Thermodynamic Study of Intercooled and Regenerated Turbofan Engine

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Abstract

The need to increase engine power, without penalize too much the fuel consumption, in the civil aviation, has led to the development of very high by pass ratio turbofan engines. In this way the two aims described above have been reached increasing the propulsive efficiency as consequence of the high by pass ratio of the engines. In this work it has been considered the possibility to increase the efficiency of the engine modifying the working thermal cycle. In fact, by means of the development of a numeric thermodynamic code, it has been simulated the thermal behavior of a turbofan engine in which the practices of intercooling and regeneration are introduced.

Nomenclature

T	=	temperature	z	=	altitude
s	=	entropy	M0	=	fight Mach number
c_p	=	constant pressure specific heat	*TSFC*	=	thrust specific fuel consumption
c_v	=	constant volume specific heat	*I*	=	specific thrust (or impulse)
_	=	specific heat ratio	$\_{th}$	=	thermal efficiency
R	=	effectiveness of regeneration	*TET*	=	turbine entry temperature
E	=	efficiency of intercooling	I-R engine	=	turbofan with intercooling and regeneration
Th	=	engine thrust	ref. engine	=	reference engine (turbofan without intercooling and regeneration)
$\dot{m}_f$	=	fuel mass flow rate			

Introduction

In the development of new aircraft engines one of the most important target for the engineers is the achievement of very high performance characteristics without increasing fuel consumption too much. In fact the new generation wide body passenger aircrafts need engines generating such power levels never seen before, while the need to save fuel is not only dictated by economic reasons, but it is a necessity for the protection of the environment. Moreover in propulsion power systems the possibility to have engines of great power and low fuel consumption is of great importance since they affect directly payload and maximum range. Under a thermodynamic point of view the main aspects one can consider to increase those parameters are thermal efficiency and propulsion efficiency. For what concerns propulsion efficiency researcher have developed in the last years turbofan engines with always greater bypass ratio, so to minimize the kinetic energy of exhaust gas. Now the value of BPR is near its limit, and it is difficult to think to continue this trend indefinitely. Thermal efficiency has been raised during the years increasing the maximum cycle temperature, according to new turbine blade alloy steel availability, and pressure ratio. However also this way seems to be limited, and there is not much scope in further increase in temperature. The most feasible action one can think to rise the thermal efficiency is to change some features of the basic cycle, introducing some practices, as regeneration and intercooling, able to improve performances and reduce fuel consumption. These practices are widely used in ground based power plants, and their benefits in reducing fuel consumption and increasing output power are well known. In fact regeneration, recovering part of the heat available in the exhaust stream, otherwise lost, to pre-heat air from the compressor before it is introduced into the combustion chamber saves fuel, and consequently, considering negligible the reduction of output power due to the pressure loss in the heat exchanger, rises the thermal efficiency. However the presence of the heat exchanger introduces two main problems: the size and weight of the component (extra size and extra weight are always prohibited on an aircraft) and the complexity of the flow pattern. In fact it becomes possible to fit an heat exchanger in an aircraft engine only if you can count on a compact air-to-gas one. Obviously this problem is negligible in a ground based plant, where size and weight do not represent a limit and the coolant can be a liquid. Intercooling is a practice that reduces the compression work allowing as consequence more power available at the output shaft, or at the exhaust nozzle. In fact the compression work depends, among other factors, by the air temperature at the compressor inlet, in particular, in adiabatic compressors, it rises with it. Also intercooling is used in ground based plants, but it presents the same difficulties seen for regeneration to be transferred to an aircraft engine. Respect to regeneration the flow pattern imposed by the presence of the intercooler is less complicated, since the two flows do not need to be turned from rear to leading direction. However also the intercooler must be as compact as possible for the same reasons discussed above. To see if the advantages, in terms of reduction of fuel consumption and increase of output power, given by these two practices to the ground power plants can be transferred to a propulsion systems and how great they could be, we have developed a zero-dimension thermodynamic code to simulate the behavior of an aircraft gas turbine engine in which the two practices described above are introduced.

