DOI: 10.13009/EUCASS2025-562
11TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

THERMAL ANALYSIS OF RECUPERATED AND INTERCOOLED GAS TURBINE ENGINE

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Abstrtact

The reduction in the use of fossil fuels has pushed also the aeronautical sector to find new propulsion solutions, in particular electric propulsion. However, now this step is not completely possible, especially about larger airplanes that need to travel very long distances, as the weight of the batteries would be too high. For this type of airplane, the use of fossil fuels is still necessary. However, it is possible to think of reducing polluting emissions, in particular CO_2, by improving the thermodynamic operating cycle efficiency. In this sense, the recovery of part of the heat present in the exhaust gases, and the air cooling during the compression process, greatly reduce the fuel consumption and consequently the pollution. The aircraft engines that are most suitable for the use of these techniques are turboprops, and high bypass ratio turbofans. Through a calculation program that simulates the thermodynamic behavior of a turbofan engine, a parametric analysis was performed, for different engine and operating conditions. Hence the main propulsion parameters were calculated.

1. Introduction

Over the next 25 years, forecasts from various agencies indicate a significant increase in air traffic. Specifically, in Europe, the number of flights is expected to grow by between 1% and 2.4% per year. Since the end of the COVID-19 period, there has been a steady recovery in the number of flights, returning to pre-pandemic levels by the end of 2025. It is projected that by 2050, the number of flights will have increased by approximately 50% compared to 2023. The chart in Fig. 1 shows the projected increase in flights in Europe from 2024 to 2050, assuming two growth scenarios: Low 20% and High 78%, centered around an average forecast of 52% [1]. Moreover, in line with CO_2 emissions reduction targets, the aviation sector has set the goal of achieving fossil fuel emissions neutrality by 2050. The chart in Fig. 2 illustrates, based on the air traffic growth described in Fig. 1, the expected increase in CO_2 emissions under different scenarios of technological advancement and air traffic management over the same period.

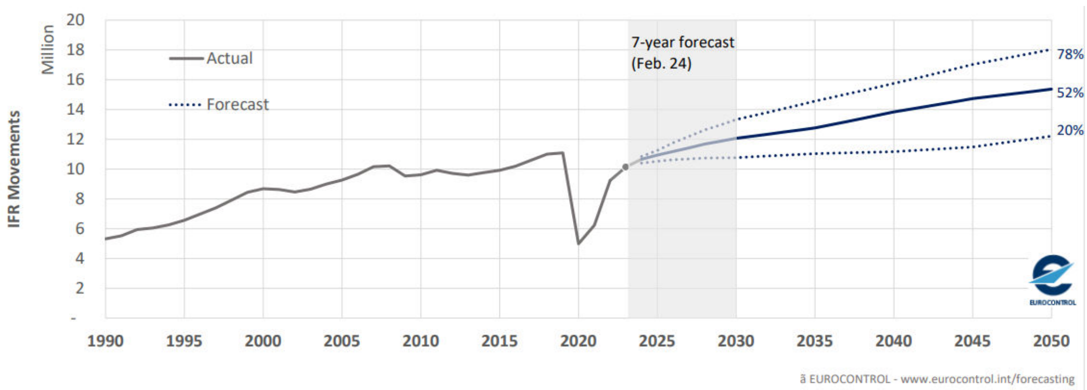

Fig. 1 Flight forecast for Europe, with total growth between 2024 and 2050 [1]

