"ACTIVE CORE" – A KEY TECHNOLOGY FOR MORE ENVIRONMENTALLY FRIENDLY AERO ENGINES BEING INVESTIGATED UNDER THE NEWAC PROGRAM

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Abstract

The continuous growth of air traffic and raised environmental awareness put increasing pressure on aero engine manufacturers to reduce fuel burn and emissions. NEWAC is a new integrated program of the European Union with focus on innovative core engine concepts to achieve this task. Within NEWAC, four different core engine configurations will be investigated:

- *Intercooled recuperative aero engine*
- *Intercooled core*
- *Active core*
- *Flow controlled core*

These configurations are complemented by the development of innovative, low emission combustor technologies.

This paper presents the overall structure of NEWAC and focuses on the sub-project "Active Core". In this sub-project, the emphasis lies on active systems in the core engine which alter and improve current thermodynamic cycles. Two distinct active technologies are presented, one using active cooling air control for the high pressure turbine and the other using active elements in the high pressure compressor.

Both technologies are presented and a snapshot of the ongoing research and current results on both topics is given.

Abbreviations

AEROHEX	Advanced Exhaust Gas Recuperator Technology for Aero-Engine Applications
ACAC	Active Cooling Air Cooling
ACARE	Advisory Council of Aeronautic Research in Europe
ACC	Active Clearance Control
ASC	Active Surge Control
BPR	Bypass Ratio
CFD	Computational Fluid Dynamics
CLEAN	Component Validator for Environmentally Friendly Aero-Engine
CO_2	Carbon Dioxide
EEFAE	Efficient and Environmentally Friendly Aero- Engine
EU	European Union
HP	High Pressure
HPC	High Pressure Compressor
LDI	Lean Direct Injection
LPP	Lean Premixed Prevaporized
NEWAC	New Aero Engine Core Concepts
NO_x	Nitrogen Oxides
OPR	Overall Pressure Ratio
PERM	Partial Evaporation and Rapid Mixing
SFC	Specific Fuel Consumption
SP	Sub-Project
SRA	Strategic Research Agenda
TERA	Technoeconomic and Environmental Risk Analysis
T/O	Take-off
TiAl	Titanium-Aluminum Alloys
VITAL	Environmentally Friendly Engine

1 Introduction

With the increasing amount of air traffic, the reduction of its environmental impacts is becoming ever more important. Over the last 40 years, aero engines have already improved tremendously in fuel consumption, noise and air pollutant emissions while, at the same time, becoming more reliable. However, with the increasing evidence for global warming, the constant rise in air traffic volume and the economic pressures of high fuel prices, even more improvement is needed.

In 2001, research for cleaner, more efficient aero engines was intensified after the “Vision for 2020” report was published by ACARE which defined ambitious goals in the areas of NO_X, noise and CO_2 reduction. In order to reach these goals, several research projects have been launched.

One major project, the EU integrated project VITAL [1], is focusing on technologies for low pressure system improvements to reduce CO_2 and noise. To further reduce these emissions and also reduce the NO_X production, however, complementary research is needed on the technology for high pressure components and combustors. This research is being performed in the EU integrated program for NEW Aero engine Core concepts (NEWAC).

2 Overview of the Activities Within NEWAC

NEWAC has set forth its goals of developing technologies for a reduction of 6% in CO_2 emissions and 16% in NO_X emissions.

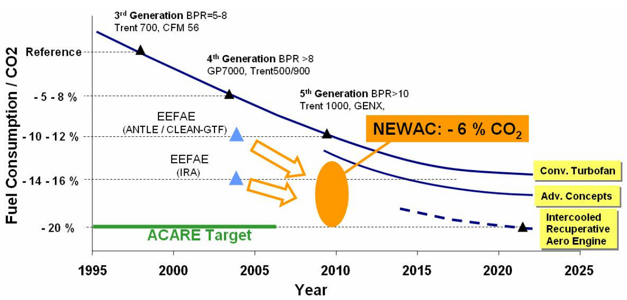

Fig. 1. CO_2 reduction target for NEWAC

Fig. 1 illustrates the reduction of fuel consumption achieved over the last 12 years and the 2010 targets for NEWAC as further improvements on EEFAE results. In order to reach these goals, four major core concepts are being evaluated and additional research is carried out in the development of improved combustors. The four core concepts as depicted in Fig. 2 are:

