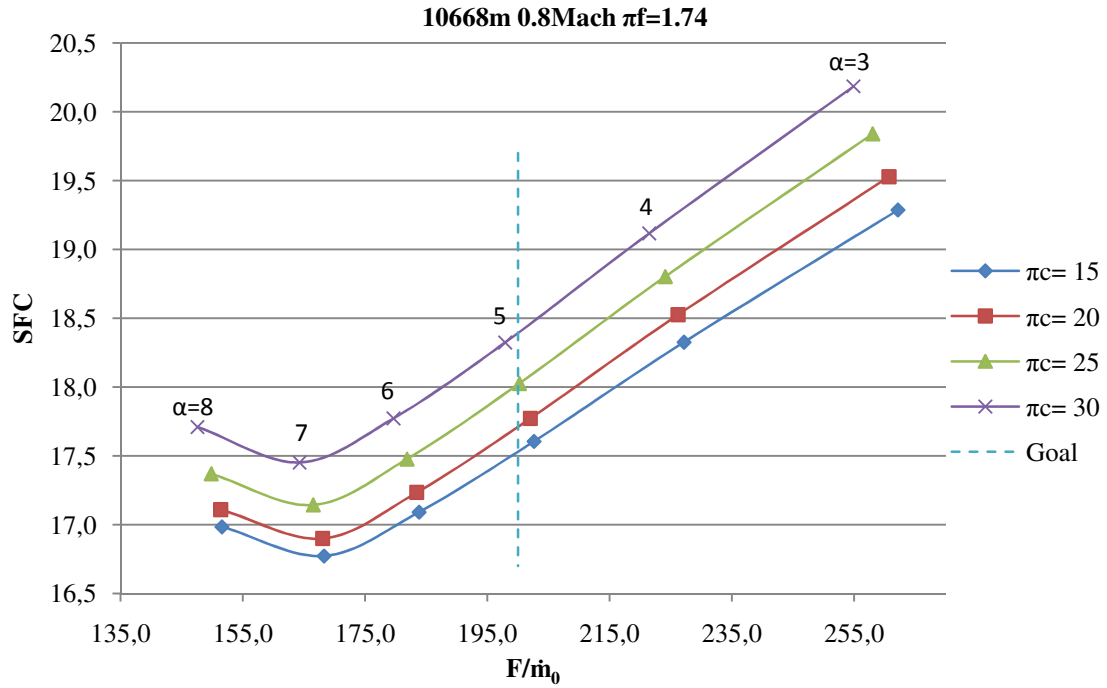


Figure 34: Specific Fuel Consumption vs Specific Thrust at cruise conditions for an engine with regenerator.

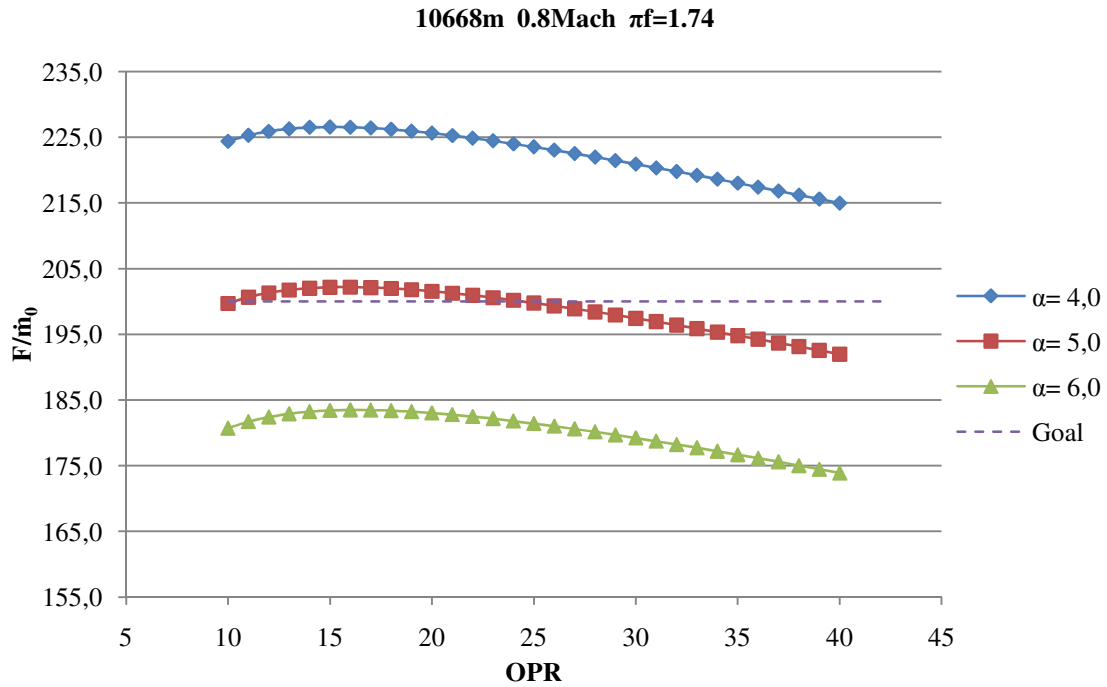


Figure 35: Specific Thrust vs Overall Pressure Ratio for engine with regenerator.

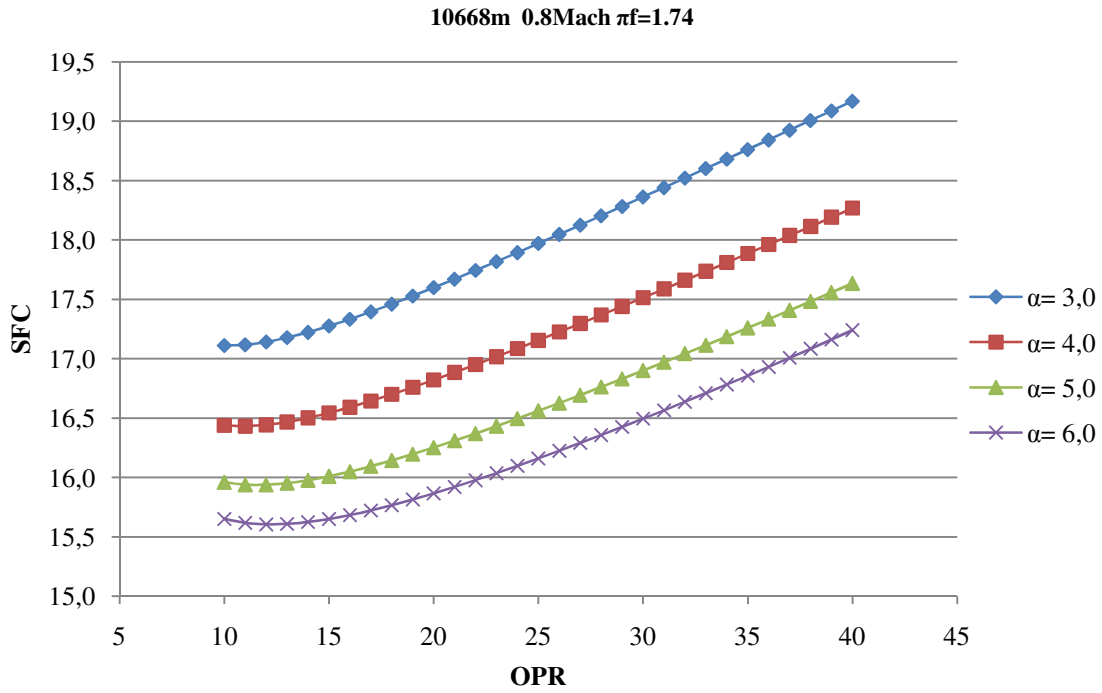


Figure 36: Specific Fuel Consumption vs Overall Pressure Ratio for an engine with regenerator.