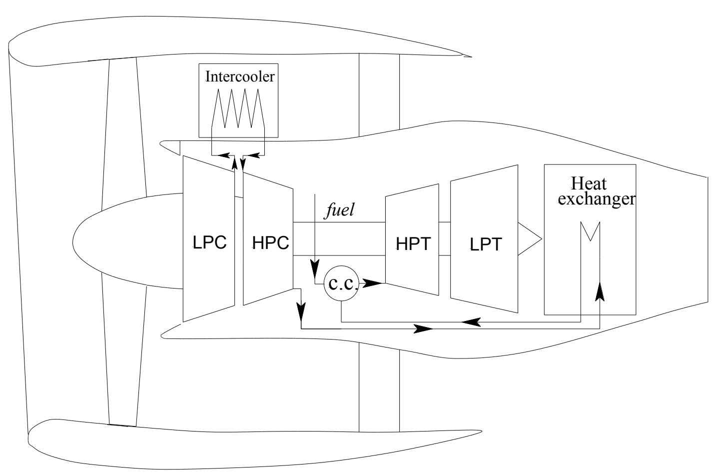

Fig.1 Scheme of a turbofan engine with intercooling and regeneration.

The code developed studies the influence of intercooling and regeneration on the performances of an aircraft gas turbine engine computing the thermal cycle of the engine, and hence obtaining the main engine parameters, as specific thrust, thermal efficiency, propulsive efficiency, overall efficiency and specific fuel consumption.

The engine analyzed is a turbofan engine at high bypass ratio. The choice to study this kind of jet engine comes from the fact that it is the most diffused jet engine in modern commercial aviation. Moreover, at high bypass ratio the majority of the thrust is provided by the secondary flow; in this case to recovery heat from the primary flow exhaust does not penalize too much the global thrust of the engine. Furthermore the large dimension of the fan allows to fit the intercooler without increasing the frontal section of the engine.

Figure 1 shows the scheme of a turbofan engine with intercooling and heat regeneration, and in figure 2 it is reported in a *T-s* (Temperature-Entropy) diagram its thermal cycle.

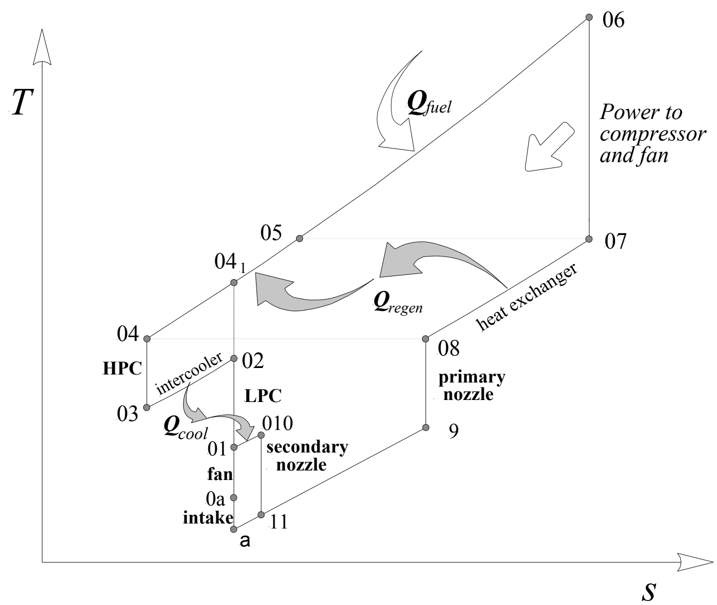

Fig.2 Thermodynamic cycle of a turbofan engine with intercooling and regeneration.