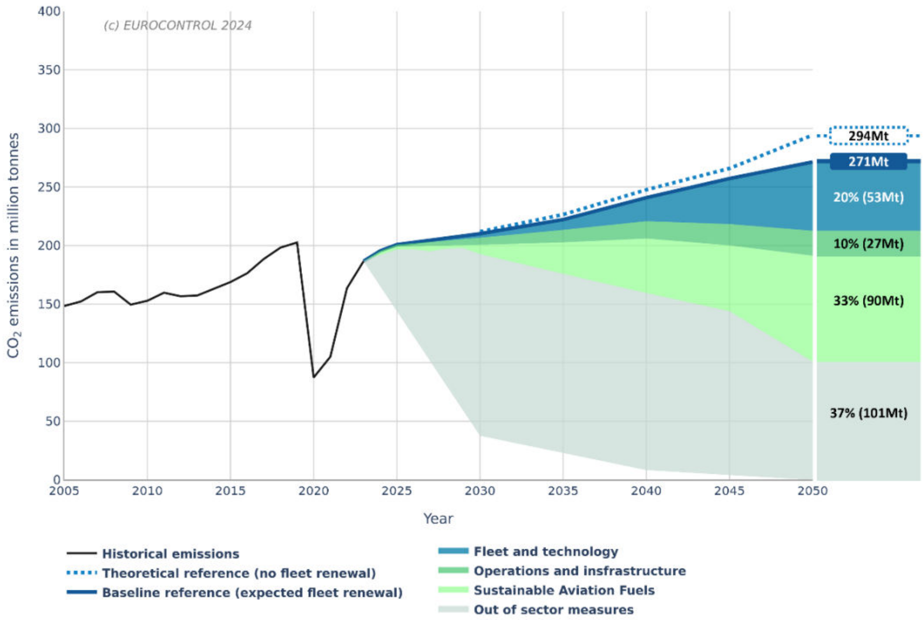

Fig. 2 Estimate of CO_2 emissions from 2005 to 2050, with potential reductions related to improvements in technology and operational conditions [1].

The chart shows how a significant reduction in CO_2 emissions related to air traffic can only be achieved through a combined use of various technologies, operational conditions, infrastructure, and new fuels for sustainable aviation. As in other sectors, one approach that has seemed immediately feasible is electrification. In this regard, electric motors are being developed with the aim of replacing existing internal combustion engines. However, a full electric motor requires an energy storage system (batteries) which, depending on the motor's power and flight duration, can be very heavy. Currently, the batteries available with the highest energy-to-weight ratio are lithium-ion batteries, with a specific energy of about 200 Wh/kg, which is significantly lower compared to the approximately 12,000 Wh/kg of jet fuel [2]. Figure 3 shows the specific energy values for different types of batteries [3].

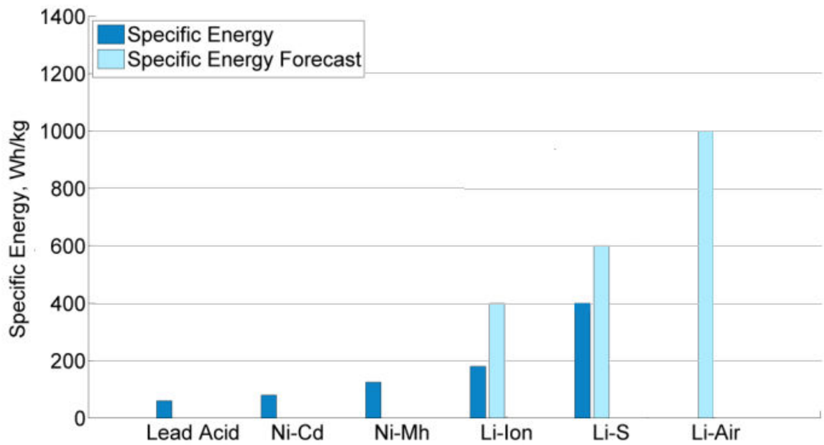

Fig.3 Mass specific energy characteristics (Wh/kg) of different energy storage systems (Adapted from [3])

For this reason, given the current state of energy storage system development, a fully electric airplane can only be used with limited power and for short-duration flights, typically small-sized tourist or regional aircraft for distances of a few hundred kilometers (Fig. 4).

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Fig.4 Small-sized aircraft for short-range flights of the full electric type.

The use of electric motors for higher power and longer flight durations is currently possible if coupled with an internal combustion engine, creating a hybrid motor. The reduction of pollutants, particularly NO_x and CO_2, can also be achieved through optimization of the combustion process, and use of biofuels. It is also evident that the main way to reduce pollutants is by lowering fuel consumption. In the field of ground turbines, some techniques are commonly used to reduce fuel consumption, and the main ones include the regeneration of heat from the turbine's exhaust gases, coupled with intercooled compression, which helps improve performance. These practices are certainly an effective method for improving the efficiency of gas turbine engines, reducing fuel consumption, and consequently decreasing pollutants, particularly CO_2 and NO_x. These techniques can also be applied in aviation, especially in turboprop and high bypass ratio turbofan engines. The biggest challenge to overcome in this case is the size and weight of the heat exchangers, which are not an issue in ground-based systems but become a problem on an airplane. In the past, there have been some implementations of regenerative engines, particularly turboprop engines [4-6], as these engines have a lower airflow than jet engines and thus require smaller heat exchangers (Fig. 5). Additionally, the thrust produced by the exhaust gases in a turboprop engine is much smaller compared to the thrust generated by the propeller, meaning that energy recovery from the exhaust gases is considered a net gain.