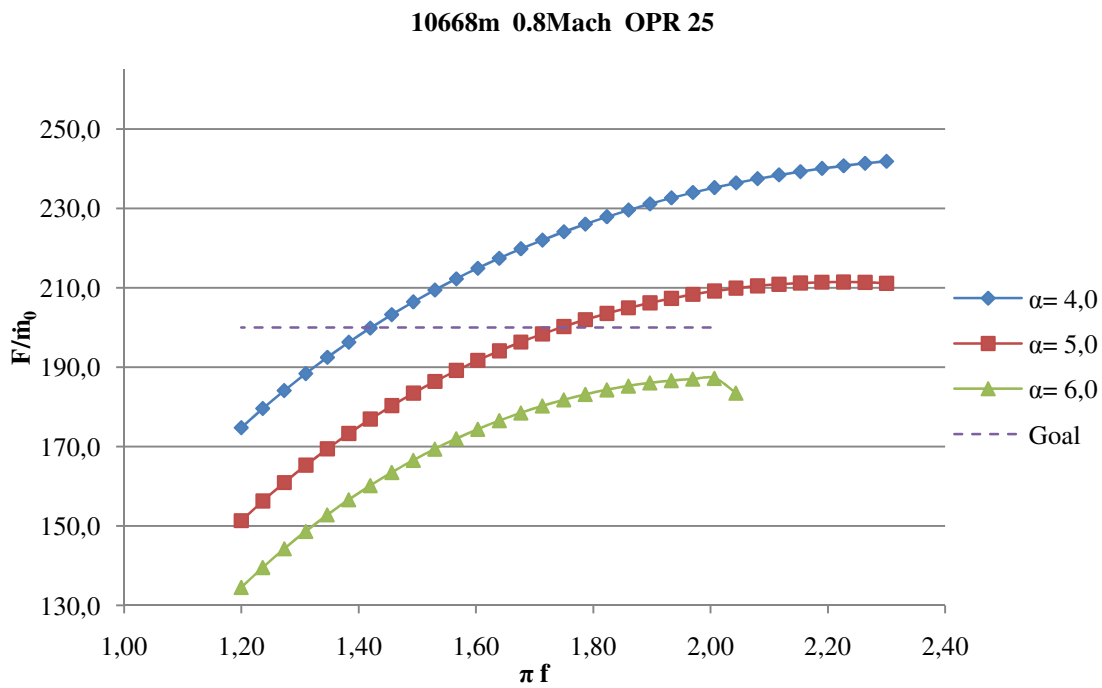


Figure 37: Specific Thrust vs Fan Pressure Ratio for an engine with regenerator.

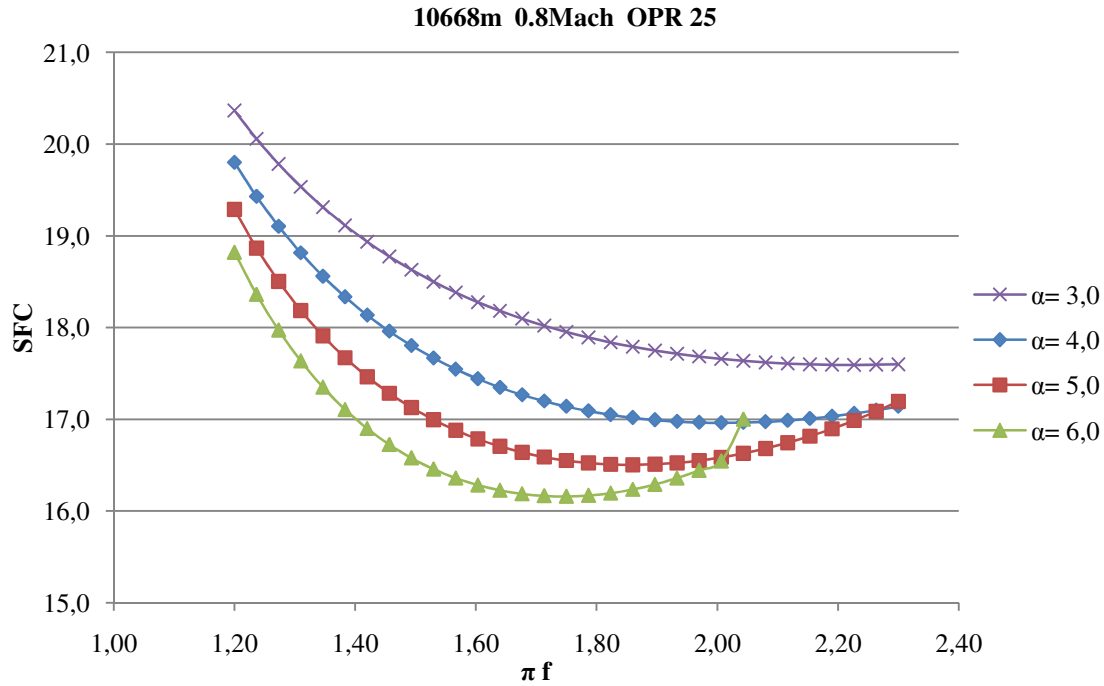


Figure 38: Specific Fuel Consumption vs Fan Pressure Ratio for an engine with regenerator.

The values of bypass remain in the same range as that in engines previously seen: $4 \leq \alpha \leq 6$. Through the requirements in Section 3 were obtained values for the OPR and π_f . Table 8 shows the main parameters for an engine with regenerator.

Table 8: Main parameters for an engine with regenerator.

Main Parameters	Value
Overall pressure ratio	25
Fan pressure ratio	1.74
Bypass ratio	5

5.3. Intercooled Recuperated Engine

This type of engine is the combination of the two configurations mentioned above. As seen in previous settings, using the intercooler, takes the temperature between the compressors down, thus decreasing the entropy. As seen above the regenerator recovers heat from the hot air leaving the nozzle to heat the air before its entry in the combustion chamber, thus saving some fuel. Figure 39 shows a cycle of an engine with intercooler and regenerator with a load turbine.

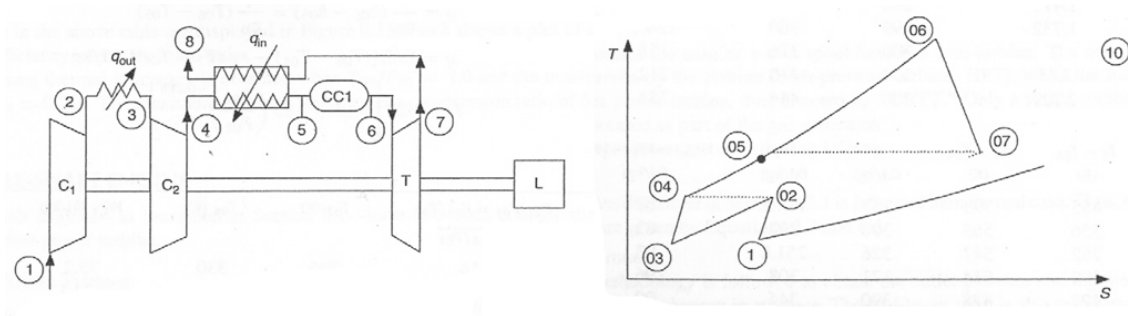


Figure 39: Single spool with intercooler and regenerator loaded. [4]

5.3.1. Configuration

In an analogous way as in the sections 5.1 and 5.2 the engine station numbering is shown in Figures 40-41. In that figures is shown the engine resulting from the combination of the intercooled engine with the regenerated engine.

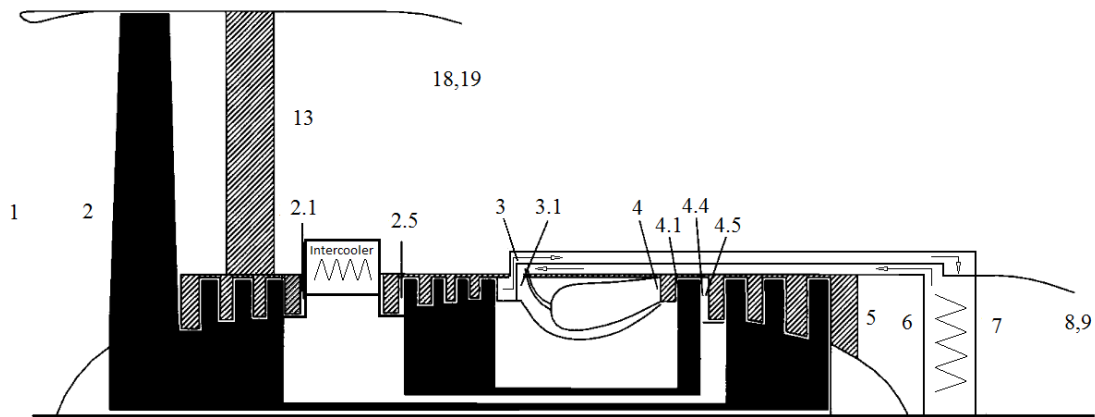


Figure 40: Scheme and reference numbering of a turbofan engine with intercooler and regenerator. [Adapted by 1]