The numeric simulation has been done through a computational code written in FORTRAN 77 running on a personal computer. By means of the program it is possible to compute the thermal cycle of the engine for different engine characteristics, as pressure ratio, maximum turbine inlet temperature, component efficiencies, etc. and operating conditions, as altitude, flight Mach number (parametric study). In the developing of the numerical program some simplifications in the engine operations have been done: no air bleeding for auxiliary or cooling system, perfect gas, no auxiliary power extracted from the turbine. Although these assumptions seem not to be realistic, they have been chosen because the main aim of this analysis is not the design of the engine itself but to point out the differences in terms of performances and efficiencies between the reference engine and another in which intercooling and regeneration are introduced. As mentioned above perfect gas is the model chosen, but air and gas constant pressure and constant volume specific heat, c_p and c_v, and their ratio _ are not kept constant in the calculations but variable as function of temperature and humidity. Real component behavior has been simulated with the introduction of component efficiencies. In tab.1 are listed the component efficiencies used in the calculations.

Tab.1 Efficiencies of components used in calculations

Component	Value
Intake efficiency	0.960
Low pressure compressor polytropic efficiency	0.840
High pressure compressor polytropic efficiency	0.840
High pressure turbine polytropic efficiency	0.900
Low pressure turbine polytropic efficiency	0.900
Primary nozzle adiabatic efficiency	0.970
Secondary nozzle adiabatic efficiency	0.970
Intercooler efficiency	0.6
Recuperator efficiency	0.6
Intercooler pressure drop (both sides)	5%
Recuperator pressure drop (both sides)	5%

Results

In fig. 3 are reported the results of the numeric simulation in terms of specific thrust (thrust per unit mass flow rate) of the cycle, expressed in seconds. The graphics are computed at an altitude of 10000 meters with flight Mach number of 0.85 (cruise conditions). The maximum turbine entry temperature TET is in one case 1300 K, and in the other 1500 K. The curves are plotted as function of the compressor over all pressure ratio (the actual pressure ratio between high pressure compressor exit and external conditions is greater than that indicated in the graphics because of the inlet ram effect).

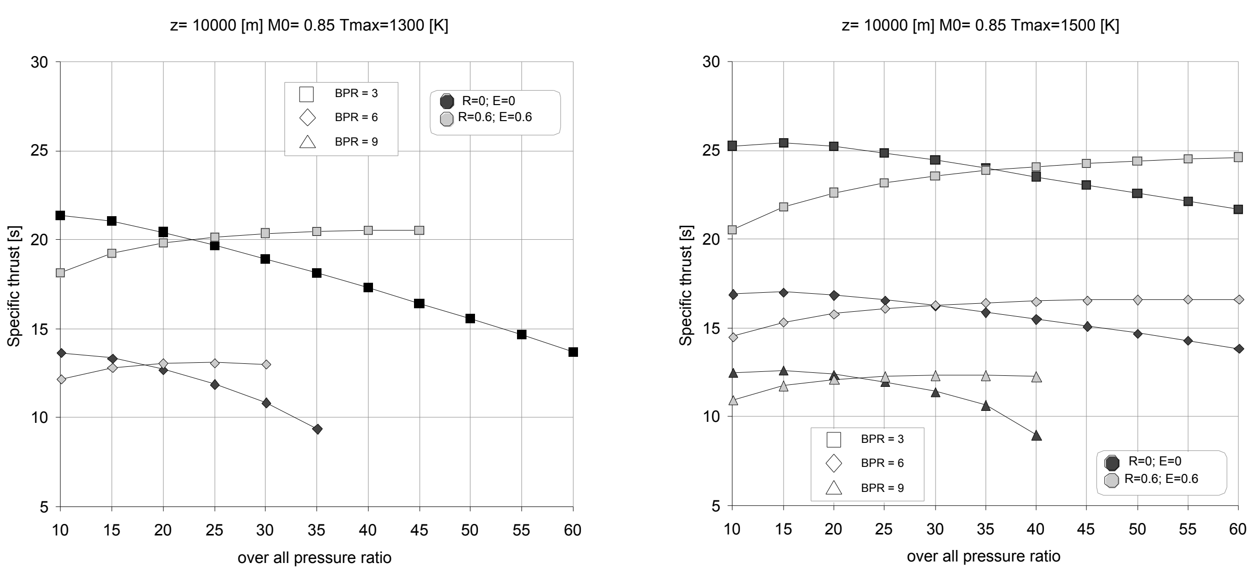

Fig.3 Specific thrust as function of pressure ratio and BPR for the two engines for two values of Turbine Entry Temperature.

