HOT END TECHNOLOGY FOR ADVANCED, LOW EMISSION LARGE CIVIL AIRCRAFT ENGINES

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Abstract

The Paper describes key technologies within aircraft engine Combustion & Core Turbine Systems contributing to low emissions products, fuel efficient in the large civil aircraft engine market. Emphasis will be on the aerothermal, combustion, material & sub-system technologies, the corresponding demonstrator programmes and the technology incorporation into new engine architectures.

1 Introduction

Reducing aero engine emissions is of vital strategic importance to the industry, driven by tightening legislation, customer demands and competitive pressures. Large investments are being made in the combustion and controls technology needed to reduce NOx levels by at least 50%, relative to conventional technology. Low emissions, improved fuel efficiency and advanced temperature capability are a major goal of the Rolls-Royce three ongoing engine demonstrator programmes for 2 shaft, 3 shaft and Open Rotor architectures: “Advance3” for the 3 shaft engine family for wide-body aircraft, “Advance2” for the 2 shaft engine family for middle of market, corporate and regional and Geared Open Rotor engine family for “middle of the market”, see figure 1.

Beside the propulsive efficiency, which is in direct correlation to specific thrust or bypass ratio of an engine, the second main contributor to reduced fuel consumption and emission is the cycle, or thermodynamic efficiency. Gas turbines convert the energy from burning fuel into useable work via three main elements – a compressor, combustor and turbine. Work output increases with [1]:

- Higher overall pressure ratio
- Higher combustor exit temperature, restricted by the high temperature capability combustor and turbine components (with ultimate limits imposed by stoichiometry in combustion)
- More efficient secondary systems (cooling, sealing)

As gas turbines operate in a continuous thermodynamic cycle, they have a higher power density than internal combustion engines. In aero engines, the gas turbine can accelerate air to create thrust and power to drive the LP turbine system which drives the Fan system to generate the majority of the forward thrust. Figure 2 depicts the relative importance of propulsive and the thermal efficiency in this context. This paper will concentrate on the thermal efficiency improvement programmes, whilst the significant work on propulsive efficiency technology clearly exist and play a vital role but shall not be subject of this paper. Rolls-Royce aims continually to improve the efficiency of its products and the key components that they embody. There is a clear desire to increase component efficiencies and at the same time, reduce weight and cost in order to achieve the optimum technical solution. As can be seen from the range of the most recent products, from the 2000 until today, Rolls-Royce engines have reduced about -15% in fuel burn and improved CO2 emission respectively (see figure 3 a and b). The further emission reduction is supported by technology improvement, especially in the hot section of the engine (Combustion and Turbine systems) [2],[3].

The combustion section of this paper outlines the requirement for low emissions, and the route to achieving these goals. Theoretical and experimental evaluation of fuel injector and combustor design concepts has enabled a selection of a preferred architecture which is undergoing a multi-strand maturity programme, which will be described in overview [4].

In the hot section technology part of this paper the emphasis will be on technologies aiding the improvement of thermal efficiency.

The thermal efficiency of the engine is dominated by the capability of the hot section sub-systems (Combustors and core turbines) in terms of cooling flow consumption, performance and durability (life cycle), in combination with the maximum achievable turbine entry temperature. The key technologies for advanced hot section technologies will be evaluated. Aerothermal design concepts, materials and aspects of sub-system integration and cross sub-system optimisation will be discussed.

The third section of the paper will combine the strands of combustor and turbine technology programmes towards the combined assessment and validation of the technology benefits for the overall impact on large civil engines and will discuss future potential.