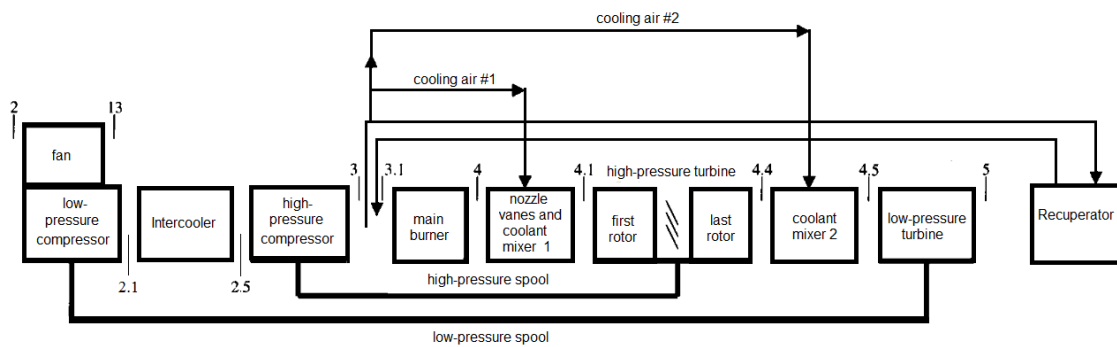


Figure 41: Reference station – turbine cooling airflows, intercooler and regeneration. [Adapted by 1]

5.3.2. Calculation method

The method used for the calculation of an engine with intercooler and regenerator was the same used before. In this engine the main nomenclature was kept constant like in the engines studied before, changing only in the place where the component was introduced.

5.3.3. Analysis and comments

It can be observed in Figure 42 that α remains around the value 5, as seen in other engines studied before. Based on Figures 43-46 the choice of OPR and π_r are like on the engine with a regenerator. The graphics of both engine types (with intercooled regenerator and regenerator) have the same behavior.

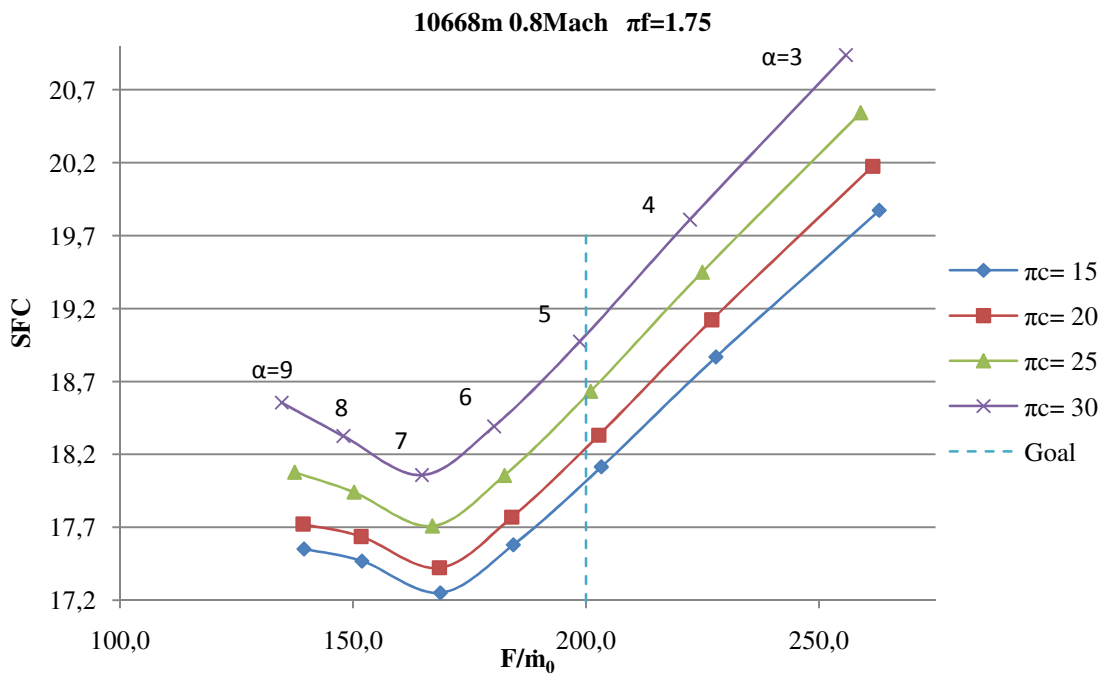


Figure 42: Specific Fuel Consumption vs Specific Thrust at cruise conditions for an engine with intercooler and regenerator.

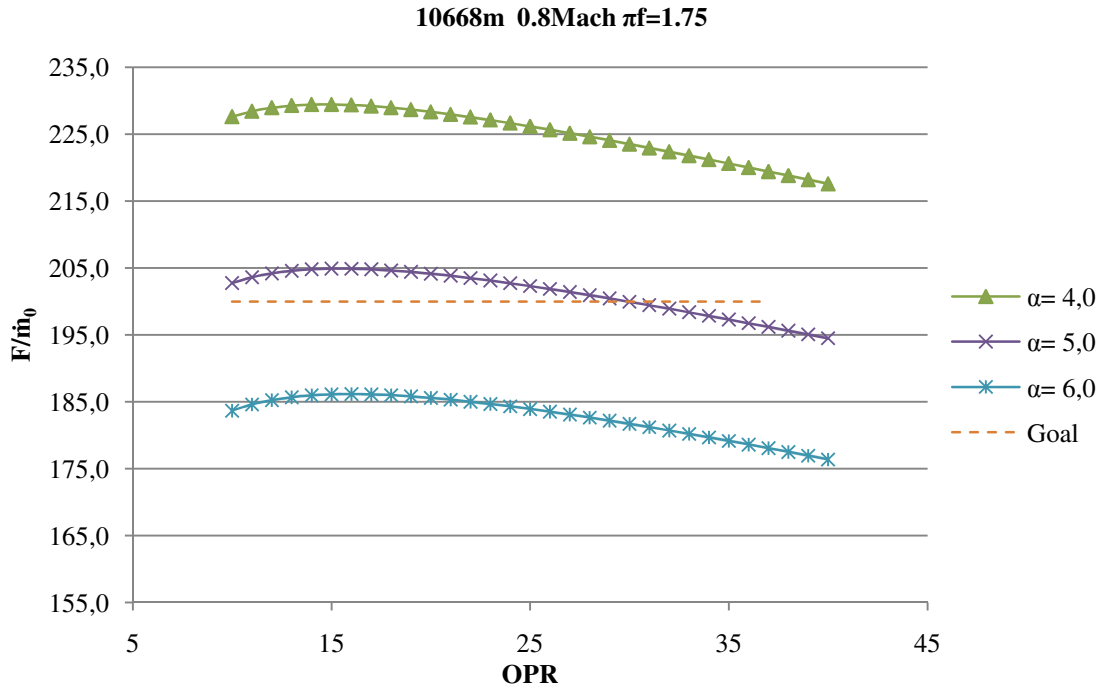


Figure 43: Specific Thrust vs Overall Pressure Ratio for engine with intercooler and regenerator.

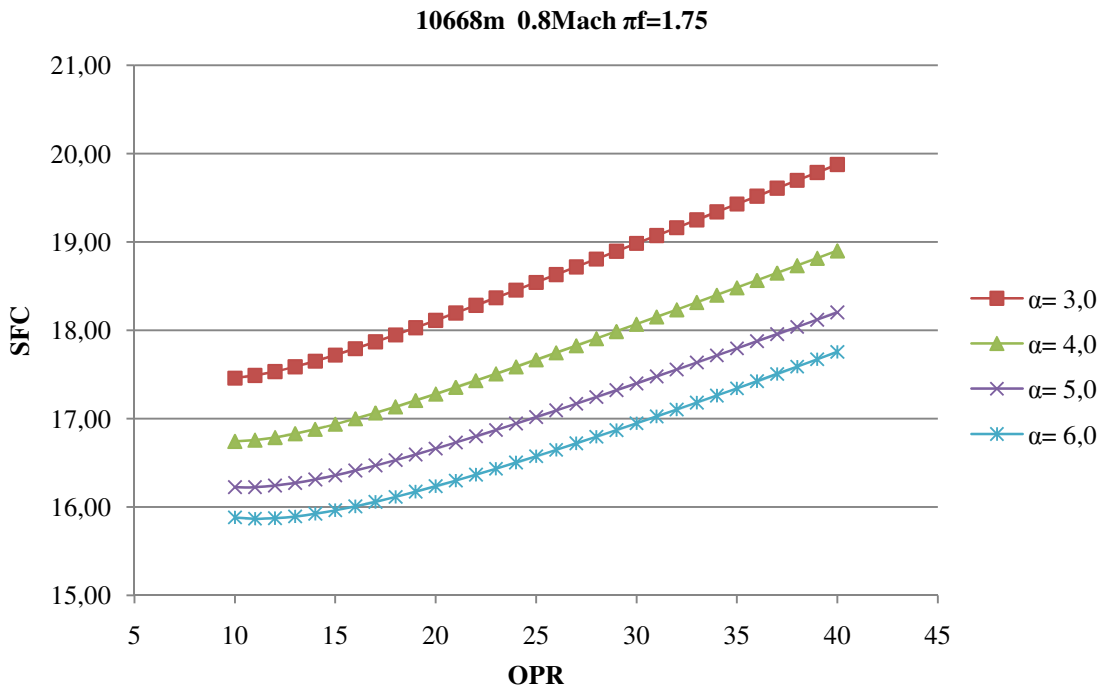


Figure 44: Specific Fuel Consumption vs Overall Pressure Ratio for an engine with intercooler and regenerator.