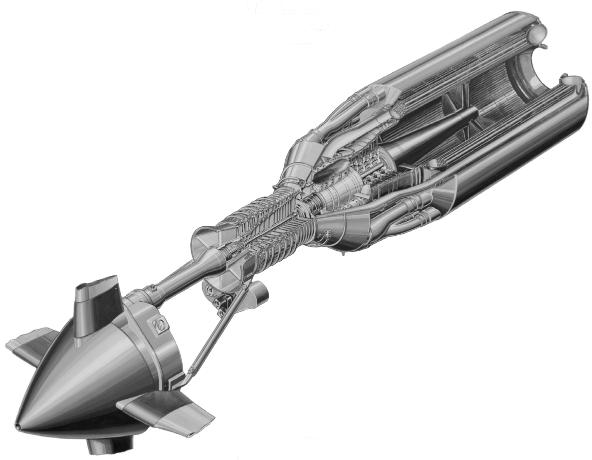

Fig.5 Layout of T78 recuperated turboprop engine (Source Allison Engine Company)

Currently, several studies are underway to develop engines with regeneration and intercooled compression. In particular, the NEWAC program – New Aero Engine Core Concepts, developed with the support of the European Commission and in collaboration with several European universities, research centers, and companies, has demonstrated the feasibility of creating a high bypass ratio turbofan engine with regeneration and intercooled compression. The goal, alongside the use of other techniques, is to reduce CO_2 and NO_x emissions [7-9].

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2. Heat recovery and intercooled compression

Figure 6 shows the diagram of a separate flow turbofan engine with exhaust gas heat recovery and intercooled compression.

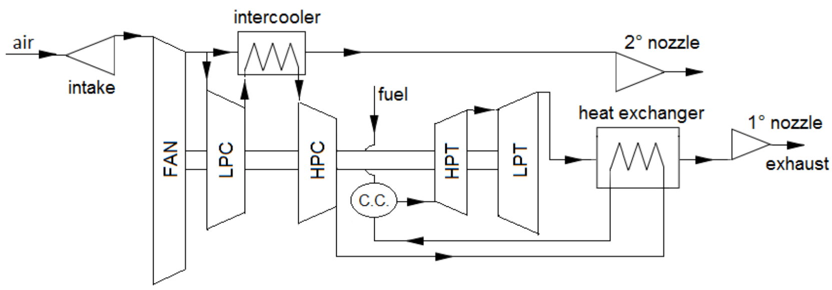

Fig.6 Diagram of a turbofan engine with regeneration and intercooled compression.

Through the development of a calculation program that simulates the behavior of the engine described in Fig. 6 by calculating its thermodynamic operating cycle, the main characteristics and performance have been determined as a function of various engine parameters and operating conditions. Figure 7 shows the thermodynamic operating cycle of the engine in a temperature/entropy diagram.

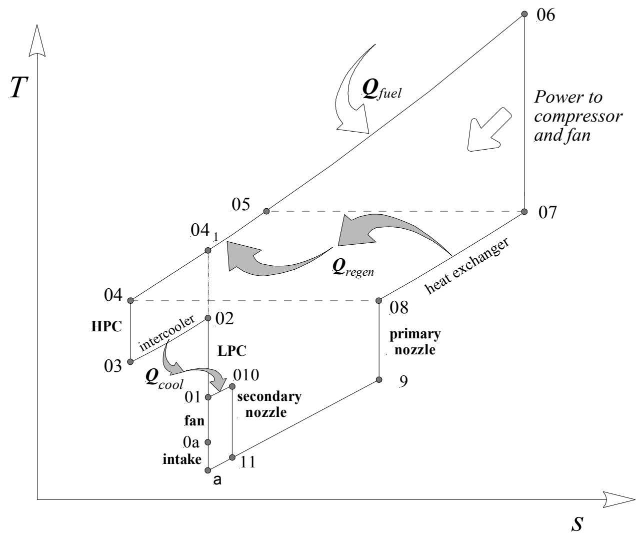

Fig.6 Thermodynamic cycle in a Temperature/Entropy diagram of a turbofan engine with regeneration and intercooled compression.