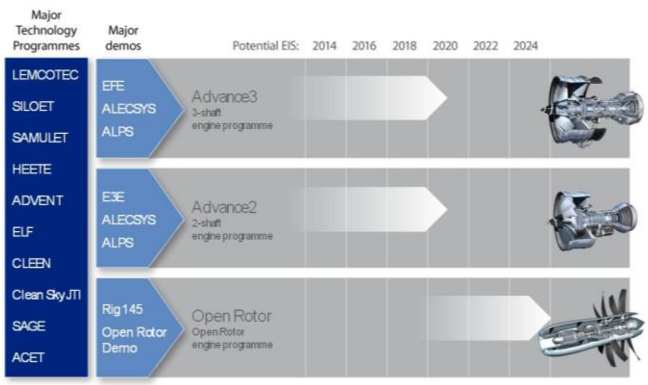


Figure 1: Future Engine Programmes of Rolls-Royce plc

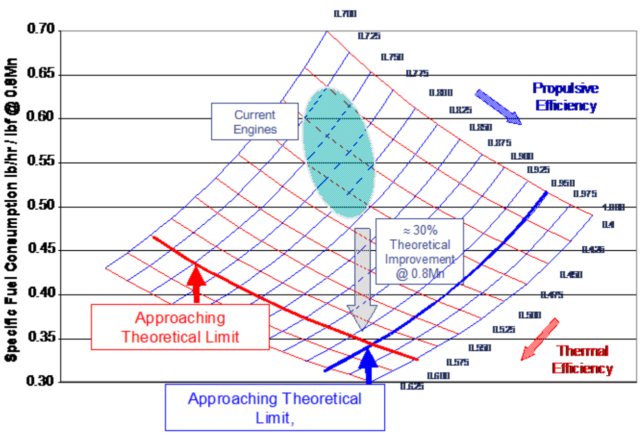


Figure 2: SFC as a function of propulsive and thermal efficiency

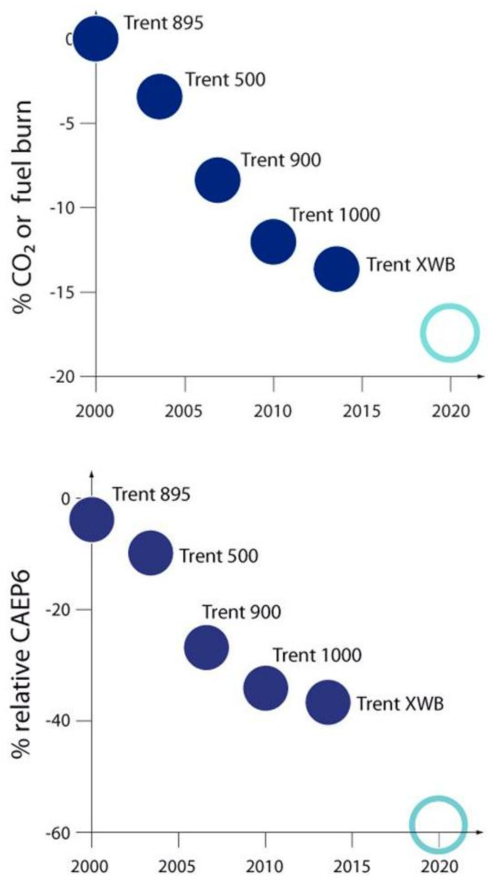


Figure 3: a) SFC/CO2 performance vs. ACARE target and b) % reduction of NOx emission relative to CAEP6

2 The Combustion Sub-System

Fuel and air are mixed and burned within the combustion chamber to convert chemical energy of the fuel into thermal energy within the gas-stream prior to entry into the turbines. The temperatures within the combustion chamber are the hottest in the engine - fuel is burned in the combustion chamber at temperatures of over 2000°C yet they are still expected to last the many thousands of hours of operation between overhauls. This requires substantial technology in the form of wall materials (both metallic and ceramic), coatings and manufacturing technology. In a conventional combustor, a rich diffusion flame is generated in the primary zone recirculation at the front end of the combustor. This rich zone provides a high level of resistance to flame out, keeping the combustor alight at low power conditions where the combustor overall is running very lean. Controlled introduction of air down the length of the combustor dilutes the mixture and enables most of the soot produced from the rich zone at high power to be consumed. However, as the mixture passes from the rich to the lean side of stoichiometric, there will always be regions of the combustor at the rapid NOx forming mixture strengths. It is important the time spent by the mixture in these regions is minimised. So called 'Phase 5' combustor technology employed throughout the Rolls-Royce Trent engine family, Figure 4, has successfully optimised this approach to control NOx to below currently proposed CAEP6 legislation levels.

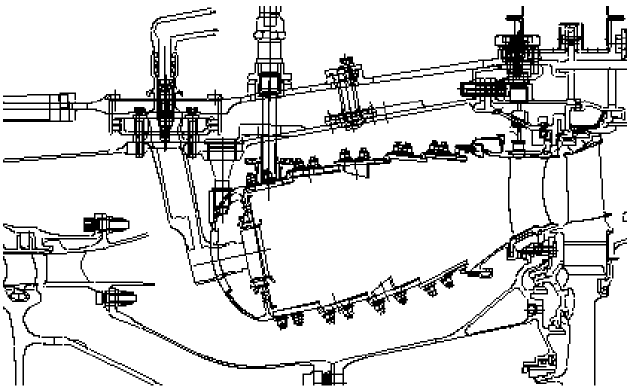


Figure 4. Trent 'Phase 5' tiled combustor and combustor design space & requirements

2.1 Combustion cooling

As mentioned earlier, the temperature of the gases released by the combustion process may peak above 2500 K with average temperatures of 2000 K. As this is much higher than the melting point of the combustion chamber and turbine materials all surfaces must be adequately cooled. Moreover, the amount of air used for cooling must be minimised in order to maximise the air available to the cycle, for emissions control or the turbine static components. Minimum pressure loss should be achieved in order to maximise overall engine performance, but sufficient pressure loss across the rear end of the combustor must be generated to drive a predetermined amount of cooling air through the turbine. Figure 5 gives an overview over various cooling styles used in combustion systems. Cost needs to be kept low, but cost is mainly seen as overall operating cost, not only initial or unit cost. Higher unit cost could be justified by a longer service life of a component. Safety in air-transport is paramount; hence a high durability for reliability, long life, and to minimised maintenance is required.