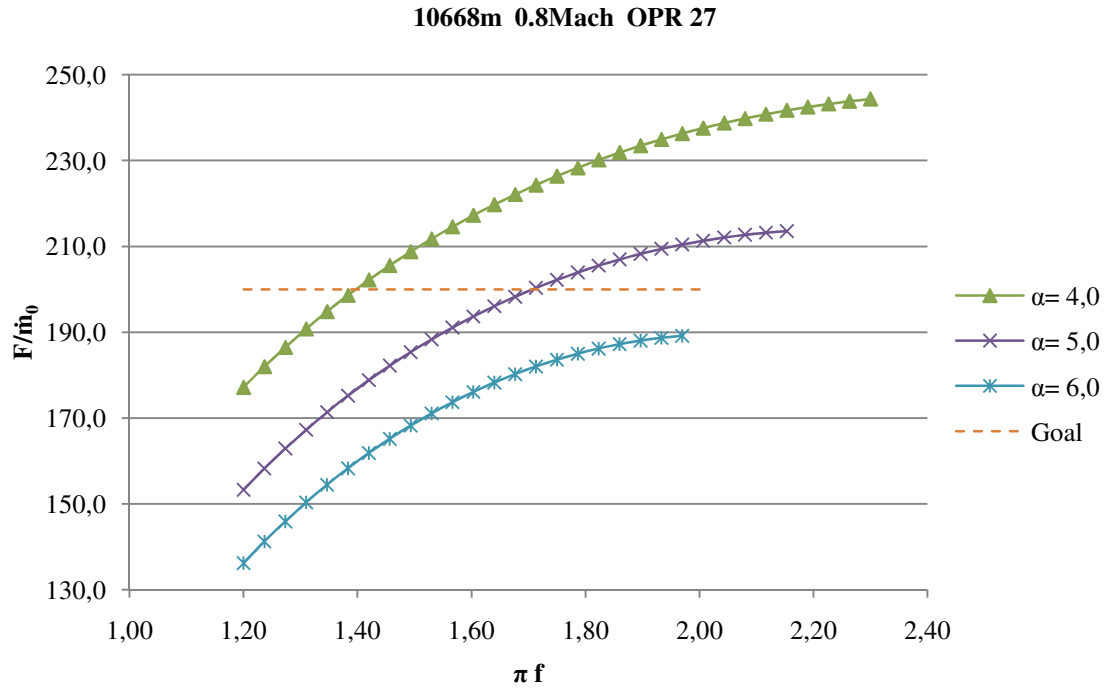


Figure 45: Specific Thrust vs Fan Pressure Ratio for an engine with intercooler and regenerator.

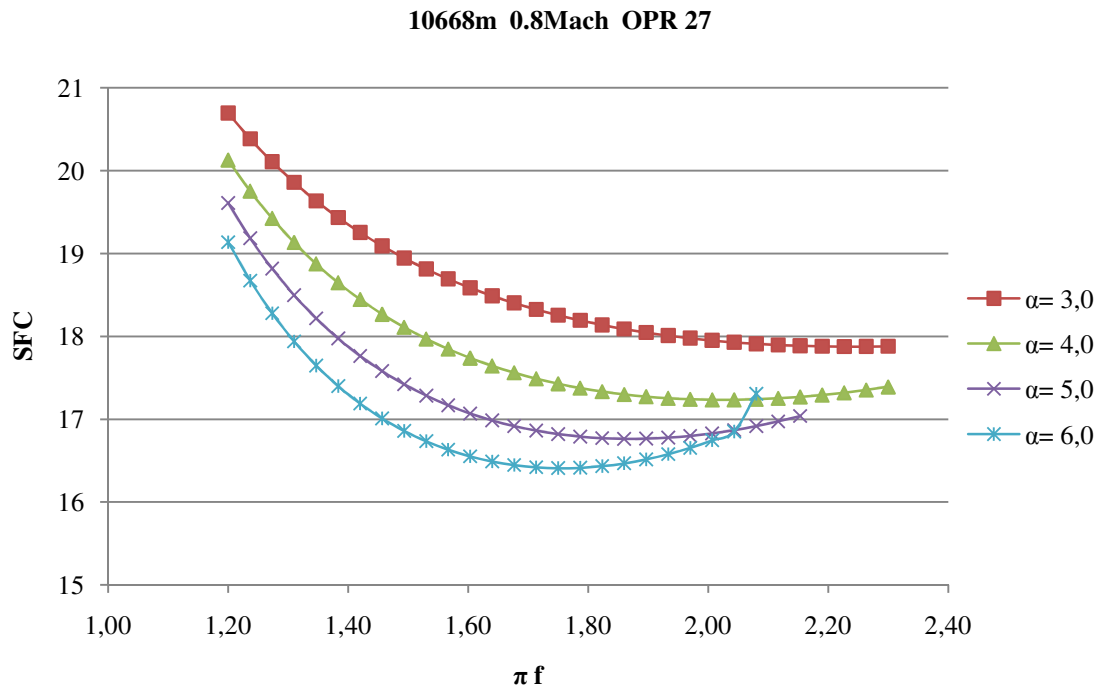


Figure 46: Specific Fuel Consumption vs Fan Pressure Ratio for an engine with intercooler and regenerator.

So the choice is based on the same principles. Table 9 shows the main parameters for the engine studied in this section.

Table 9: Main parameters for an intercooled recuperated engine.

Main Parameters	Value
Overall pressure ratio	27
Fan pressure ratio	1.75
Bypass ratio	5

5.4. Engines comparison

The comparison between all engine types studied is shown in Figures 47-53. These figures compare the specific fuel consumption and specific thrust with the different performance parameters and have as target to show the effect of variation of the parameters of performance in specific fuel consumption and specific thrust. The engines here compared have the main parameters chosen before. Figure 47 shows the variation of specific fuel consumption as a function of specific thrust for different values of bypass. It can be observed that all engines meet the requirements described in section 3.3. The engine with better consumption is the engine with only regeneration. Rather, the engine with only intercooling has the worst results in what concerns the specific fuel consumption. The values for the minimum specific fuel consumption vary with the type of engine. For the conventional engine and the one with intercooler, the minimum is when the value of bypass is near 8, while for the engine with intercooler and intercooler and regenerator the SFC have the minimum value when the bypass is 7.

