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Performance of a Turbofan Engine with Intercooling and Regeneration

J. Lebre, F. Brójo

***Abstract*—**Pollution emission levels of aircraft engines are a nowadays high concern. Any technological advance that could reduce emission levels is always welcome. In what concerns aircraft engines, a possible solution for this problem could be the use of regenerators and intercoolers. These components might reduce the specific fuel consumption, increase efficiency and specific thrust and consequently reduce the pollution levels of the engine. This is not a novel solution. These heat exchangers are already is use in stationary engines. For aircraft engines, the extra weight of the needed hardware could overcome the fuel saved. This work compares a conventional engine with configurations that use intercoolers and regenerators.

***Keywords*—**Intercooler, pollution, regenerator, turbofan

I. Introduction

A LONG time, the thrust demanded to an aeronautical engine has increased. To obtain these higher values, one must burn more fuel, which increase the pollutants produced by the engine. Nowadays, environmental considerations about aeronautical engines reduce the allowable pollution levels [1, 2, 3, 4, 5]. Accordingly, methods that could allow the increase in thrust, without compromising the pollution levels are being researched. For this study, the working parameters were varied and its influence in the usual performance parameters was verified. Intercooling is obtained by placing a heat exchanger between the low and high pressure compressors, allowing the inducted air to be cooled between compressions, reducing the work needed for the compression [6, 7]. Nevertheless, since the exit temperature of the air from the high pressure compressor is lower, there is more fuel needed to heat the working fluid to the same temperature. For the regenerator, it is placed after the turbine and before the propulsion nozzle and its function is to heat the compressed air before entering the combustion chamber, reducing the fuel consumed [8]. The problem now is only a matter of comparison between energy gains and losses by the use of these components. Calculations were made using the method defined by J. D. Mattingly in Aircraft Engine Design [9].

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II. Engines Studied

Aircraft engines can be classified according to several classifications. When the concern is the application, the engines with three shafts have high thrusts and are mainly used to medium and long-haul flights. The ones with two shafts (moderate thrust class) are used in short and medium-haul flights. For this study was considered a turbofan engine with two shafts, with a thrust of about 50,000 lbs, working with moderate values of Overall Pressure Ratio, Turbine Entry Temperature and Bypass Ratio.

TABLE I
EFFICIENCIES AND PRESSURE DROP OF COMPONENTS

Component	Values [9]
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)	0.6
Regenerator efficiency (ereg)	0.6
Difuser drop (π_d)	0.99
Fan nozzle drop (π_{nf})	0.99
Burner drop (π_b)	0.96

Several assumptions can be used in order to simplify the calculation work: steady and one-dimensional flow; perfect gas; isentropic bypass flow; without external mechanical power; with cooling air but not bleed; common efficiencies and pressures drop for the components (Table I) and standard atmospheric conditions.

The estimated values of the working parameters for a conventional engine, with two spools, turbine inlet temperature of 1500K, specific thrust of 200, cruise altitude of 10668 m and flight Mach of 0.8 are presented in Table II.

TABLE II
MAIN PARAMETERS FOR CONVENTIONAL ENGINE

Main Parameters	Values
Overall Pressure Ratio (OPR)	26
Fan Pressure Ratio	1.71
Bypass Ratio	5

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In what concerns the intercooled engine, the calculation method is similar to the one used in the calculation of the conventional engine. The main difference is the temperature drop between the low compressor exit and the high pressure inlet. In Figure 1, is shown schematically the intercooled engine.

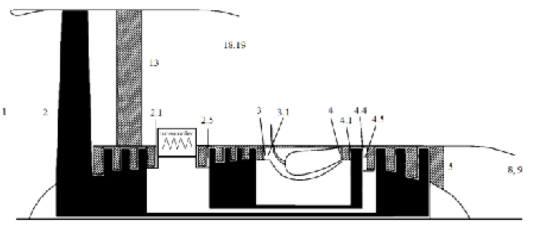

Fig. 1 Scheme and reference numbering of a turbofan engine with intercooling (Adapted from [1])

The Table III shows the main working parameters for the engine considered engine with intercooler.

TABLE III
MAIN PARAMETERS FOR ENGINE WITH INTERCOOLER

Main Parameters	Values
Overall Pressure Ratio (OPR)	29
Fan Pressure Ratio	1.71
Bypass Ratio	5

The exhaust gases temperature leaving the low pressure turbine is usually higher than the temperature of the air leaving the high pressure compressor, what allows transferring heat between the hot exhaust gases and the colder air in a counter-flow heat exchanger. This heat exchanger is commonly called a regenerator. Fig. 2 shows schematically a turbofan engine with regenerator.

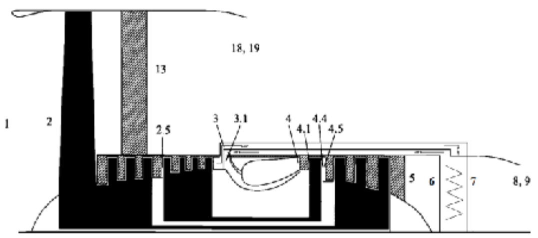

Fig. 2 Scheme and reference numbering of a turbofan engine with regenerator (Adapted from [1])

In Table IV are presented the main working parameters for a turbofan engine only with regenerator.

