Main Performances of a Turboprop Engine With Heat Exchange and Intercooling

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Abstract

In many modern gas turbine engine ground based power plants, utilized for the production of mechanical power, several auxiliary systems are integrated with the main gas generator with the aim to improve the generated output power or to reduce the fuel consumption. Two of the most important practices used to achieve these goals are regeneration and intercooling. The first consisting in recovering part of the enthalpy present in exhaust gas to pre heat air before introducing it into the combustion chamber, the second consists in cooling the air during the compression process so to reduce the compression work needed, and consequently obtaining more power at the output shaft. A thermodynamic cycle analysis is performed to put in evidence the advantages, in terms of power increase and fuel consumption reduction, of the introduction of regeneration and intercooling in a turboprop engine.

1. Introduction

Many efforts of gas turbine engine designers are in the direction to increase the power attainable without increasing the fuel consumption too much. This is more needed in propulsion power systems, where it is of great importance to have engines of great power and low specific fuel consumption, since these 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. 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.
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2. Thermal Analysis

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, propulsion efficiency, overall efficiency and specific fuel consumption. The engine analyzed is a turboprop engine, and this mainly for two reasons: the first is that its smaller mass flow rate respect the jet engines has good benefits on the size and weight of the intercooler and heat exchanger, that can be smaller and lighter; the second is because in a turboprop engine the heat recovery from the exhaust gas is practically a net advantage because its expansion in the discharge nozzle provides a very little propulsion power respect the propulsion power provided by the propeller. This should be different in a jet engine where all the propulsion power is provided by the exhaust gas. In the analysis carried in this work we will consider that the enthalpy drop available for propulsion will be assigned completely to the power turbine, and no fraction to discharge nozzle. This for not complicating too much the numeric analysis and to point out the limits these practices can achieve. Moreover this scheme represents the way of functioning of a turboshaft engine, and can be considered the limit a turboprop tends to when the enthalpy drop in the exhaust nozzle vanishes. Figure 1. shows the *T-s* diagram of a turboprop engine with intercooling and heat regeneration thermal cycle. The far stream flow (state *a*) is compressed through the intake and the compressor to state 02, where 0 indicates the stagnation state. The compression process is divided in two stages: first stage *a* – 02, second stage 03 – 04. Between the two stages the flow passes through an heat exchanger (intercooler) where the amount of heat Q_{cool} is transferred to external air. This procedure lower air temperature before the second stage compression, allowing to reduce the compression work to increase air pressure from state *a* to final pressure 04. In fact if we consider the conventional compression process from 02 to 04_1, where points 04_1 and 04 have the same stagnation pressure, the compression power is given by:

$$W_{conventional} = m_a c_p T_{02} \left(\pi_{II}^{(\gamma-1)/\gamma} - 1\right); \qquad W_{intercooler} = m_a c_p T_{03} \left(\pi_{II}^{(\gamma-1)/\gamma} - 1\right) \qquad (1)$$

Where π_{II} is the common pressure ratio of the second stage compression. Since T_{03} is smaller than T_{02} the power needed to increase the pressure in the second stage after the intercooler is less respect the conventional case.