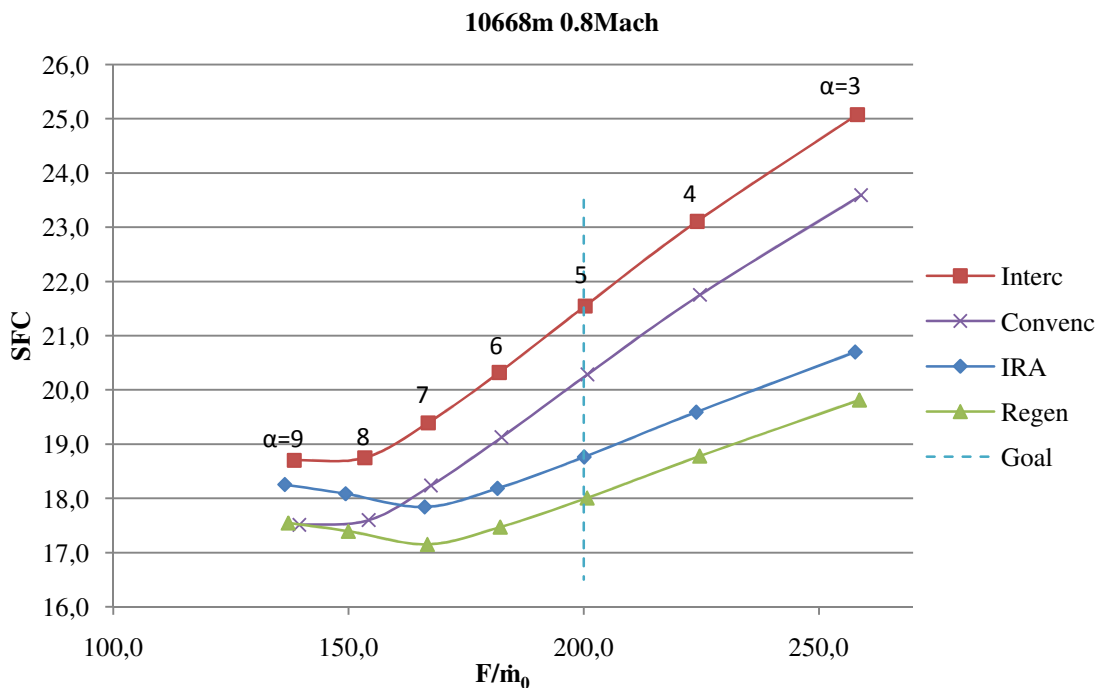


Figure 47: Specific Fuel Consumption vs Specific Thrust

The variation of fan pressure ratio has impact on specific thrust and on the specific fuel consumption, as shown in Figures 48-49. The variation of the specific thrust in function of the fan pressure ratio is equal for all types of engines. Figure 48 shows that the specific fuel consumption of the engine with intercooler is larger than the one of a conventional engine. While an engine with only regeneration have lower specific fuel consumption. The Figure 49 shows the variation of specific thrust with fan pressure ratio. That shows the curve, with or without components, have the same behavior. The specific thrust doesn't have a significant variation when compared with the other engines configurations.

In Figure 50 the specific fuel consumption is not affected by the Low Pressure Compressor Ratio for the conventional engine and engine with regenerator. This happens because these engines do not have components that interfere with temperatures in the compressors. So, in Figure 51, the conventional engine and the engine with regenerator have identical curves. These curves are not exactly identical due to different values of overall pressure ratio and the drop pressure in the nozzle due to the use of the regenerator. In Figure 51 can be seen that the specific thrust on all engines is above 200, thus fulfilling the requirements.