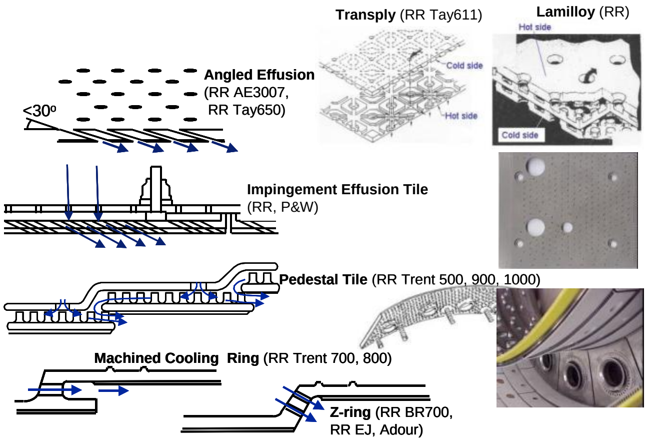


Figure 5: Various cooling styles (single- and double-skin)

A general requirement for every component of an aero-engine or an aircraft as a whole is low weight. For many applications, especially if the focus is on cost and weight, single-skin shallow-angle effusion cooling is selected. If the cooling performance of effusion cooling alone is deemed not to be sufficient, an intensified rearside cooling via impinging air or increased surface area of internal channels of a transpiration cooling sheet is seen as the logical addition. Ceramic matrix composites (CMC) are being investigated as a potential future combustor material. CMC technology has had great potential for many years, see Figure 6, and CMC components have been run in several demonstrator engines. CMC components are successfully used in the exhaust section of some military engines (flaps & seals, mixers/diffusers), but to date, there is no core engine application in a civil engine in service. This will change soon as CMC will progressively make its way into the hot section. For example, the development of CMC shroud (sealing) segments and further static turbine and combustor components is well advanced.

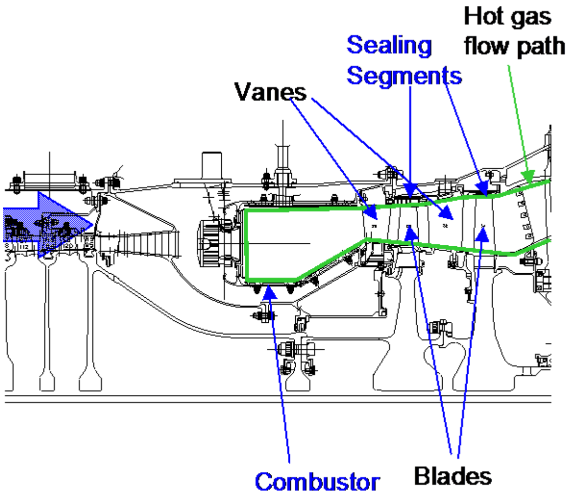


Figure 6: potential long term applications of CMC material

2.2 Combustion emissions

To give an impression of the complexity of the variety of design requirements for the overall combustion sub-system, figure 7 shows the main influencing interfaces, boundary conditions and requirements. However, the key discriminating technology of combustion is the generation and control of emissions: in particular NOx, particulate matter, unburned hydrocarbons and carbon monoxide. For each product, these are closely regulated and monitored. Rolls-Royce has a clearly laid-out, long term strategy and commitment to control gaseous emissions [5]. The fundamental challenge of aero-engine combustion is that it has to be accomplished within an environment, which usually is not conducive to stable combustion. This is due to the excess of air beyond stoichiometric conditions and the high air speeds exiting the compressor: The AFR (air-to-fuel ratio) is used to describe the local and overall fuel and air mixing conditions within the combustor and the combustor exit. The stoichiometric condition burning kerosene corresponds to an AFR of 14.8: lower numbers correspond to fuel rich, higher numbers to lean conditions. The combustor exit AFR at given overall pressure ratios (OPR) corresponds directly to the HP turbine inlet temperature.

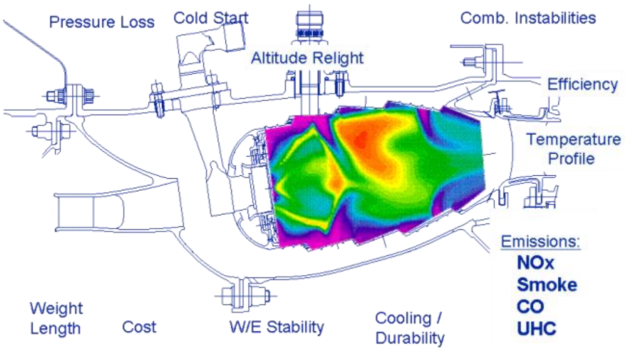


Figure 7: Design requirements for the overall combustion sub-system [4]

The emission characteristic of an aero-engine combustion process is illustrated schematically in figure 8. Unburnt hydrocarbons (UHC or HC) and carbon monoxide are low power emissions caused by incomplete combustion at low combustion temperatures. These are directly linked to combustion inefficiency, which increases significantly at low power conditions. High power emissions, such as smoke or soot and nitrogen oxides (NOx), are caused in fuel rich zones and/or due to high combustion temperatures. Soot, or black smoke is formed due to an excess of fuel in flame-rich zones. The amount of smoke at engine exit is dependent on the capability of the combustion system to consume the smoke within the combustion chamber before exiting into the turbine.