TABLE IV
MAIN PARAMETERS FOR ENGINE WITH REGENERATOR

Main Parameters	Values
Overall Pressure Ratio (OPR)	25
Fan Pressure Ratio	1.74
Bypass Ratio	5

The previously mentioned components (intercooler and regenerator) can be combined in one engine. The intercooler reduced the work consumed by the high pressure compressor and the increases the fuel consumed in the combustion chamber. The regenerator reduces the fuel consumed in the combustion chamber. In Fig. 3 is presented schematically the intercooled recuperated engine.

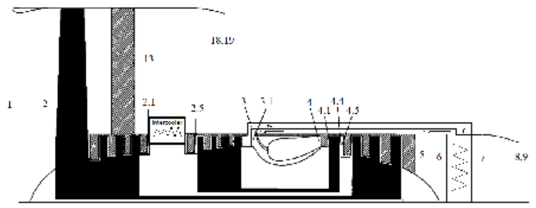

Fig. 3 Scheme and reference numbering of an intercooled recuperated engine (Adapted from [1])

Table V shows the main working parameters for an intercooled recuperated engine.

TABLE V
MAIN PARAMETERS FOR AN INTERCOOLED RECUPERATED ENGINE

Main Parameters	Values
Overall Pressure Ratio (OPR)	27
Fan Pressure Ratio	1.75
Bypass Ratio	5

III. RESULTS

Figures 4 to 10 present the performance parameters for the engines previously referred. Considered performance parameters are specific fuel consumption and specific thrust as function of several working parameters, as pressure ratios and bypass ratio. In what concerns the main parameters, their values are the ones presented previously. In Fig. 4 is presented the variation of the specific fuel consumption as function of the specific thrust for different values of bypass ratio. For the considered value of specific thrust, the engine with lower specific fuel consumption is the one with only regeneration. The engine with only intercooling has the worst results. The values for the minimum specific fuel consumption vary with the type of engine and the specific fuel consumption difference between the different engines becomes smaller with the reduction of the bypass ratio. 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.

The influence of the fan pressure ratio on the specific fuel consumption and specific thrust are shown in Figs. 5 and 6. For the specific fuel consumption (Fig. 5), the engine with intercooler has the higher value and the engine with only regeneration has the value. As seen in Fig. 6 the influence the intercooling and regeneration is negligible.in the specific thrusts. Nevertheless, the specific thrust increases with the

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increase of the pressure ratio, being the influence hiher for lower fan pressure ratios.

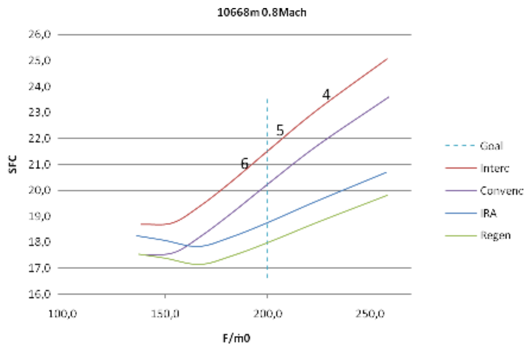

Fig. 4 Specific fuel consumption vs specific thrust

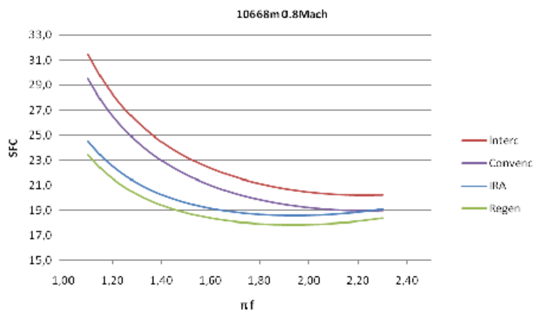

Fig. 5 Specific Fuel Consumption vs Fan Pressure Ratio

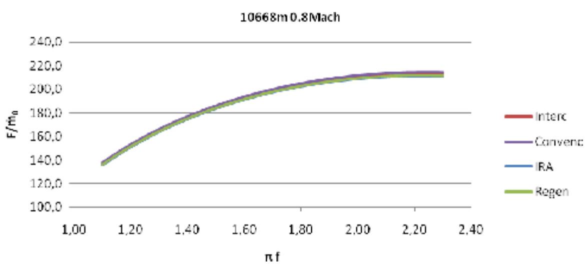

Fig. 6 Specific Thrust vs Fan Pressure Ratio

As expected and can be seen in Fig. 7, the specific fuel consumption for the conventional engine and the regenerated engine is not affected by the low pressure compressor ratio and consequently, in Fig. 8, 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 Fig. 8 can be seen that the specific thrust on all engines is above 200, thus fulfilling the requirements.