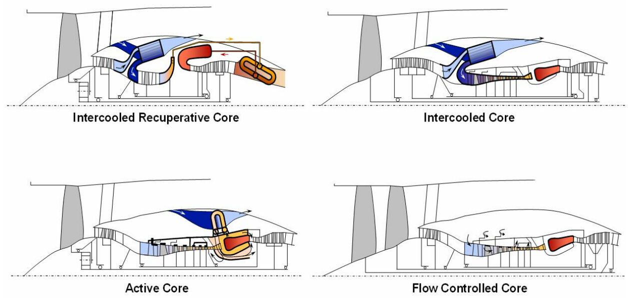

Fig. 2. Engine configurations investigated under NEWAC

- Intercooled Recuperated Core

This concept exploits the heat of the engine exhaust gas and maximizes the heat pick up capacity of the combustor inlet air by intercooling in front of the HP compressor.

- Intercooled Core

The introduction of an intercooler to a core configuration allows for very high overall pressure ratios. It reduces the compression work for such cycles and improves fuel burn.

- Active Core

The active core incorporates actively controlled systems such as surge control, tip clearance control and cooling air cooling. These active systems enable the engine to be adjusted to the current flight condition and allow for the reduction of design margin that is needed in conventional systems to cover various engine conditions.

- Flow Controlled Core

High BPR direct driven turbofan engines require a compact HP compressor with very high pressure ratio which has to compensate for the low booster pressure ratio. Therefore, flow control technologies are being investigated under NEWAC that strongly increase efficiency and stall margin which helps in the specific field of aerodynamically very highly loaded HP compressors.

These four core concepts are being investigated in the dedicated NEWAC sub-projects (SPs) SP2 to SP5. To complement this core architecture research, additional research is ongoing in SP6 to improve upon current combustor technology. Here, especially “lean” combustion, which operates with an excess of air, is investigated to significantly lower flame temperatures and, therefore, greatly reduce NO_X formation in order to reach the 16% target shown in Fig. 3.

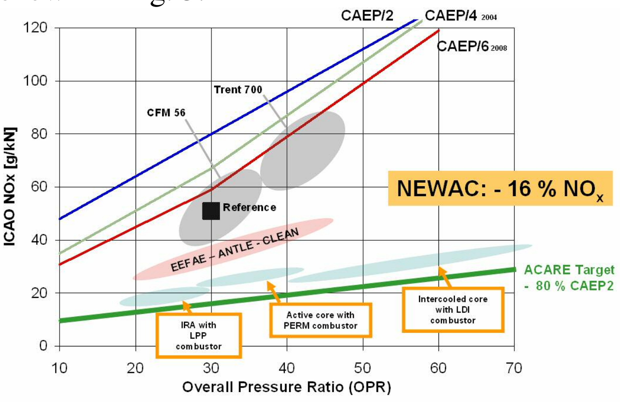

Fig. 3. NO_X reduction targets for NEWAC

The research comprises three major concepts that cover a wide range of overall pressure ratios in the engine. These concepts are

- Lean Pre-Mixed Pre-vaporized (LPP)
- Partial Evaporation & Rapid Mixing (PERM)
- Lean Direct Injection (LDI)

The evaluation of the effects of all the technologies investigated in the different core concepts mentioned above and the combination with combustor technology is carried out by the dedicated sub project SP1. Fig. 4 shows the entire sub project structure of NEWAC and the connecting role of SP1.

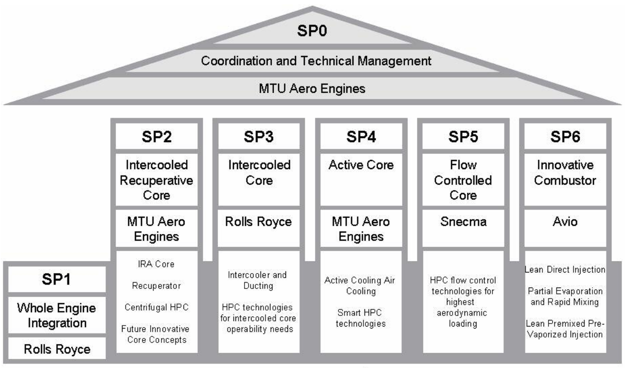

Fig. 4. Structure of NEWAC

This engine integration task started in 2006 with the definition of the requirements and objectives for all other tasks by using whole engine performance cycle data. It will then compare, assess and rank the benefits of the advanced concepts, ensuring consistency of the results and monitoring progress towards the ACARE technical and economic objectives. The new engine designs will be assessed in typical aircraft applications and for relevant flight missions as illustrated in Fig. 5.