The graphics represent the behavior of a conventional turbofan engine (reference engine, black mark graphics) and one in which both intercooling and regeneration are present (I-R engine, grey marks). At both temperatures three values of by pass ratio (BPR) are considered: 3, 6 and 9. It has to be noted that the choice of these range of temperatures and BPR has been done to represent actual engines, and so considering intercooling and regeneration as changes on actual technology turbofan engines. The cycles computed are real and not ideal, and this through the introduction of component efficiencies as reported in Tab.1. The fan pressure ratio as been kept constant in all cases at 1.70. The efficiency of intercooling and regeneration are defined as the ratio between the actual amount of heat transferred from the hot fluid to the cold and the maximum amount of heat that could be transferred between the two fluids in an ideal heat exchanger of infinite exchange surface and with counter flow arrangement. The values 0.6 chosen for both intercooler and heat exchanger are not vary high. However we must consider that the value depends, among other factors, on the size of the components. It is difficult to think of reaching the same efficiencies of ground based power plants, since the size and weight of such heat exchangers should be too great for an aircraft. This is the main reason for which in the simulation it has been chosen a relatively small value of effectiveness.

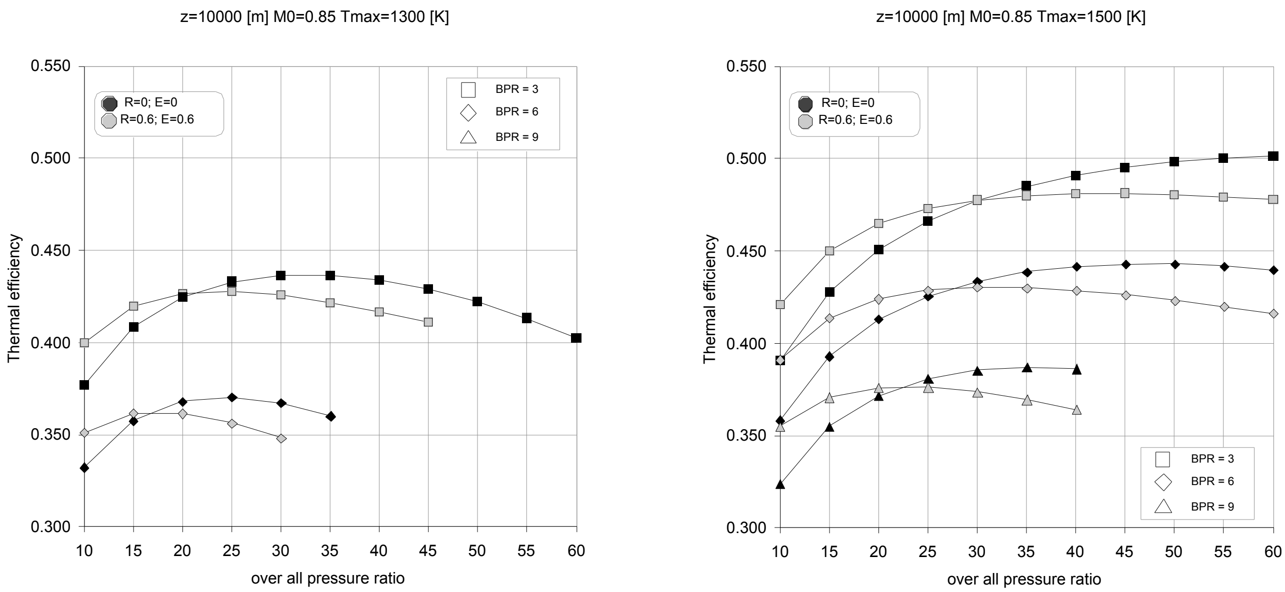

Fig.4 Thermal efficiency as function of pressure ratio and BPR for the two engines for two values of Turbine Entry Temperature.