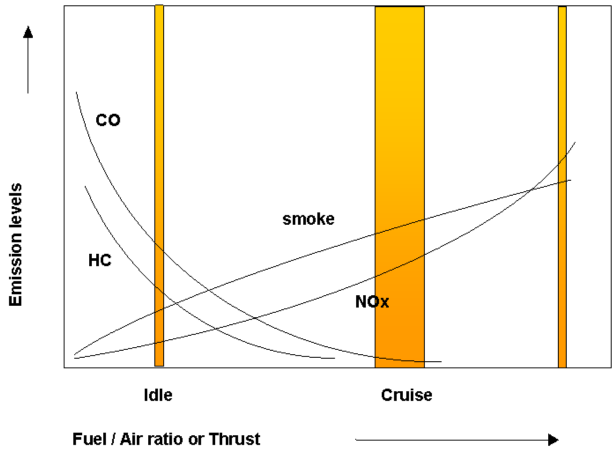


Figure 8: Aero-engine emissions characteristics

2.3 Low emission combustion systems for future engines

The development of combustors for the next generation of aero-engines is mainly driven by future NOx requirements. Beside the new emission legislation limits for NOx with CAEP/6 (January 2008), NOx emissions are increasingly in the focus of public discussion and are expected to be restricted further within future CAEP initiatives. In addition to these challenging emission requirements, future engine cycles will be characterised by the demand for still lower fuel consumption and CO2 emissions, causing highly-loaded core engines with increased combustor inlet pressures, temperatures and significant lower air-to-fuel-ratios. All these parameters are burdening the NOx performance of a combustion system.

Figure 9 demonstrates the trades driving new engine design with respect to optimum fuel burn (CO2), minimum noise (by minimum fan pressure ratio FPR) and minimum NOx (by minimum OPR). The difference in LTO NOx levels between the best design for low NOx and best design for low CO2 can be up to 30%. Also, noise reduction obligations for new aircraft as introduced at some airports can lead to a divergence from the optimum engine design for lowest CO2 (sfc). Engine bypass ratios, driven up to reduce noise impact, larger than required for optimum propulsion efficiency, have an impact on fuel burn in cruise condition. The current tendency for engine cycles will require low emissions combustion technologies for OPR > 50 and combustor inlet temperatures ~1000K. Therefore, a revolutionary step towards highly advanced rich or lean burn combustion techniques is inevitable to meet future certification requirements for new engine cycles and architectures with sufficient margin.

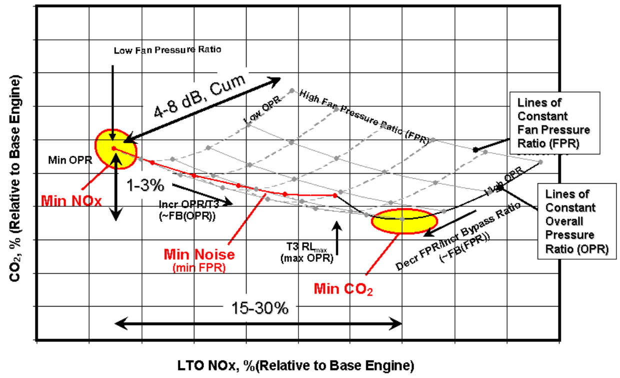
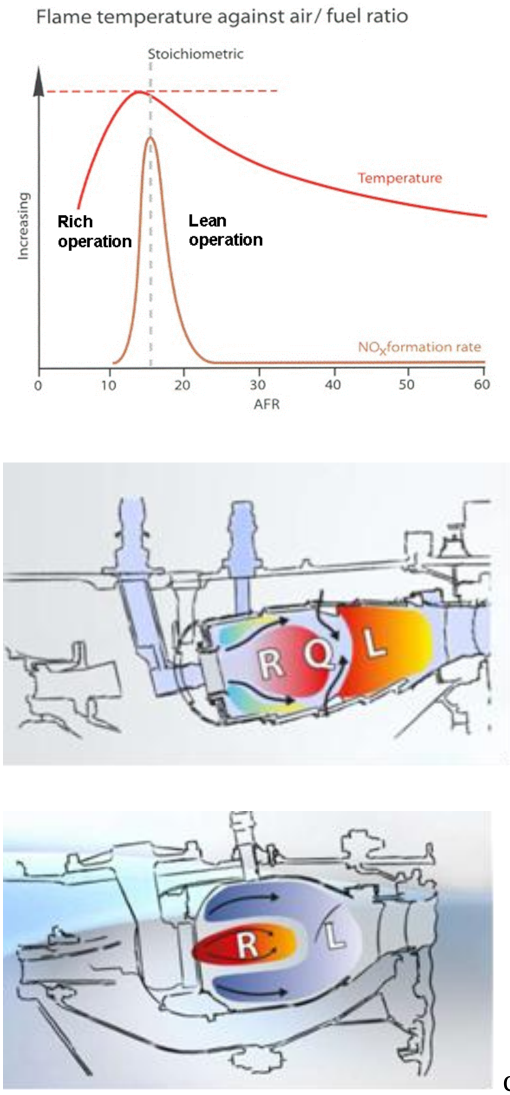


Figure 9: Aero-engine Optimisation trades for new engine design [4]