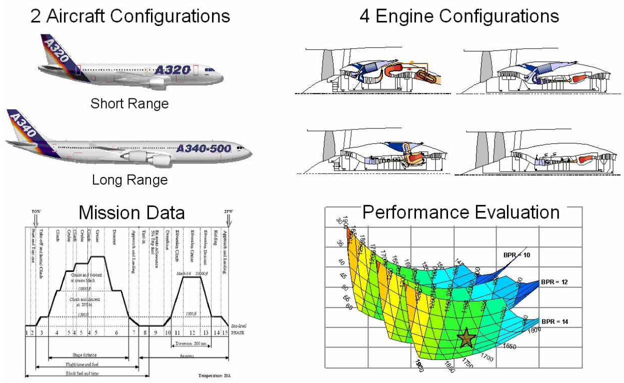

Fig. 5. Illustration for the approach to whole engine evaluation with different aircraft and engine configurations as well as mission and performance parameters.

In this context, NEWAC will also adapt and further develop the software tool "TERA 2020" (Techno-economic and Environmental Risk Analysis), previously created under the VITAL program, in order to compare the environmental and economic impacts of the new designs.

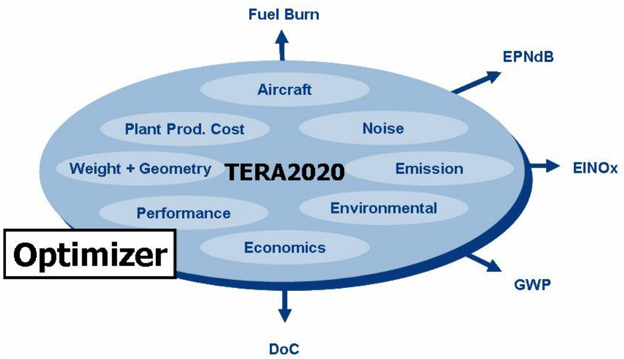

Fig. 6. Approach for whole engine optimization within TERA 2020

Parameters that are included in "TERA 2020" include performance, weight, engine installation, NO_X and CO_2 emissions, noise, fuel costs, maintenance cost and aircraft flight path and altitude. This techno-economic model will identify engines with minimum global warming potential and lowest cost of ownership as shown in Fig. 6.

3 Research Performed within SP4 – "Active Core"

The sub project SP4, the "Active Core", is being lead by Germany's MTU Aero Engines. Its concept follows two major strategies. First, it aims at developing new active systems to improve stability and efficiency of the high pressure compressor and second, it tries to improve the overall core efficiency by cooling of high pressure turbine cooling air in order to improve the cooling efficiency and reduce the required cooling air mass flow. Both strategies complement each other, but can also be used separately if desired.

3.1 Research on smart HPC technologies

Today's compressor designs require high efficiency levels to provide low fuel consumption and high aerodynamic loading for lightweight and cost effective engine designs. At the same time, safety and reliability demands require the provision of sufficient surge margin for the compressors. In the high pressure compressor, the handling of tip leakage flows and the off-design behavior are the major challenges to achieve these ambitious targets. NEWAC is focusing on the improvement of current designs by the means of active control. Compressor efficiency and stability will be optimized by a reduction of tip leakage losses due to an innovative radial clearance management while the compressor stability will be enhanced with active surge control (ASC) through air injection. Additional aerodynamic stability offers new improvement potentials, such as a higher overall pressure ratio, reduced blade count or even fewer compressor stages. This opens up opportunities for improvement of SFC as well as cost and weight reductions.

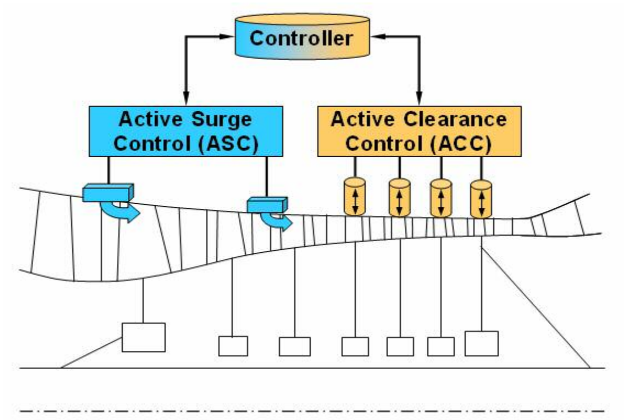

Fig. 7. Schematic of closed loop control system for ACC and ASC

3.1.1 Active Clearance Control

Tip clearance, the radial gap between rotating blades and the stationary compressor casing, varies significantly during different operating conditions due to centrifugal forces on the rotor and different thermal expansions of airfoils, disks and the casing as shown in Fig. 8.