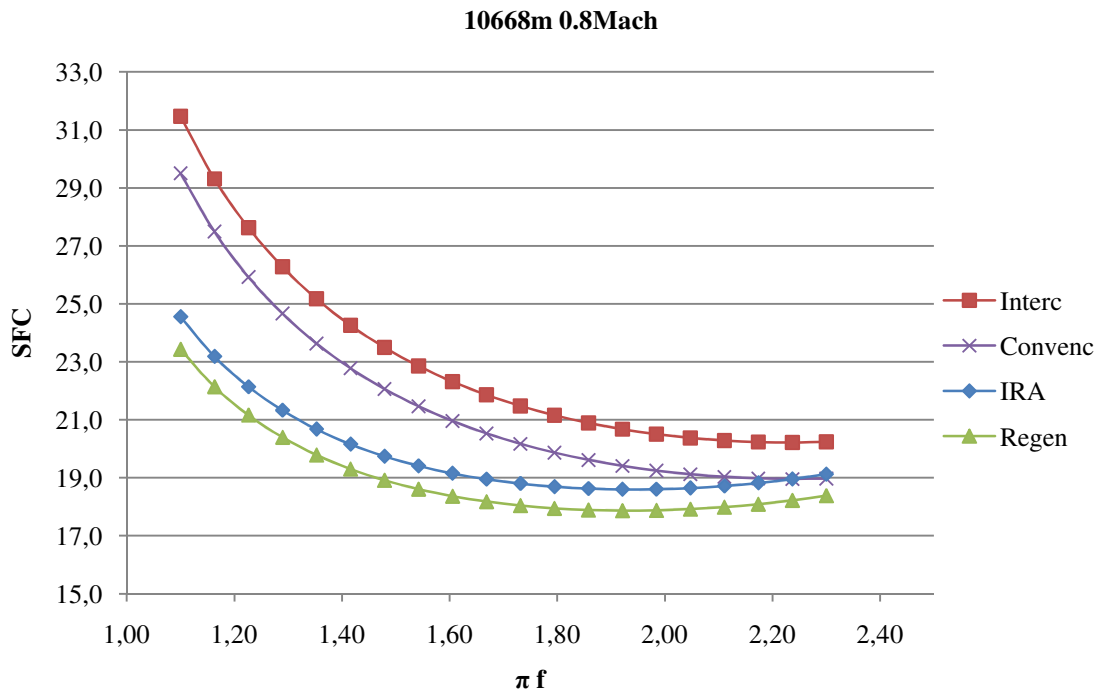


Figure 48: Specific Fuel Consumption vs Fan Pressure Ratio

10668m 0.8Mach

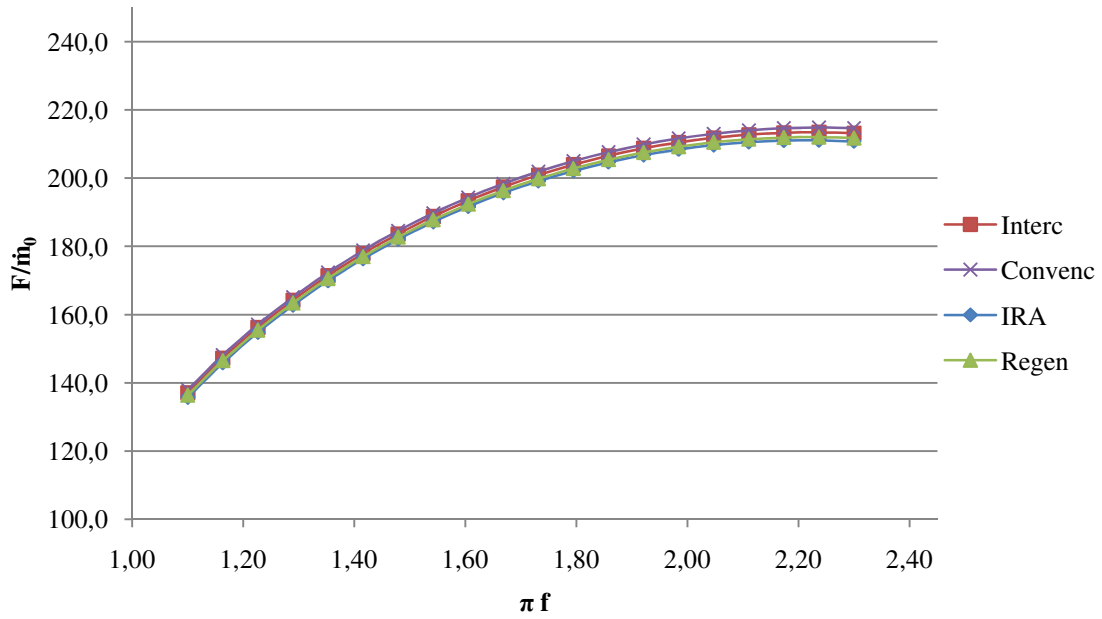


Figure 49: Specific Thrust vs Fan Pressure Ratio

10668m 0.8Mach

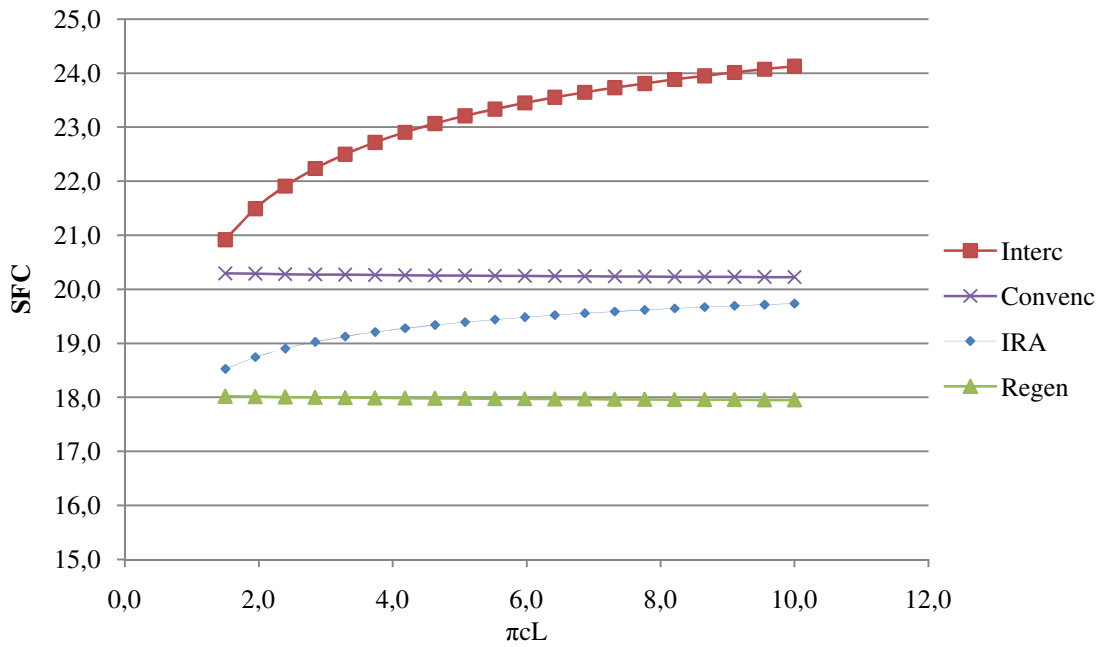


Figure 50: Specific Fuel Consumption vs Low Pressure Compressor Ratio

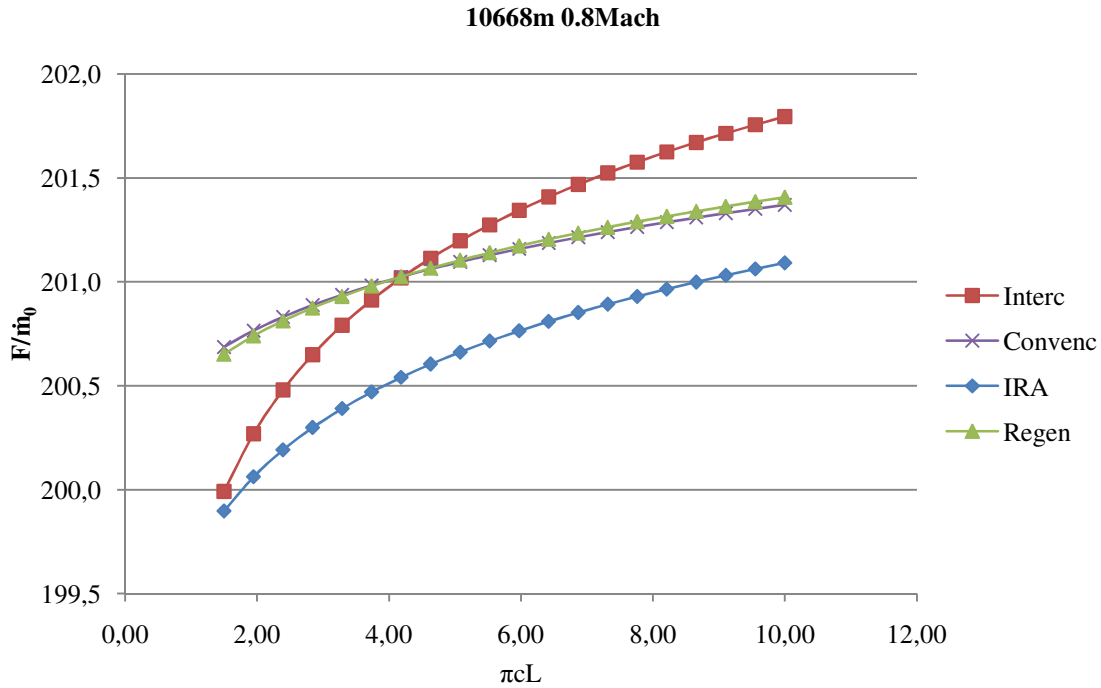


Figure 51: Specific Thrust vs Low Pressure Compressor Ratio

The overall pressure ratio is a very important parameter for obtaining the design point. In the Figures 52-53 can be seen the influence of this parameter in specific fuel consumption and specific thrust. In the conventional engine the increase of overall pressure ratio have the same behavior as in the engine with intercooler. The increase in the overall pressure ratio causes a decrease in specific fuel consumption. For the engine with regenerator or IRA the opposite occurs, an increase in the overall pressure ratio leads to an increase in specific fuel consumption. Figure 53 shows that the specific thrust have a maximum value but this value is not desired for this study, because the overall pressure ratio, to the maximum value of specific thrust, is very low. If it had been used, this value would lead to a significant change in engine parameters and thus failing to meet up the requirements.

Figures 54-57 show the behavior of the thermal efficiency in relation to different parameters of performance for the engines studied previously. The thermal efficiency is a parameter that increases with the use of the regenerator. Figure 54 show that engines with regenerator have higher efficiency than the engines that do not use regenerator. In this figure you can see that the thermal efficiency have a maximum value for all types of engines. The value of Bypass ratio for the maximal thermal efficiency is lower for engines that use regenerator. The fan pressure ratio is a parameter that interferes with the thermal efficiency. The thermal efficiency increases at a higher rate for low values of the fan pressure ratio. For engines without regenerator, the thermal efficiency increases at a lower rate after reaching a value of the fan pressure ratio of approximately 1.3. After this value the thermal efficiency decreases with the increase of the fan pressure ratio. This way is proved that exist a maximum value for the thermal efficiency for engines with regenerator, like IRA and the regenerative engine.