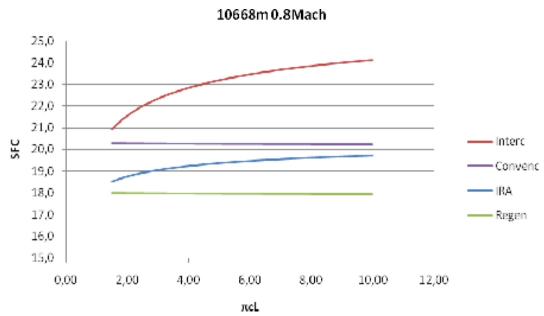

Fig. 7 Specific Fuel Consumption vs Low Pressure Compressor Ratio

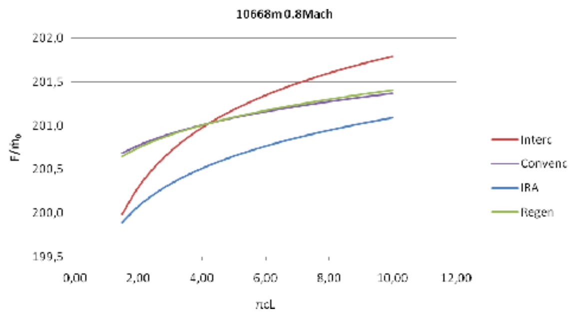

Fig. 8 Specific Thrust vs Low Pressure Compressor Ratio

A very important parameter in the design point is the overall pressure ratio. In Figs. 9 and 10 can be seen the influence of this parameter in specific fuel consumption and specific thrust. For the conventional and intercooled engines, the increase of overall pressure ratio decreases the specific fuel consumption, while for the engine with regenerator and intercooler and regenerator, the behaviors is just the opposite. For the specific thrust the behaviors is similar to all the engines, presenting a maximum. Nevertheless, this maximum value for the specific thrust is not the desired one for this study, because the overall pressure ratio, to the maximum value of specific thrust, is very low. If it had been selected, this value would lead to a significant change in engine parameters and thus failing to meet up the requirements.

Figs. 11 n 12 show the influence of the bypass ratio and overall pressure ratio in the thermal efficiency. The thermal efficiency is a parameter that increases with the use of the regenerator. Fig.11 shows 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.

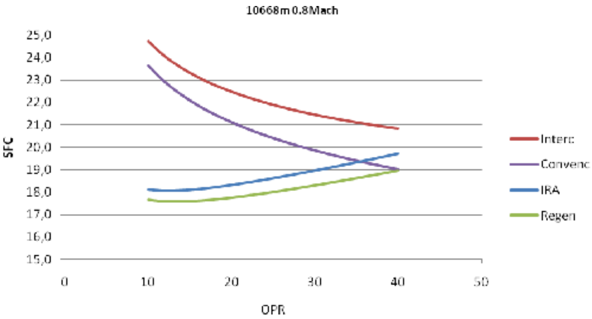

Fig. 9 Specific Fuel Consumption vs Overall pressure ratio

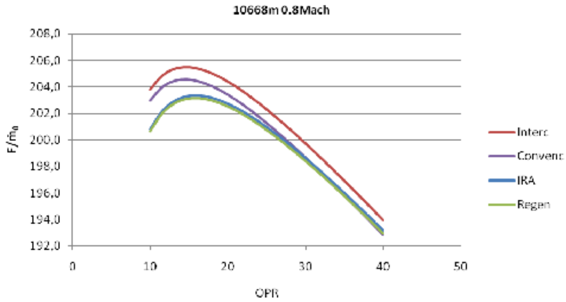

Fig. 10 Specific Thrust vs Overall pressure ratio

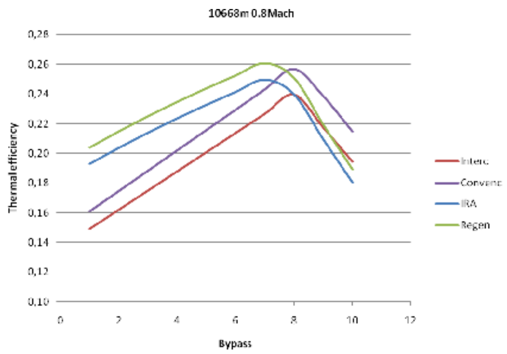

Fig. 11 Thermal Efficiency vs Bypass Ratio

In what concerns the overall pressure ratio and for engines that use 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 (Fig. 12).

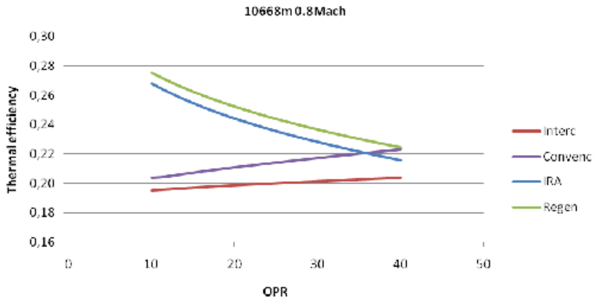

Fig. 12 Thermal Efficiency vs Overall pressure ratio

IV. Conclusions

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, IR, 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 for the IR configuration have similar behavior as the curves of the configuration with only regeneration. However, the IR configuration has lower values of performance than the engine with regenerator. By this behavior can be inferred 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. Accordingly, 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.

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