The compression divided into two stages, with cooling between the two stages, allows for a reduction in the compression work. This is, of course, an advantage, as it enables a higher temperature at the turbine exit, and thus a greater enthalpy drop available at the exhaust nozzle, resulting in an increase in thrust. Additionally, the heat removed from the air during compression is transferred to the secondary flow upstream of the exhaust nozzle, which, although limited in amount, increases the available enthalpy drop of the cold flow. However, since the air temperature at the exit of the second stage of the compressor is lower, a greater amount of fuel must be introduced to achieve the same turbine inlet temperature, leading to an increase in fuel consumption. Therefore, it can be said that the practice of intercooling allows for an increase in achievable thrust, but at the cost of higher fuel consumption. To balance this increase in specific fuel consumption due to intercooled compression, the practice of regeneration is introduced. This involves recovering part of the heat present in the exhaust gases to pre-heat the air before sending it into the combustion chamber. In this way, the amount of heat that needs to be supplied through the fuel, referring to the graph in Fig. 6, is given by:

$$Q_{fuel} = c_p(T_{06} - T_{05})$$

This represents a significant reduction compared to the case without regeneration, both in the case of single-stage compression, and even more so in the case of two-stage intercooled compression. The regeneration degree R is defined as the ratio between the amount of heat exchanged in the regenerator and the maximum amount that can be exchanged in a counterflow heat exchanger with infinite exchange surface:

$$R = \frac{c_p(T_{07} - T_{08})}{c_p(T_{07} - T_{04})}$$

3. Results

Through the calculation program, written in FORTRAN 77, the performance of a turbofan engine with regeneration and intercooled compression was calculated, varying the engine parameters and operating conditions. Figure 7 shows the trend of specific thrust (thrust per unit mass flow rate) for different values of intercooler cooling efficiency and regeneration degree. The cases for a conventional engine, without intercooling and regeneration (I=0, R=0), and the cases with intercooling and regeneration efficiencies of 0.7 and 0.8 are presented. The ideal case (I=1, R=1) is also shown, representing the limit that can be approached. The bypass ratios (BPR) considered are 6 and 9, the maximum turbine inlet temperature is 1500 K, and the operating conditions are a flight altitude of 10,000 meters and a flight Mach number of 0.85.

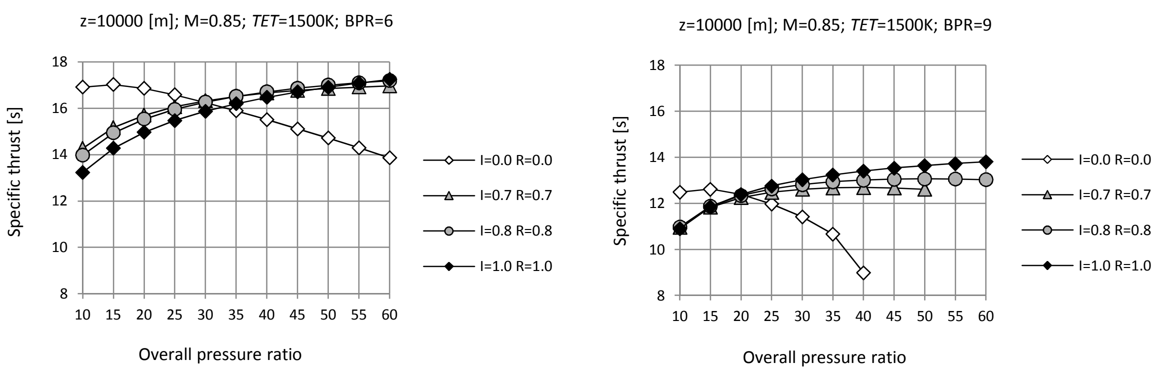

Fig.7 Specific thrust of a conventional turbofan engine (I=0, R=0), compared with one featuring regeneration and intercooled compression, with efficiencies of 0.7, 0.8, and 1, as a function of the overall compression ratio, with BPR values of 6 and 9. The altitude is 10,000 meters, the Mach number is 0.85, and the maximum temperature is 1500 K.