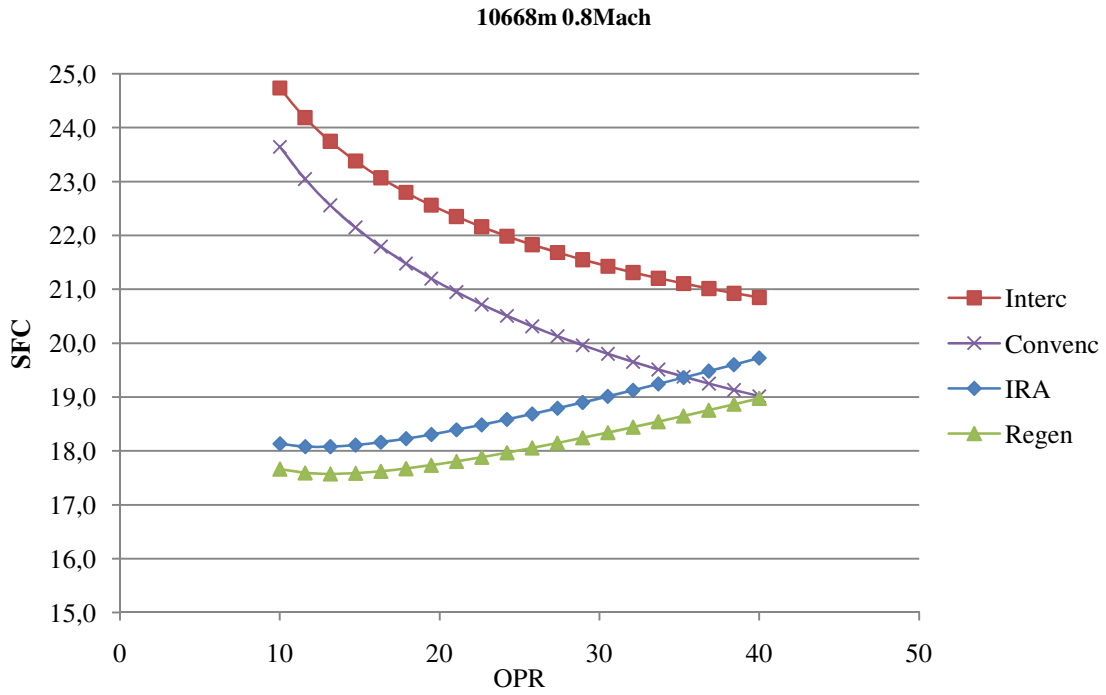


Figure 52: Specific Fuel Consumption vs Overall Pressure Ratio

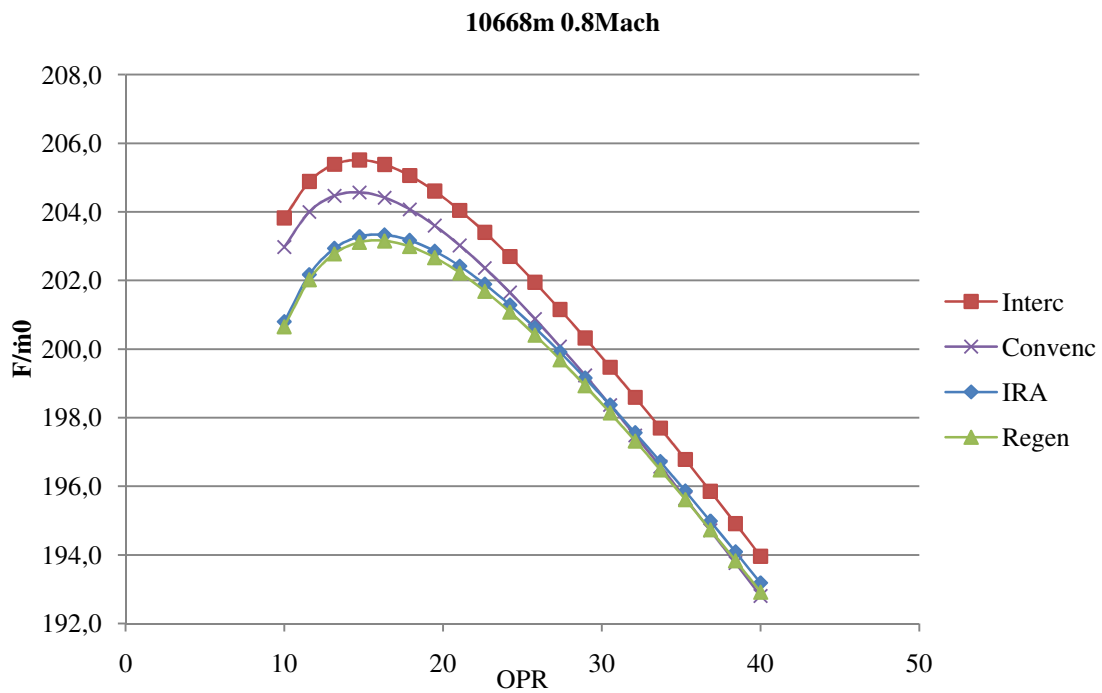


Figure 53: Specific Thrust vs Overall Pressure Ratio

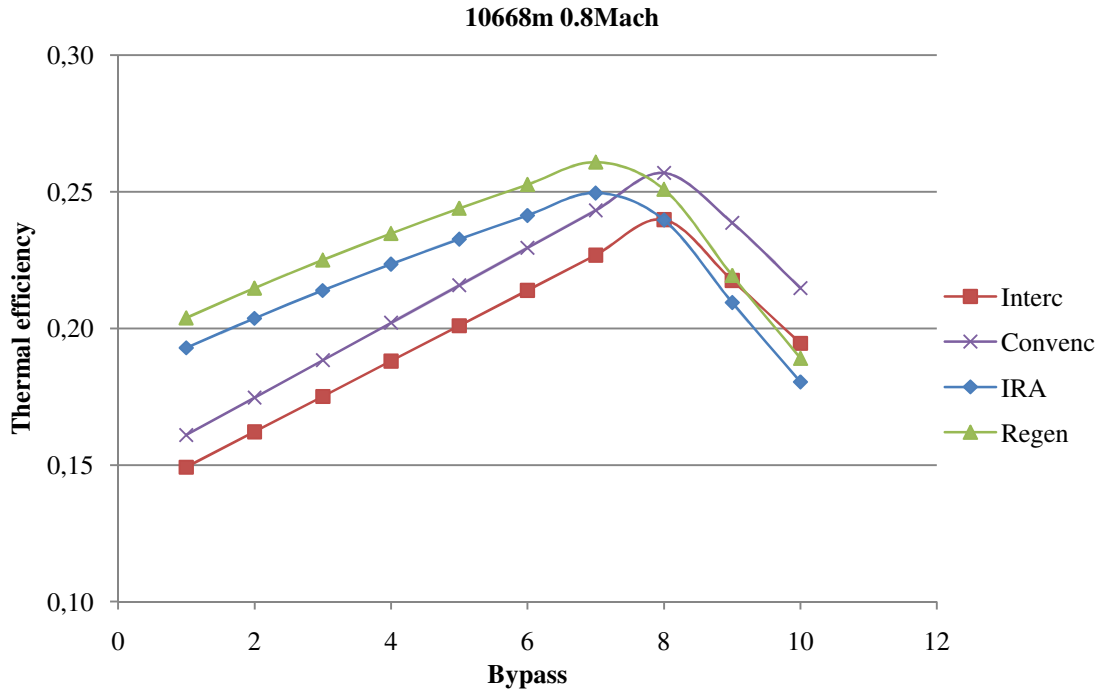


Figure 54: Thermal Efficiency vs Bypass Ratio

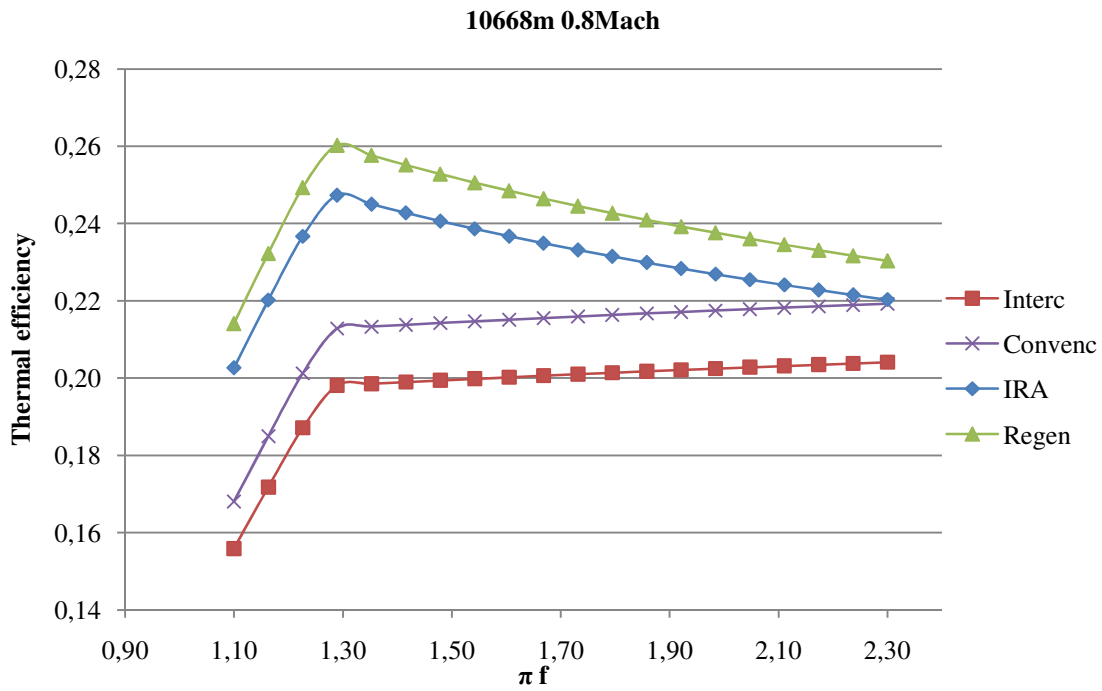


Figure 55: Thermal Efficiency vs Fan Pressure Ratio

The variation of thermal efficiency with the low pressure compressor ratio, have the same behavior as the specific fuel consumption in Figure 56. This behavior shows that the thermal efficiency is not influenced in the case of engines without regenerator. While in Figure 50 the SFC increases with the low compressor pressure ratio, in this case, the thermal efficiency decreases. This shows that an increase in the low pressure compressor ratio leads to an increase in specific fuel consumption and a decrease in thermal efficiency.