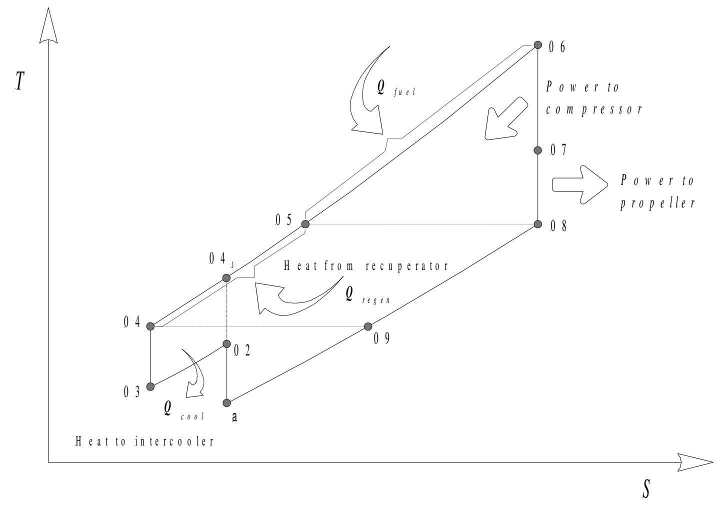

Fig.1 *Thermodynamic cycle with intercooling and regeneration.*

To reduce the compression work is important because it increases the power available for the propeller. In fact the enthalpy drop that turbines have at their disposal must supply power to both compressor and propeller; reducing the power needed by compressor we can give more power for the propeller, that means for propulsion. This is the main reason why intercooling is adopted in ground based power plants: to increase output power. However there are not only advantages in staged-cooled compression process. In fact, since we lower air temperature to the level 04 (see fig. 1), we need extra heat (Q_{extra}) to rise air temperature until the value 04_1, that should be the temperature level at the compressor exit in the cycle without intercooling. This lowers the thermal efficiency and consequently rises fuel consumption. We can see it also considering that with intercooling we add the cycle 02-03-04-04_1 to the basic cycle a-04_1-06-08. Since the added cycle is of the same type of the basic cycle but with smaller pressure ratio, it has lower thermal efficiency, and hence the thermal efficiency of the composed cycle is lower than the basic cycle. We can say that intercooling has the same effect of afterburning on the performances of gas turbine engines: to increase both output power and fuel consumption. We can see an analogy between afterburning and intercooling: in the first case we introduce heat at *lower* pressure respect the main cycle, in the second we remove heat at *higher* pressure respect the basic cycle. Both these heat exchanges reduce the efficiency. The amount of heat we need to increase air temperature at the compression second stage exit is:

$$Q_{extra} = m_a c_p(T_{041} - T_{04}) \qquad (2)$$

We need extra fuel, and hence the specific fuel consumption growth, to provide extra heat, unless we find inside the cycle another heat source available: this source is exhaust gas and the procedure to recover the heat available in the exhaust is regeneration. By means of regeneration we can recover the heat available in the gas after the expansion in the power turbine (station 08 in fig.1) and utilize this heat to pre heat air from compressor exit (station 04) before introducing it into the combustion chamber (point 05), without burning fuel. In this way the simultaneous utilization of intercooling and regeneration allows to increase the specific power attainable by the engine without increasing fuel consumption.

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 γ 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.

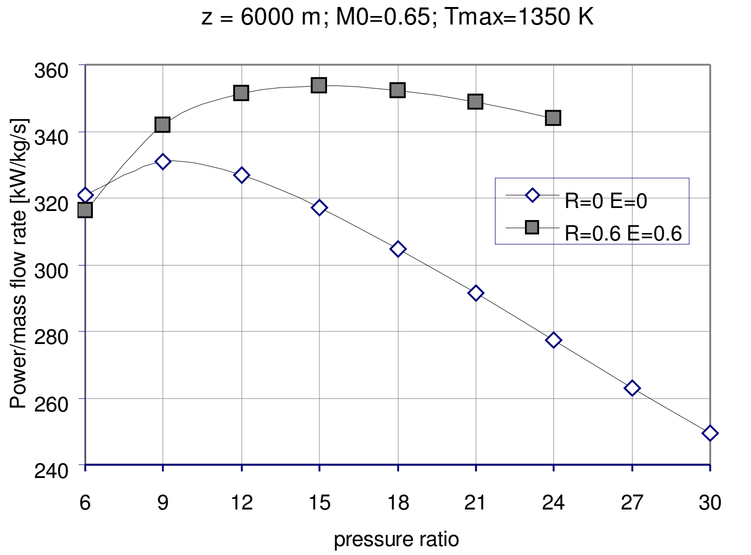

Fig.2 *Output power per unit mass flow rate (kW/kg/s) as function of pressure ratio for a conventional turboprop and one with intercooling and regeneration.*

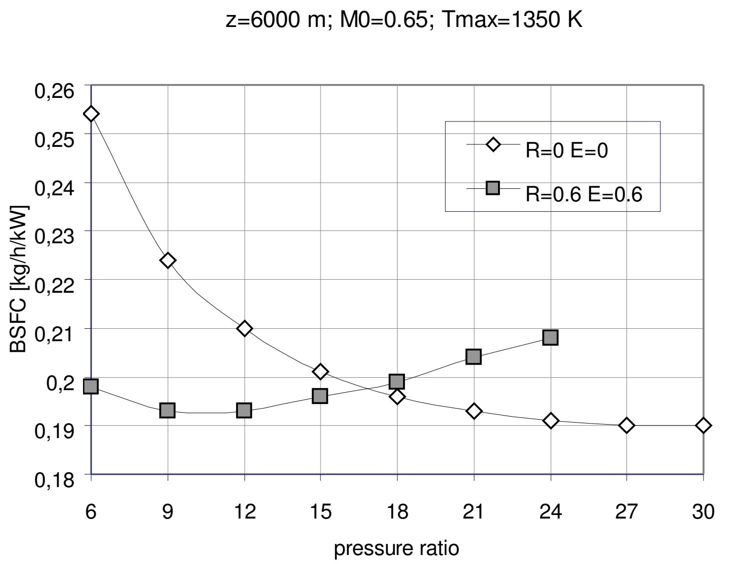

Fig.3 *Specific fuel consumption as function of pressure ratio for a conventional turboprop and one with intercooling and regeneration.*