In the graphics at 1300 K we notice as the curves at BPR = 9 are not reported. This because 9 of BPR is too large for that set of conditions, in particular the TET is not high enough to allow the low pressure turbine (LPT) to drive the fan. We notice also that at BPR = 6 the reference engine specific thrust is computed only until an over all pressure ratio of 35: also in this case the power adsorbed by fan and compressor becomes too high, and the TET is too low to supply it. The curves of the I-R engine are interrupted at a pressure ratio of 45 for BPR = 3 and 30 when BPR is 6. This because at larger pressure ratios the gas temperature at the low pressure turbine exit is lower than that of the air at the high pressure compressor exit and so heat regeneration becomes impossible. At TET of 1500 K only the curves at BPR = 9 are interrupted at 40 of over all pressure ratio. Looking at the graphics we notice as the specific thrust of the reference engines have their maximum at low pressure ratio (10 at 1300 K and about 15 at 1500 K of TET) and then decrease with pressure ratio. The I-R engine shows opposite behavior respect to the pressure ratio: specific thrust is small at low pressure ratio and then rises with it. This because at low pressure ratio the intercooling effect is small while in the regenerator a great amount of heat is exchanged. So the effect of regeneration prevails against intercooling and the specific thrust is reduced (regeneration reduces the core engine exhaust

velocity). As the pressure ratio rises the effect of regeneration vanishes (the amount of heat exchanged is reduced with pressure ratio) while the heat transferred in the intercooler becomes great, reducing considerably the compression work. The maximum values for the two engines are similar, slightly higher the values of the ref. engine at 1300 K, and at low BPR (3 and 6) at 1500 K.
In fig.4. are reported, for the same operating conditions described above for the specific thrust, the graphics regarding the behavior of the thermal efficiency.
We see that at low pressure ratio the I-R engine has better performances at both temperature, while as pressure ratio rises, the ref. engine behaves better. Also for what concerns the thermal efficiency these features of the curves are due to the effects of intercooling and regeneration. At low pressure in fact, the effect of intercoling is small while the heat regenerated is high. We must remember that the thermal efficiency of a gas turbine cycle with intercooling is lower than that of the base cycle. As the pressure ratio rises the heat exchanged in the intercooling increases, and consequently the effects of intercooling becomes great, while the heat transferred in the regenerator vanishes. For this reason at high pressure ratio the ref. engine has thermal efficiency higher than I-R engine. The pressure ratio at which the two engines have the same thermal efficiency depends on temperature and BPR. We can see that at 1300 K this happens at about 15 – 20, while at 1500 K the points at same value are between 20 and 30.
Another important aspect to consider comparing the two engines is the propulsion efficiency, that can be considered as the effectiveness with which the mechanic energy developed by the engine is converted into thrust power. In the graphics of fig.5. are reported the behavior of propulsion efficiency for the two studied engines.