There are, in principle, two different combustion operation zones possible to reduce NOx, the rich burn and the lean burn mode, see figure 10. For low NOx, it is clearly desirable to operate the front end of the combustor on the lean side of stoichiometric. However, at lower power conditions this low temperature flame is at odds with the operability requirements of flame stability, efficiency and altitude restart. Staged combustion is a means of overcoming the problem of a high turn down ratio. It provides an added degree of freedom for control of the combustion processes. In a staged combustor, zones are created which are tailored for specific ranges of engine operation. For example, at low power, fuel may be supplied only to a dedicated set of Pilot fuel injectors. Higher up the running range, fuel may be introduced to a number of Main fuel injectors, the remainder of Main injectors being introduced at still higher power (i.e. implementing circumferential staging for the Mains).



a)

b)

c)

Figure 10: NOx formation (a), Rich (RQL) (b) and lean combustion topology (c)

The use of staged combustion systems is not new in Rolls-Royce. They are extensively used on the industrial Dry Low Emission (DLE) machines. The technology was also used in the 70's and 80's in the Bristol twin flow concept and the double annular Phase 4 combustion systems. Both of these latter systems were tested to technology readiness levels (TRL) 5 and 6, respectively. Rolls-Royce has a history of devoting significant effort to the development of new technologies. For example, the ANTLE (Affordable Near Term Low Emissions) technology demonstrator programme [lit]. Launched in March 2000 and partially funded by the EU and DTI, this programme represented a major investment in the acquisition of low emissions technology. Key to it was the demonstration of a low emissions combustion system with associated fuel system and control technology. The ANTLE programme has entailed close collaboration between Rolls-Royce and its partners in industry and the universities. There has also been considerable shared learning between the ANTLE programme and the German, E3E engine core demonstrator programme. Cutting edge experimental and numerical techniques have been used to evaluate a wide range of design alternatives, enabling selection of the hardware standards for the engine demonstration phases of the programme. Building upon those roots, the current demonstrator programme for the 3rd generation of hot-end technology and low emission is the UK Environmentally Friendly Engine (EFE) programme, which will be discussed later in this paper.

3 High Pressure Turbine Design and Materials

The turbine sub system is a complex assembly of discs with blades attached to the turbine shafts, nozzle guide vanes, casings and structures. The turbine extracts energy from the hot gas stream received from the combustor. This power is ultimately used to drive a fan, propeller, compressor or generator. As in the combustion sub-system, the turbine environment is particularly harsh, and the components require active cooling techniques superalloy materials and protective coatings. One added complexity in the turbine system clearly is caused by the presence of fast spinning components, leading to considerable stresses in the material, and adds difficulty for component cooling and sealing between stationary and rotating parts.

High pressure turbine blades and nozzle guide vanes are designed with cooling passages and thermal barrier coatings, to ensure long life while operating at high temperatures. Cooling air is taken from the compressor and is fed around the combustor into the blades to cool the aerofoils. Design of cooled turbine components, to meet target metal temperatures, requires accurate understanding of thermal boundary conditions. CFD is used to provide gas temperature profiles and component wall heat-transfer coefficients, and this is coupled with Finite Element Analysis (FEA) to predict metal temperatures accurately. Increasingly, conjugated CFD approaches are being used where both the fluid environment and the solid part of the Turbine aerofoil are being solved for using the same CFD solver. In-engine validation of cooling designs is provided by thermal paints, which are used to assess both internal and external component surface temperatures. Laboratory interpretation of painted components taken from dedicated test engines is increasingly supplemented with in-engine boroscope paint assessment, thus providing additional validation data. Nickel-based superalloys have come to dominate the high temperature stages of the gas turbine engine, from the high pressure compressor through the combustor and turbine stages to the exhaust outlet. The success of these materials is due to their unique combination of mechanical strength and resistance to oxidation and corrosion at elevated temperatures. Two components which have driven the development of the nickel-based superalloys are the high pressure turbine blade and disc.

The high pressure turbine blade sits in the harsh environment behind the combustor and rotates at high speed in order to extract energy from the high temperature gas stream. It is required to withstand centrifugal loads of up to ten tonnes while operating at temperatures several hundred degrees in excess of the melting point of the alloy. Operation in this environment makes severe demands on both the mechanical properties and environmental stability of the blade system and is only possible through the close integration of design, materials and manufacturing. Figure 11 shows the development of the high pressure turbine blade system (material, cooling, coatings) over the last few decades. A step change in temperature capability was realised through the introduction of directional solidification (DS), eliminating transverse grain boundaries, a source of weakness in a creep dominated application.

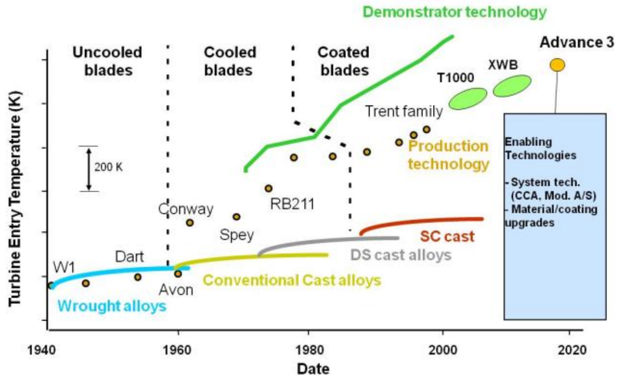


Figure 11: Development of HPT blade system Turbine inlet temperature capability

It was then a natural progression to the complete elimination of grain boundaries via single crystal (SC) casting, and the continued drive for more temperature capability has led to successive generations of alloy with ever more exotic alloying additions.