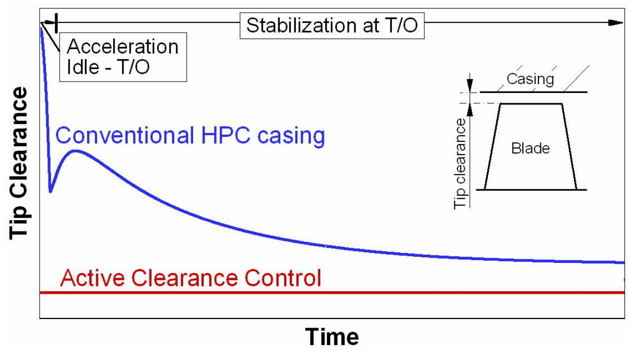

Fig. 8. Tip clearance behavior over time during an acceleration for take-off (T/O)

To avoid any contact between rotating and stationary parts, the radial clearance has to be designed with enough margin to cover any worst case scenario. Another approach consists of the use of abradable liners which allow a rub of the blades into the casing. Both approaches lead to larger clearances than necessary during most of the flight and especially during cruise, leading to higher fuel consumption and lower safety margin. Aircraft engines which have been in service for a long time period often suffer from large clearances due to worn airfoils and liners. Active clearance control systems (ACC) can help overcome this situation. They target optimum performance and operability over the full flight envelope by adjusting the radial casing position to a minimal gap as shown by the bottom curve in Fig. 8. Currently, different "conventional" ACC systems are in use, both for turbines and compressors [2,8].

These conventional systems are slow acting and of the "open loop" type without any feedback signals, which restricts the benefit to a large extent. NEWAC is evaluating innovative "closed loop" systems, which promise better performance [3]. A thermally and a mechanically actuated ACC compressor casing have been studied to provide the lowest clearance levels in any flight condition. The technology is applied to the rear stages of a modern high pressure compressor as these stages are more susceptible to tip clearance problems. This is in part due to larger thermal expansion resulting from higher gas temperatures, but also because of the higher impact on the aerodynamic losses due to smaller blades in the last stages.

In order to control the tip clearance, two concepts have been investigated under NEWAC. The first one is a thermal system using customer bleed air from front stages to cool the rear stages, the second is a fast acting, mechanical system using hydraulic actuators and variable liner segments (Fig. 9).

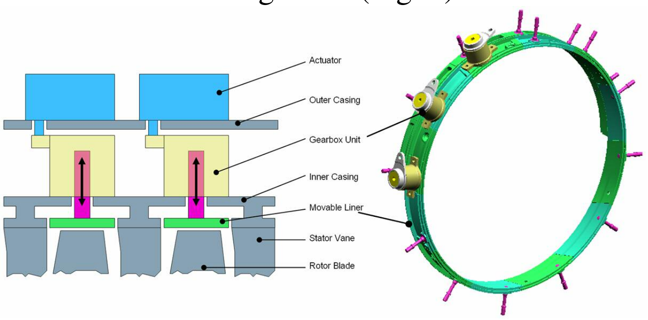

Fig. 9. Schematic of hydraulically actuated mechanical ACC with adjustable liner segments.

Both systems were compared with respect to efficiency improvement, surge margin gain, weight, cost, safety, reliability and ultimately overall fuel burn benefit. The results showed that the thermal system, while being significantly simpler and inherently more reliable, showed only a small benefit. One major reason for this small benefit lies in the slow response time of such a system, that makes it impossible to react to fast transient operating conditions and, therefore, still requires relatively large tip clearances in the HPC.

Therefore, the more promising – albeit complex - technology of a mechanical ACC system was chosen to be investigated in more detail. Currently, such a system is in the detail design phase and prototype testing will start in 2009. The technological challenges for such a system lie in the hot environment, the need for almost complete elimination of leakage and play (caused by tolerances, thermal expansion and wear) as well as the weight and size of the overall system. These are topics that will be addressed and investigated in a series of component tests that pave the road for a prototype test of a complete ACC system on a rig towards the end of the program.

In order to create a "closed loop" system, sensors have to measure the actual tip clearance and feed their data into a control loop that actuates the clearance control system. One partner, Vibrometer of Switzerland, has the dedicated task to study and develop sensors for such active systems, that can withstand the rigors of revenue service. These high temperature gap sensors are currently being tested and will become a cornerstone of any active tip clearance system.