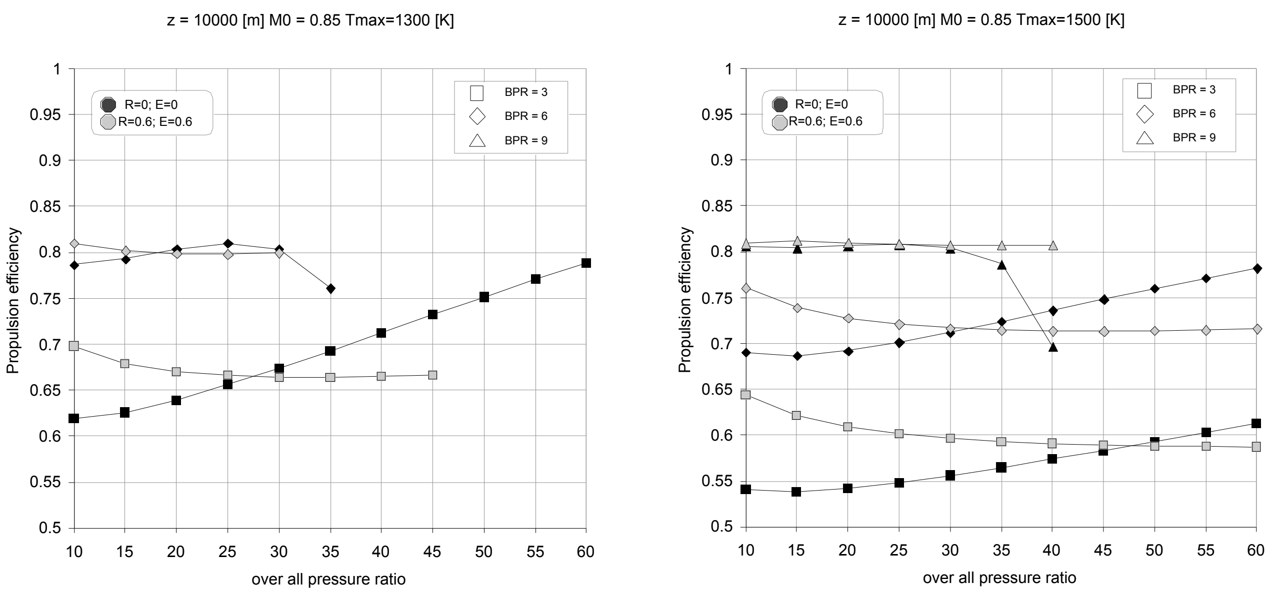

Fig.5. Propulsion efficiency as function of pressure ratio and BPR for the two engines.

We notice as at low pressure the I-R engine has efficiency higher than the ref. engine. As the pressure ratio rises the behavior changes, and the ref. engine reaches higher values. At high BPR (6 at 1300 K and 9 at 1500 K) the behavior is very similar and at 1500 K and BPR = 9 the two lines nearly clash. We notice as the lines at 1300 K BPR = 6 and at 1500 K BPR = 9 sharp decay after 30 and 35 of pressure ratio respectively, while the corresponding I-R engine lines remain nearly constant. This because the specific thrust of the ref. engine, as shown in fig.3, at those pressure ratio becomes very small, while in the I-R engine maintains the same levels. As over all effect of the specific thrust, thermal efficiency and propulsion efficiency we can obtain the behavior of the specific fuel consumption (TSFC), defined as the fuel mass flow rate per unit thrust:

$$TSFC = \frac{\dot{m}_f}{Th}$$

In fig.6 they are reported the graphics of TSFC at the same operating conditions above discussed. If we look at the graphics at 1300 K we notice as the ref. engine, both at 3 and 6 of BPR has lower values respect than of the I-R engine. Only at very low pressure ratio (10 -15) the I-R engine has better behavior. As the pressure ratio grows the TSFC of the I-R engine rises slightly, while that of the ref. engine reduces.