It can be seen that at low compression ratios, the conventional engine provides more power than the I-R engine. However, as the compression ratio increases, the trend reverses, and the I-R engine provides higher power. This is because at low pressures, the effect of intercooling is negligible, but the losses due to the presence of the heat exchanger reduce the power. As the pressure increases, the staged compression starts to show its effects, increasing the available thrust. The effect of regeneration on thrust is negligible, and its impact is only related to the pressure losses in the heat exchanger. Figure 8 shows the trends in specific fuel consumption (TSFC) under the same conditions as the graphs in Fig. 7. It can be seen that the I-R engine has a significantly lower specific fuel consumption compared to the reference engine, especially at low compression ratios. However, as pressure increases, the trend reverses. This is because, at low compression ratios, the amount of heat that can be exchanged in the regenerator is very high, while as the pressure increases, the temperature difference between the gas exiting the turbine and the air exiting the compressor becomes smaller and smaller, until it disappears, making heat transfer impossible. At low compression ratios, the reduction is still considerable, with values that can reach up to 20%, depending on the maximum temperature and the regeneration degree.

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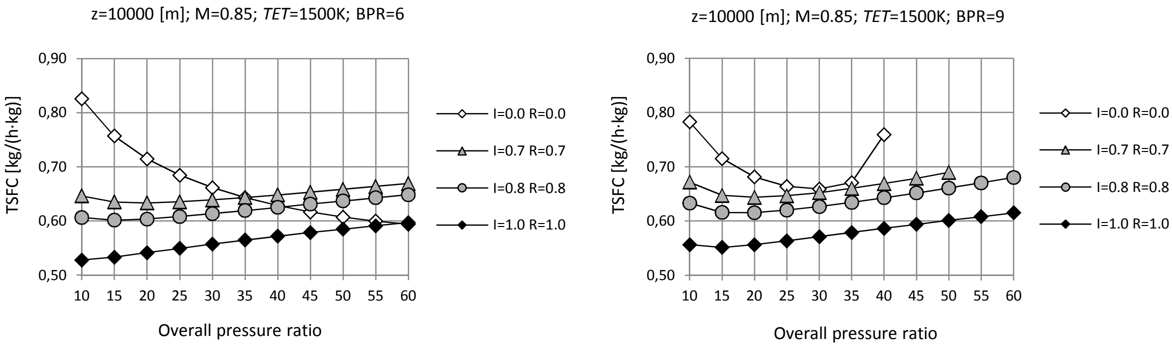

Fig.8 Specific fuel consumption (kg/h per kilogram of thrust) of a conventional turbofan engine (I=0, R=0), compared with one featuring regeneration and intercooled compression. The operating conditions are the same as those of Fig. 7.

4. Conclusions

The reduction of environmental pollution from aircraft engines must be achieved by addressing several aspects, such as the way flights are operated and the various infrastructures required, like airports, the development of new fuels that generate a low environmental impact, and, of course, technological progress related to the development of increasingly efficient engines. At the current state of technology, it has been shown that fully electric airplanes are not yet feasible for large aircraft and long-haul flights, but only for smaller aircraft and shorter routes. For long-haul flights, gas turbines currently do not seem replaceable. However, even gas turbines can be improved to reduce their environmental impact, particularly by reducing fuel consumption. In this regard, it has been shown that the practices of heat regeneration and staged compression with cooling offer valuable opportunities in this sense. In fact, the two associated practices allow for a significant reduction in fuel consumption without compromising performance. Of course, this requires considerable effort in terms of system design, related to the construction of heat exchangers and their integration into the engine architecture. The weight and size of the exchangers, especially if high regeneration levels are desired, represent the biggest challenge. However, technology has made significant progress in this field, and more compact and lighter exchangers than those from a few decades ago are now available. As for the weight penalty of the engine due to the presence of the exchangers, this is certainly offset by the reduction in specific fuel consumption, which allows for carrying less fuel on the aircraft.

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