3.1.2 Active Surge Control

At low power settings, engine operability can be critical due to compressor stage matching and special flight or engine conditions. Especially the compressor front stages operate close to their stability limit at low off-design conditions. Here, active flow control offers new possibilities to enhance compressor stability. NEWAC is focusing on the application of controlled air injection through the compressor casing into the blade tip region as shown in Fig. 10.

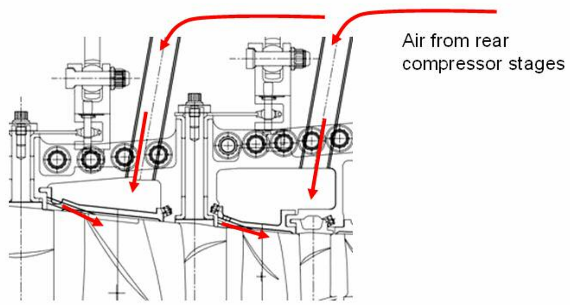

Fig. 10. Cross section through HPC tip injection system

The high speed injection jet alters the three-dimensional flow field at the rotor tip, especially the behavior of the tip clearance vortex. Additionally, the injected jet reduces the blade incidence and thus unloads the rotor tip [4].

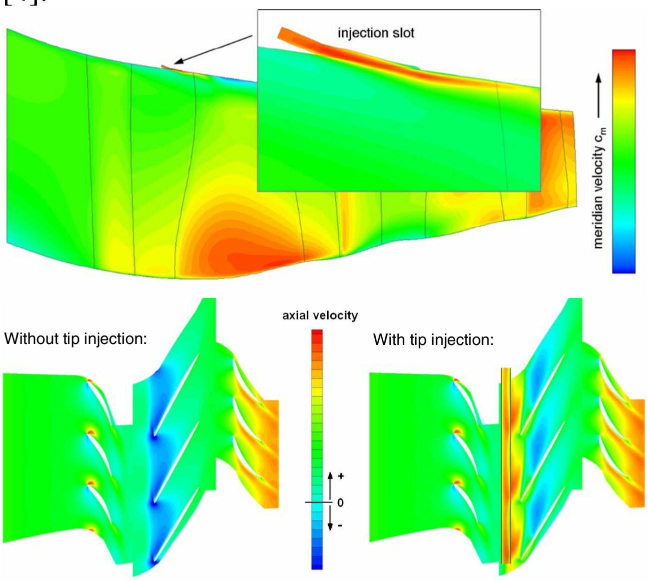

Fig. 11. Cross section through a flow field near the surge line with tip injection (top) and reduced blockage close to the casing wall as result of the injection (bottom).

Fig. 11 shows the injector flow (top) as well as the effect of reduced blockage close to the outer casing wall (bottom) in a CFD-simulated compressor flow field.

The required mass flow is taken from a downstream compressor stage. Since this recirculation is associated with an overall efficiency penalty, only a small portion of the gas flow can be used for flow control [5]. Modulated injection flows are generally regarded as being more effective than steady-state blowing while obtaining a comparable stability enhancement. Their control and application, however, are more complex than those of steady state flows.

NEWAC SP4 currently plans to investigate the effects of tip injection in two campaigns. The first campaign focuses on calibration of the applied CFD tools and results in a first database for the use of tip injection in multi-stage compressors. The second campaign will then fine tune the injection parameters in order to maximize the compressor surge margin. This campaign will take into account, that the work balance of the compressor is affected by tip injection. Therefore, a completely new stage matching is likely to be needed. This new stage matching will be carried out with the use of variable injection parameters as well as the use of variable stator vanes.

Currently, the complex interaction between injection flow, main flow field and downstream stages is poorly understood. The NEWAC program will help the consortium partners to increase their knowledge of these effects.

In parallel to the active tip injection experiments, the research program also studies advanced multistage casing treatment designs as benchmark and alternative solution for stability enhancement. This work is lead by the RWTH Aachen University on a two stage compressor rig setup. Today's third generation of casing treatments, as shown in Fig. 12, is capable of improving the surge margin of a compressor stage almost without efficiency penalty [6].

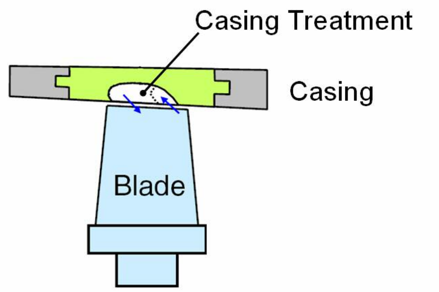

Fig. 12. HPC casing treatment

The aerodynamic design and prediction is a challenging task, however, as the related flow mechanisms are highly complex and the calculation of aerodynamic stability requires the use of unsteady CFD codes over several stages. Fig. 13 shows the complexity and required resolution of such a computational domain.