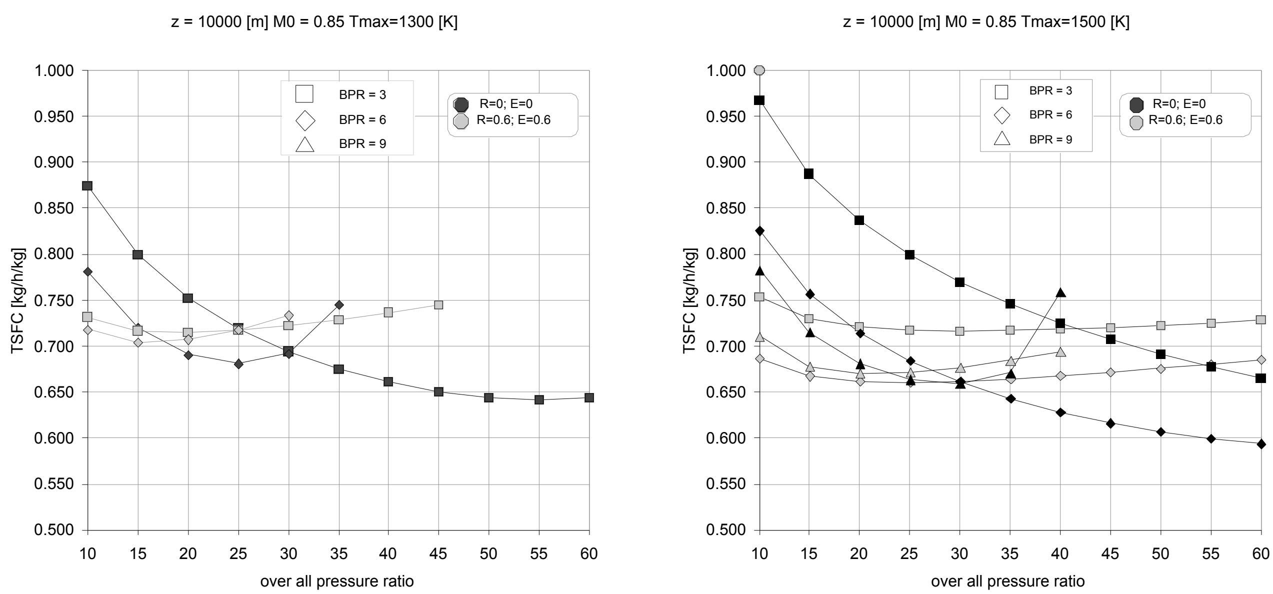

Fig.6. Specific fuel consumption as function of pressure ratio and BPR for the two engines.

It is interesting to note as the case at BPR = 6 shows a marked minimum at 25 of pressure ratio, while the case at BPR = 3 has its minimum at very high pressure ratio (about 55). We can also notice as the curves of the I-R engine are more flat over the whole range. A similar behavior is shown by the curves at 1500 K, although in this case the I-R engine has lower TSFC values at low pressure in a wider range (until about 25). The lowest values of TSFC for the I-R engine at 1500 K are in the case at 6 of BPR, over the whole range of pressure. However the curves at 6 and 9 of BPR are very closed to each other. Also the two minimums of the curves are about at the same value of pressure ratio: 20 – 25. The curve at BPR = 9 of the ref. engine has a behavior similar to that at 1300 K and BPR = 6: after a minimum at 30 of pressure ratio it increases rapidly as pressure ratio rises (see point at 40 of pressure ratio). This depends on the marked reduction of the impulse I (specific thrust) of the ref. engine after those values of pressure ratio. The cases with intercooling and regeneration instead, have a much more smooth behavior, without pronounced minimums, since their impulse remains nearly constant (it slightly increases) also at high values of pressure ratio, as shown in the graphics of fig.3.

Comments

The analysis carried on until now has shown as the simultaneous introduction of the practice of intercooling and regeneration can have good effects on the performances and the efficiencies of a turbofan engine at cruise conditions. However has also put in evidence as these good effects can be limited to more or less narrow range of operating conditions. This mainly because the introduction of intercooling on one side increases the performances, but, on the other side, it increases the fuel consumption (its effect is similar to that of afterburning in a jet engine). A double side effect is also caused by regeneration: it recovers heat, but at the same time reduces the enthalpy level of the core engine jet, lowering the exhaust velocity and hence the thrust. This effect is negligible in a turboprop engine, since the core engine jet provides a small thrust, and the heat subtracted can be considered as a net gain, not affecting greatly the over all performances of the engine. Starting from this consideration the study done should be carried on considering higher values of BPR and, consequently, higher values of turbine entry temperatures, so to make some features of the high by pass turbofan engine more similar to those of a turboprop engine. Another fundamental aspect to consider is the efficiency of intercooling and regeneration. Of course if we consider higher efficiencies in both practices the specific fuel consumption of the I-R engine is greatly reduced, becoming lower than the ref. engine practically at any pressure ratio. It becomes then interesting to evaluate, for a fixed set of engine conditions, as BPR and TET, which values of intercooling and/or regeneration efficiency must be reached to have considerable reduction of fuel consumption.

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