With increasing blade operating temperatures, the intrinsic resistance of the metal to environmental attack is no longer sufficient. Protective coatings are therefore required to provide a thermal barrier and/or impart the necessary oxidation and corrosion resistance, see Coatings. The net effect of all the advances in blade technology outlined above, coupled with alloy development, has been to increase metal temperatures by approximately 300°C over the last 50 years: this figure can be doubled when the delta temperature to the gas stream itself is considered, giving an idea of the cooling effectiveness of the modern systems.

Turbine discs operate at lower temperatures than blades, as they are not in the direct gas path exiting the combustor, however, they must attain the most stringent levels of mechanical integrity. The development of disc alloys has traditionally been driven by the requirements of the high pressure turbine disc. The consistent objective is a hotter disc with an equivalent cyclic life, requiring highly alloyed, higher strength materials. Traditionally the manufacture of turbine discs has been via a cast and wrought route. However, for advanced nickel-based superalloys with high alloy contents segregation at the ingot stage becomes problematic. The solution has been to move to a powder processing route involving the atomisation of a molten stream of metal in an inert atmosphere. The resultant rapid solidification and fine powder size restricts segregation. Consolidation is then achieved by hot isostatic pressing (HIPping), followed by extrusion to provide a fully dense billet for subsequent isothermal forging.

Components produced with a single microstructure throughout invariably result in a trade-off in design and/or component life because of the relationship between various critical mechanical properties and grain size. Therefore, further temperature capability and weight optimisation is achieved by producing dual-microstructure components, whereby a fine grain size is retained in the lower temperature bore region to maximise tensile and fatigue strength, whilst the hot rim of the disc is selective coarse grain to enhance creep and fatigue crack growth resistance. By selectively developing this coarse grain microstructure the temperature capability of the alloy is improved by up to 30°C. Aero engine technology acquisition is a long term investment, and the fact that the RR1000 disc alloy programme (now used in Trent 1000 and Trent XWB engines) for dual micro-structure took about 20 years might serve as a good illustration.

3.1 Turbine Technology Drivers and Key Challenges

As stated already the increase of the peak cycle temperature for cycle efficiency and fuel burn is one of the key drivers for turbine technology, especially as there is the requirement to allow the cycle temperature to rise whilst maintaining or reducing cooling air consumption. Thus, minimising parasitic air consumption (cooling and leakage flows which are not contributing to direct cycle benefit), is the second major challenge for turbine design. One key element of this is to optimise the High Pressure Turbine blade tip sealing concept and the tip clearance control throughout the flight cycle.

Key enablers, in addition to the effective use of technology demonstrators and variety of civil and defence engine development programmes are:

- High degree of aerothermal and mechanical toolset calibration to improve fidelity of predictive capability
- Sophisticated 3D design capability (fully -featured 3D design of gas path components, with full modelling of sealing and leakage flows also to minimise c/a heat pickup)
- Advanved management of system interfaces between compressor & combustor and combustor & turbine
- Full exploitation of robust design methods for multi-point optimisation through the life cycle of the engine

3.2 Turbine cooling

Cooling turbomachinery components is not a new activity, but it is technically demanding. There is still no standard configuration which can sensibly be used in all circumstances. Cooling and the prediction of temperature is needed throughout the machine. There are few parts of the machine which do not experience changes of temperature during the operating cycle, and these usually result in displacements, thermally induced stresses and material property changes which need to be assessed if the design life is to be achieved at minimum cost and weight. The engine outer casings have carefully-designed cooling systems used to control blade tip clearance via casing thermal expansion. The transient heating of a disc has a big impact on its life, as well as on clearance of its various seals.

While temperature predictions are needed throughout the machine, the majority of the cooling design effort goes into the turbine aerofoils and combustor. Aircraft gas turbine engines tend to have higher gas temperatures than other turbines, and have weight as a much more important design criterion.

The combustor cooling is helped by the low Mach number needed to sustain a flame which results in relatively low heat transfer coefficients. There has also, traditionally, been a large amount of air introduced through the combustor walls to control the burn, so the gas temperatures close to the walls can be kept fairly low. This has resulted in the use of relatively simple cooling techniques, despite the very high temperatures and strong radiation in the early part of the combustor core. More recent combustors tend to have less “spare” air as mean air-fuel ratio has risen and pollution requirements have become more stringent, but the cooling is still somewhat less demanding than for the turbine aerofoils. The heat flux density is half to one third of the turbine level despite the higher radiation input. This lower heat flux density is equivalent to having higher metal conductivity, and there is more space available. The discussion which follows will therefore concentrate on aircraft gas turbine cooled aerofoils. There will be some discussion of the effect of the chosen engine operating cycle on the choice of cooling system.

There has been a long history of increasing turbine entry temperature, see figure 11. Materials improvements and cooling improvements have contributed to this. Beside the significant improvement of base material capabilities from equiax to 5th generation single crystal, the development of modern thermal barrier coatings (TBC), and advanced cooling methods enabled today’s cycle temperatures in modern large bypass ratio engines. This illustrates that cooling plays a large part in allowing the increase.