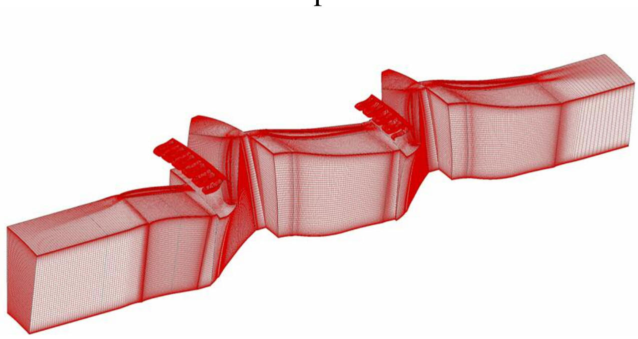

Fig. 13. Computational domain (grid) for an unsteady, two stage casing treatment calculation.

In addition to the goal of significant stability enhancement, the design point efficiency will be improved as well by lowering the tip clearance sensitivity of the rear stages. Besides the impact on aerodynamics, design issues like producibility, weight and cost will be addressed.

The smart compressor technology eliminates the need to design for worst case requirements and enables an engine optimization to individual flight missions. Active control offers the possibility of adapting the core engine to each operating condition and, therefore, allows an optimization of component and cycle behavior. The compressor can be designed for better efficiency, higher power density, lower size and weight. Finally, efficiency and surge margin reduction due to deterioration can be compensated, to a certain degree, by adjusting the core to actual conditions.

All these benefits are being assessed and quantified under NEWAC. The expected SFC improvement in the order of 2% has to be weighed against the drawbacks of these technologies, including weight, cost or complexity. This overall evaluation is currently being performed in various models on component, module and whole engine level and is closely related to the work performed in SP1.

3.2 Research on active cooling air cooling

Modern jet engines with their high turbine entry temperatures require effective cooling in order not to exceed the limits of the used materials. In today's engines, the total cooling air consumption is in the order of 25% which represents a significant portion of the total air flow. While some of this air participates in the thermodynamic cycle, it still causes a deterioration of the overall engine performance.

A reduction of this amount of cooling air can, therefore, have a very beneficial effect on engine performance as shown in Fig. 14. NEWAC SP4 is targeting such a reduction in cooling air mass flow by introduction of active cooling air cooling (ACAC).

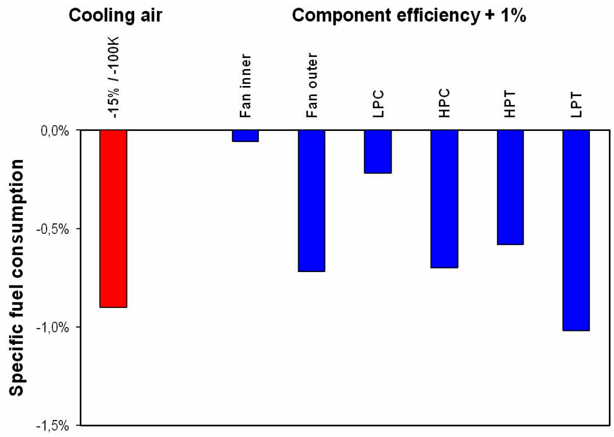

Fig. 14. Possible SFC reduction for different improvements in a turbofan engine

3.2.1 Concept of Active Cooling Air Cooling

Active cooling air cooling is based on the fact that in current engine designs, the cooling of crucial components is not actively controlled and has to be sized for the hottest conditions during the take off and climb phase of a flight mission. During the less demanding cruise portion of the flight, the cooling system delivers more cooling than would be needed, which lowers the efficiency of the engine.

With active cooling air cooling, the temperature of the cooling air is controlled by introduction of an additional heat exchanger in the engine bypass to reduce the cooling air temperature. The use of lower temperature air allows for the reduction of the total amount of cooling air consumed to achieve the same cooling benefit on hot parts.

The flow through the heat exchanger, however, has to be actively controlled because the heat that is dumped in the bypass has a negative impact on the overall engine efficiency. Therefore, NEWAC is investigating an active system in which the heat exchanger is used only during the relatively short period of take off and climb and will be bypassed during cruise, approach and landing.