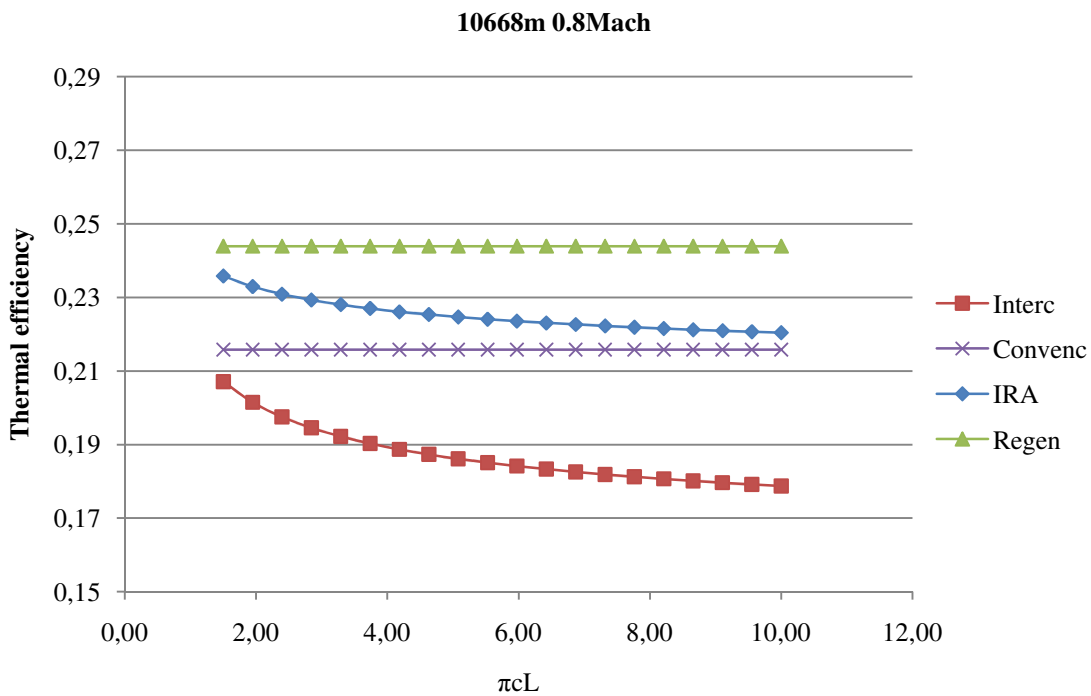


Figure 56: Thermal Efficiency vs Low Pressure Compressor Ratio

Another important parameter in the design of an engine is the overall pressure ratio. This parameter affects the thermal efficiency. For engines with a regenerator the increase of overall pressure ratio have a negative influence on thermal efficiency. While with the engine without this component the thermal efficiency increases with the increasing of overall pressure ratio. This variation is shown in Figure 57.

The Figures 54-57 show the behavior of thermal efficiency. These behaviors are similar to other parameters. Through these figures the engine with better thermal efficiency is the engine with regenerator.

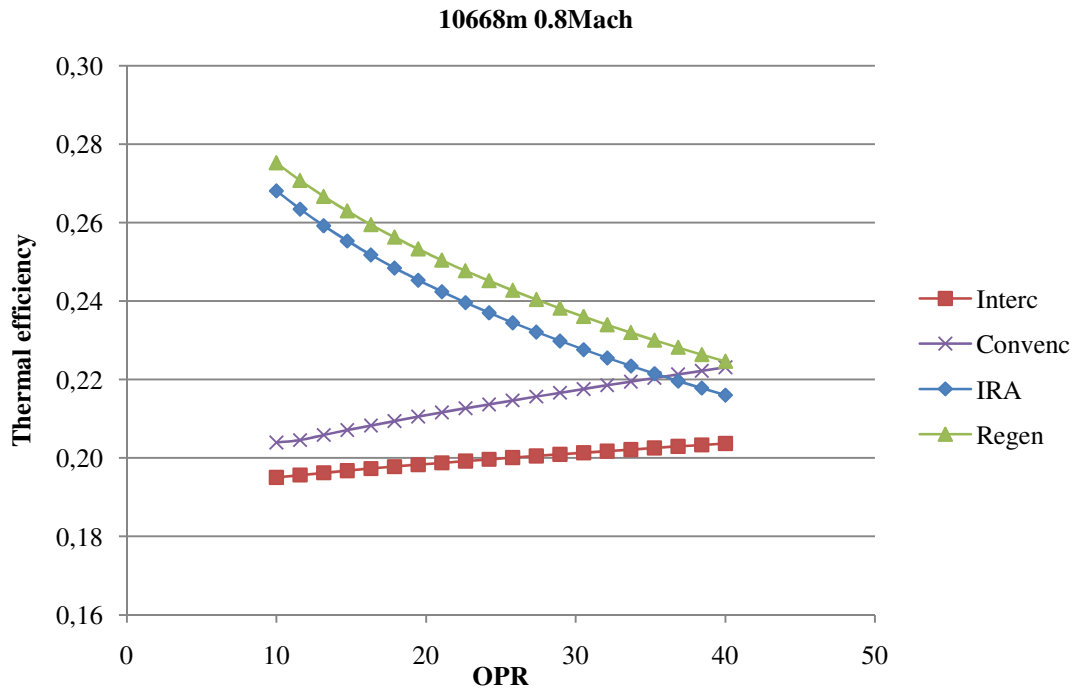


Figure 57: Thermal Efficiency vs Overall Pressure Ratio

6. Conclusions

The need for a new type of engine, cleaner and more environmentally friendly has been the leading force in aeronautical development. This thesis seeks to examine more generally the performance of four engines, each one with a different configuration. With this study are shown the different behaviors of the parameters on the design point. The configurations chosen were based on other studies that have shown the influence of the use of some components in the reduction of the specific fuel consumption and improvement of the engine performance. These components are heat exchangers strategically placed in the engine. The intercooler is a type of heat exchanger that is placed between the low and high pressure compressors. The air passes through the intercooler to be cooled before entering the high pressure compressor. This exchange of heat will cool the air and thus reduce the work required for compression. Thus the work of the high pressure compressor decreases with the introduction of this component. Another component that is used is a heat exchanger usually called the regenerator. This heat exchanger aims to heat the air leaving the high pressure compressor with heat from the exhaust gases. The introduction of this component reduces the fuel required in the burner. This reduction is due to the increase of the air temperature before entering the burner, reducing temperature difference between the entry and exit of the burner. So, the fuel needed is less. These two components have the goal to reduce the consumption, without changing the engine performance.

In this study were researched three configurations using these components and compared with the conventional engine. The conventional engine is an engine with two spools, three compressors and two turbines. The high pressure turbine transfers movement to the high pressure compressor, while the low pressure turbine transfers to the low pressure compressor and the fan. The various configurations studied consist of having or not the intercooler between compressors and use or not a regenerator.

Studying the design parameters it was possible to determine the design point for each configuration. For the different configurations the bypass value is 5. The overall pressure ratio is between 25 and 29 and the value of fan pressure ratio is between 1.71 and 1.75.

The plots obtained for the different types of engine configurations show that the engine with only intercooler is an engine with specific fuel consumption higher than the conventional one and lower thermal efficiency. This is due to the low output temperature in the high pressure compressor. The engine with intercooler and regenerator, IRA, is an engine with specific fuel consumption lower than the conventional one and a thermal efficiency higher. But it is not the one with better values of specific fuel consumption and thermal efficiency. The engine with only regeneration has the lowest values of specific fuel consumption and the highest for thermal efficiency. These two configurations have closer values of parameters.

The curves presented in the IRA configuration have similar behavior as the curves of the configuration with only regeneration. However, the IRA configuration has lower values of performance than the engine with regenerator. With this behavior can be deduced that the influence of the regenerator is larger than the intercooler for the range of parameters considered.

After this study it was possible to see the different influences of each configuration and design parameters in specific fuel consumption and thermal efficiency. So, the engine configuration with the best performance in terms of specific fuel consumption and thermal efficiency is the engine with regenerator. Despite the

drop in pressure at the nozzle exit this configuration showed to be the best for this type of engine.

7. Future Work

This thesis was the beginning of what shows the need to a more extended and deepened in respect of turbofan engines with two spools. The results obtained with this thesis show that this engine could be a good option to consider. The studies of these components and engines using these components are more extended for engines with three spools. A further thought related with this thesis could be, for example, the introduction of more parameters that had to be kept constant or not assumed in this work. One example is the power extraction in the shafts. In this thesis, these values were not undertaken due to lack of information of reference values.

Another example of possible future work concerns the optimization of these engines with especially attention for engine with regenerator and to check if the use of this component would affect extensively the engine performance. To optimize these engines, must be used an algorithm that might be able to optimize an engine, for a given specific thrust, for each type of engine configuration.

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Appendices