Cooling technology development therefore plays a vital part in global technology acquisition programme of Rolls-Royce. There are three main types of cooling used in gas turbine blades; convection, film, and transpiration cooling [6]. They do have different flow consumption and effectiveness, see figure 12. Convection cooling utilises cooling air passing through passages internal to the blade. Heat is transferred via conduction through the blade and thereafter by convection into the air flowing inside of the blade. A large internal surface area is necessary for this method, so the cooling paths tend to be serpentine and full of small fins, or turbulators. Impingement cooling is often used on certain areas of a turbine blade, such as the leading edge, whilst normal convection cooling is used in the rest of the blade. The second major cooling technology is the so-called film-cooling, which works by pumping cool air out onto the blade surface through small holes in the blade. This air creates a thin film (layer) of air on the surface of the blade, protecting it from the high temperature air. The cooling air holes can be in many different blade locations, but they are most often along the leading edge and the pressure side. The injection of the cooler bleed air into the flow reduces turbine efficiency because of mixing losses.

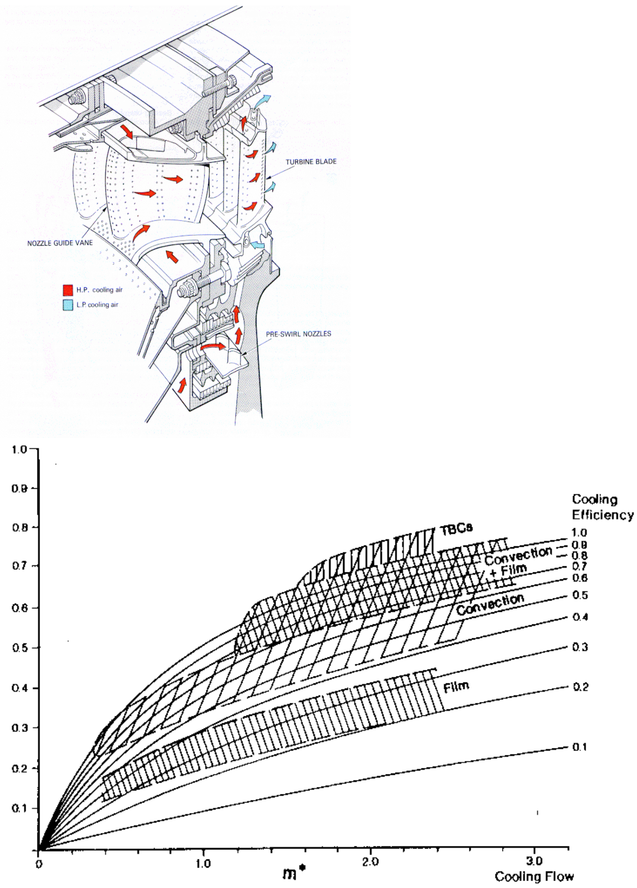


Figure 12: a) typical HPT cooling arrangement and b) Cooling effectiveness of different cooling types.

The third type of cooling is transpiration, or effusion cooling, and it is similar to film cooling, in that it creates a thin film of cooling air on the blade, but it is different in that that air is leaked through a porous wall (shell) rather than injected through holes. This type of cooling is effective at high temperatures as it uniformly covers the entire blade with cool air. Future developments of cooling technologies tend to make use of complex combinations of the above techniques and are used in all sorts of demonstrator and rig programmes. This goes concurrent with a need for more capable and reliable manufacturing techniques, which e.g. allow the direct manufacture of heat-transfer-enhancing internal features, or cascaded impingement in internal cooling schemes. Examples for these new concepts are technologies such as: Topology optimised internal impingement cooled blades and dual wall cooling; Contra flow internal cooling designs for HP blades and optimised effusion & transpiration cooling technologies for vanes and segments.

4 The EFE demonstrator programme

The environmentally friendly engine (EFE) is a UK TSB funded collaborative research programme between industry, academia, and the public sector, the objective of which is to contribute to achieving the ACARE goals. Rolls-Royce is the lead partner and is responsible for the core engine demonstrator which will develop hot end technologies. The demonstrator engine is now starting to deliver significant test results providing robust technology validation for the next generation of civil aero gas turbines. Within the programme Rolls-Royce has focussed on the development of technologies targeted at future applications using a core engine demonstrator as a technology validation platform. This is as part of an integrated programme of applied research and engine demonstrators.

The Rolls-Royce environmental strategy is based upon three themes; maintaining the drive to reduce the impact of our business activities, further reducing the environmental impact of our products and developing entirely new low-emission and renewable energy products. The EFE programme fits into the second category.

EFE falls within the company’s Vision 10 technology horizon, which covers technologies for introduction into airline service within the next ten years. The EFE focus is on improvements to the thermal or cycle efficiency of the engine which are delivered by higher temperatures, higher pressures, or improved component efficiencies within the core. An advanced low emissions combustion system will also be tested to significantly reduce NOx output.

The EFE demonstrator has been developed from the successful Trent 1000, the launch engine for the Boeing 787 Dreamliner which entered service with ANA during 2011. EFE is heavily modified from the standard engine but retains the 3 shaft Trent pedigree. As the EFE demonstrator is for core engine technology only, the fan can be removed.