3.2.2 General Concept Study

The research that is performed on this system can be divided into four portions. The first encompasses a general concept study in which the complete system is laid out and its benefit from an overall engine performance point of view is being evaluated. In addition, key components are being investigated in detail.

Such key components include the HP turbine airfoils, that see increased thermal stress levels or the piping and ducting for the cooling air in which pressure losses and heat pickup have to be tightly controlled.

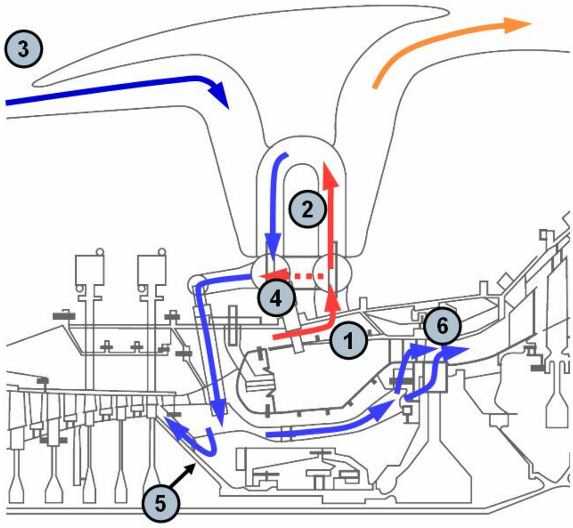

Fig. 15. Air flow scheme for active cooling air cooling

The general layout is depicted in a schematic drawing in Fig. 15. The compressed air is bled off the combustor case (1), lead through the heat exchanger matrix (2) and cooled by bypass air (3). A valve (4) allows partial or full bypassing of the heat exchanger in order to control the cooling air temperature. The cooled cooling air is then delivered to the compressor rear cone (5) and the HPT airfoils (6).

As mentioned above, one key question is whether the HP turbine airfoils can withstand the increased thermal stresses that result from cooling with cooled air. In order to evaluate this, a state-of-the-art turbine airfoil has been evaluated with a multitude of optimized cooling configurations varying mass flows and temperature levels. The basic approach for this optimization is illustrated in Fig. 16.

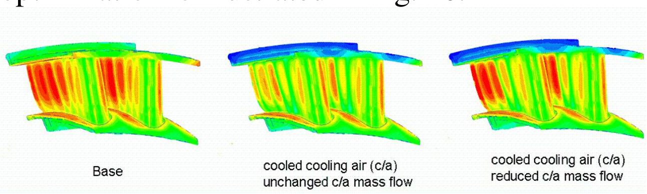

Fig. 16. Optimization process for a cooled HPT vane cluster

In a first step, the cooling air temperature was lowered which resulted in a cooler part. In a second step, the cooling air flow was reduced and redistributed to achieve a similar temperature and stress level distribution as in the original part.

This strategy gives a first indication on how much reduction in cooling air mass flow is viable, but it turns out that in order to get an optimized solution, the cooling concept of the airfoil itself will have to be adjusted. This is still subject to further research, but current values for cooling air savings range between 20% and 30% which would then lead to an improvement of up to 2% SFC for the investigated engine cycle.

3.2.3 Heat Exchanger Study

Besides this general concept study, the second portion of the research investigates the size, location, number and type of the heat exchangers needed to realize such a system. The current proposal for active cooling air cooling uses a heat exchanger with non circular tubes for the matrix. This design has been proven to provide low aerodynamic losses while maintaining a very small matrix volume which reduces the integration problems for such a heat exchanger. The use of this type of tube shape, however, has not been investigated prior to NEWAC for the high pressures encountered in modern jet engine cores.

Preliminary results show that the tubing geometry used in CLEAN and AEROHEX [7] has to be optimized in order to guarantee sufficient creep life of the heat exchanger. Fig. 17 shows a creep strain plot of a cross section of such a noncircular tube. As expected, the high pressure inside the tube creates significant stresses in the “corners” that lead to reduced creep life and require further optimization.

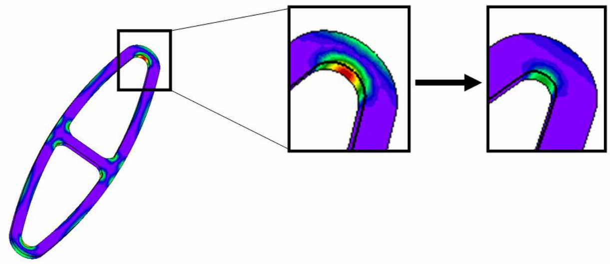

Fig. 17. Creep strain in cross section of heat exchanger matrix tube and optimization.