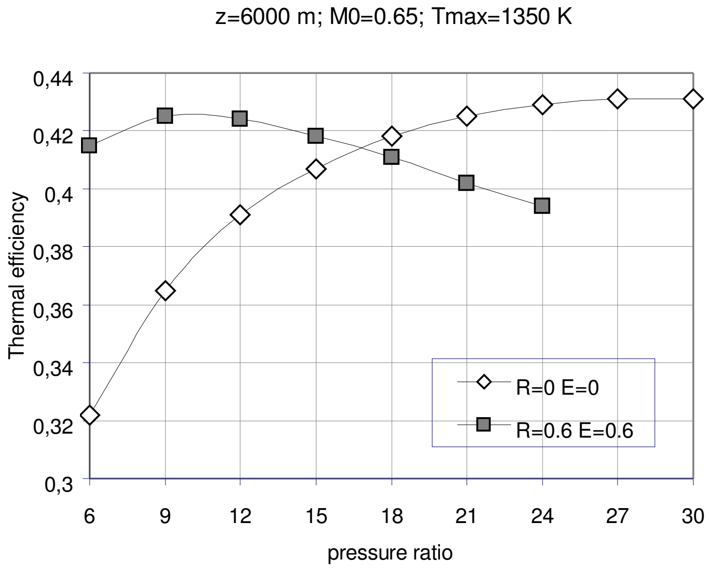

Fig.4 *Thermal efficiency as function of pressure ratio for a conventional turboprop and one with intercooling and regeneration.*

In figs. 2, 3 and 4 are reported the results of the numeric simulation, in terms respectively of out put power for unit mass flow rate, specific fuel consumption and thermal efficiency of the cycle. In the graphics are reported two lines: one of the reference engine, that means a conventional turboprop engine, without intercooling (E=0) and regeneration (R=0). The other lines represent the behavior of a turboprop engine in which intercooling and regeneration are adopted. In this case it has been chosen an efficiency of intercooling and of regeneration equal to 0.6 (E=0.6 and R=0.6). 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 operating conditions are the same for both engines: altitude is 10000 meters, flight Mach number is 0.65 and turbine inlet temperature is set at 1350 K. The graphics of fig.2 show as the specific output power of the engine with intercooling and regeneration is greater respect the reference engine, and this difference becomes bigger as the pressure ratio rises. This effect is due to the intercooling process, since the heat exchanged in the intercooler is greater as the pressure ratio grows. The regeneration practically does not influence the output power, except for what concerns a little decrease due to the pressure drop through the heat exchanger. The graphics of fig.3 show as the specific fuel consumption of the intercooled and regenerated engine is smaller at low pressure ratios and becomes greater at higher pressure ratios. In fact the practice of intercooling increases the output power but at the same time increases the fuel introduced into the cycle making the specific fuel consumption greater. However the extra fuel needed by intercooling is provided by regeneration, especially at low pressure ratios, where the amount of heat transferred in the heat exchanger is greater. In this case we have more power due to intercooled compression without the need of extra fuel; this explains the lower specific fuel consumption at low pressure ratios. As the pressure ratio rises the heat provided by the regenerator becomes smaller and at the same time the extra fuel needed by intercooled compression grows: this leads to higher specific fuel consumption at high pressure ratios. In fig.4 it is shown the behavior of thermal efficiency. Also in this case we notice as the engine with intercooling and regeneration has greater efficiency at low pressure ratios. The conventional turboprop engine reaches the same levels of thermal efficiency of the other engine but at high pressure ratios. We must notice as the graphics of the studied engine are not defined at pressure ratios greater than 24: this because for those pressure ratios air temperature at the compressor exit is higher respect gas temperature at the turbine exit and so regeneration cannot be practiced.

3. Conclusions

The thermodynamic analysis done has showed as the simultaneous introduction of the practices of regeneration and intercooling can lead to good results in terms of output power and fuel consumption. In fact thanks to regeneration it is possible to get the advantages in terms of power due to intercooling without spending extra fuel. This allows to reach higher power respect the reference engine but with the same level of BSFC. To obtain this results the engine must operate at low pressure ratio, otherwise both power and fuel consumption are increased. The main difficulties to obtain these advantages seem to be the size and weight of the two heat exchangers (intercooler and recuperator) and the complexity of the flow pattern. For this the engine that seems to be most suitable to the introduction of these practices is the turboprop, thanks to its relatively small mass flow rate. However also in high bypass ratio turbofan regeneration and intercooling could lead to good results.

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