The fan case is retained to mount the accessory gearbox, control system, wiring and other externals. The fan rotor has been replaced with a four stage booster feeding directly into the intermediate pressure compressor. The booster was designed specifically for EFE and delivers a pressure ratio of just over two and has a variable bleed from stage 4. The intermediate pressure compressor and high pressure compressor are taken directly from the Trent 1000 engine and incorporate some minor design changes to cope with the elevated conditions which EFE will achieve. The heart of EFE consists of the combustion and high pressure turbine systems; it is here that most of the innovation and technology validation will occur and these components are bespoke to the demonstrator engine (figure 13).

The engine features a low emissions combustion system, as described in section 2.3. The fundamental objective is to combust fuel and air at lower temperatures with an excess of air in the primary combustion zone. The other key area on EFE for technology validation is the high pressure turbine. On EFE the turbine rotor blades features a shroudless design [7]. Traditionally Trent engines have incorporated a shrouded blade but as the turbine entry temperature increases the benefits of a shrouded design reduce and the penalties in terms of blade weight and disc life increase.

Different cooling specifications are being tested and each build of EFE features several specific designs of the rotor blade to enable a back to back comparison to be made. Here the main areas of investigation will be iterations of the film cooling for the aerofoil of the blade and control of the tip clearance. Innovative designs have been developed to allow closed loop control of the tip clearance by both thermal and mechanical systems. The blade tip and the adjacent rotor path also feature state of the art coatings to ensure through-life performance retention. Although the end game for a demonstrator programme is the engine test results there are always some huge benefits in terms of the knowledge gained during the design and manufacturing process.

The engine first ran in 2010 with a second test in the first quarter of 2011, see figure 14. These initial runs focused on confirming the functionality of the various engine systems and to ascertain the performance of the vehicle. These results were eagerly awaited to confirm that the thermodynamics of the cycle was as predicted and that the engine was capable of delivering the conditions required for robust technology verification. Analysis of the turbine efficiencies and the air fuel ratio were all within expected scatter of the pre-test model, as was the case with the turbine capacities. Overall the initial performance analysis has supported the pre test model with the outcome that the vehicle is capable of delivering the required test conditions.

Figure 14: EFE engine in the Bristol test bed

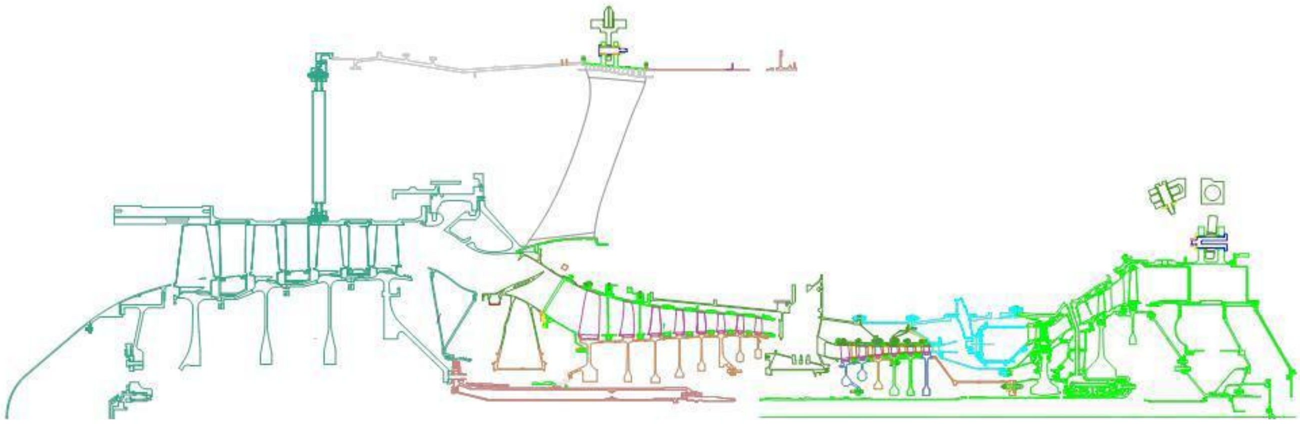


Figure 13: EFE demonstrator engine

After an extensive commissioning program, a first set of HP Turbine cooling and aerothermal upgrade packages was tested downstream of a fully operational staged Lean Burn combustion system. The next task for the EFE demonstrator is to perform a cyclic test using a similar bill of material to advance these technologies to TRL 6. Modules for this test are now on build and it is planned to conduct the test in the latter half of 2012. The first product to benefit from technologies developed on EFE will be the Trent XWB high thrust programme.

Conclusion

Key technologies for combustion & core turbine systems contributing to low emissions, fuel-efficient large civil engines have been described. Emphasis has been on cooling technologies & combustion sub-system design. Furthermore, the importance of new high temperature materials, robust and capable design tools for better control of gaps and leakages, as well as new sub-system design for the further optimization of large civil aero engines has been explained. The corresponding technology demonstrator programmes such as EFE have been explained and the technology incorporation into new engine architectures has been discussed. Low emissions, improved fuel efficiency and advanced temperature capability are a major goal of the Rolls-Royce ongoing engine demonstrator programmes for 2 shaft and 3 shaft engine families.

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