In addition to the work on the heat exchanger matrix, NEWAC is investigating the effects of such a complex system on the reliability of the aero engine. Scenarios ranging from sensor failure or the breaking of an air pipe to complete loss of a single heat exchanger due to foreign object damage are being investigated with the goal of guaranteeing safe operation and control of the engine. This, however, typically requires built in redundancy which negatively impacts the engine performance due to additional weight.

As of today, these effects have been investigated and show that a feasible design for ACAC can be achieved without excessive weight or cost penalties. One result of this analysis shows that any system with less than three independent heat exchangers is not desirable because it leads to unacceptable effects in case of a failure. With a system having three or more heat exchangers in combination with an intelligent sensor and actuator layout, the rate of in flight engine shutdowns can be kept at a level comparable to conventional systems without ACAC.

3.2.4 Combustor Case Investigation

The third portion of the task deals with the design of the combustor case for a system with active cooling air cooling. The combustor case, besides being a highly loaded pressure vessel, has to be optimized for a smooth bleed of cooling air, allow for efficient transport of the cooled air towards the HPT and reduce the inevitable heat pickup of the cooled air on its path. These requirements, in addition to the ever present tasks of cost and weight reduction, present a challenge for the design and manufacturing of the combustor case.

Under NEWAC, Volvo Aero has the responsibility of designing a combustor case that will fulfill these requirements. The goal is to build and demonstrate a combustor case that is optimized for active cooling air cooling. The high temperature gradients and the number of additional bosses for external tubing to and from the heat exchanger will be investigated and a solution that still allows for economic manufacturing is the goal for this task.

3.2.5 Weight offset investigations

Even though current results on cooling air cooling already show promising prospects, keeping the weight of the extra components under control is one of the most challenging tasks. Therefore, WSK of Poland is investigating methods for weight reduction through the introduction of new materials, namely Titanium-Aluminum (TiAl) alloys in the HPC. These alloys are just now making their debut in commercial jet engines and very little research has been done so far on how they can be used in the HPC for airfoils or structural components. The results from this task will open up more opportunities for the use of this promising material in jet engines.

3.2.6 Rear Cone Cooling Study

The fourth group of problems associated with active cooling air cooling is dedicated to optimization of the rear cone of the HPC. This part is one of the limiting components in today's jet engines because it is highly loaded by pressure, temperature and centrifugal forces and cannot be cooled effectively in current turbo machines. The availability of cooled cooling air opens a new opportunity for improvement of this critical component as it allows for reduced material temperatures. This can be used to change the material or reduce the wall thickness of the rear cone. However, machining such thin components presents a new challenge that will be addressed under NEWAC. Manufacturing

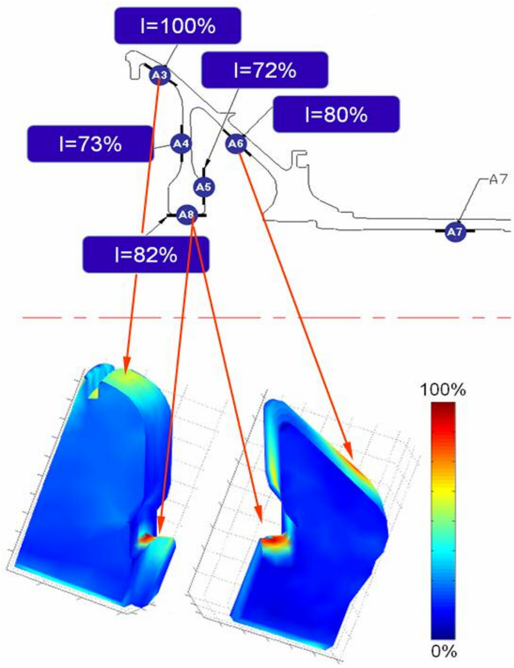

Fig. 18. Comparison of measured Almen-probe intensities (top) with simulated values (bottom) for ultrasonic shot peening of the inside of a rear HPC cone.

technologies, such as ultrasonic shot peening and electron multi-beam welding on complex, thin walled structures, are currently developed in order to address these challenges.

Fig. 18 shows a first result of these efforts. For the cross section of a rear cone, relative Almen-probe intensity values (top) can be correlated with values from a simulation (bottom). Such simulations can now be used to predict peening intensities and coverage for complex parts and help to reduce the amount of trial pieces to establish a satisfactory shot peening process.

4 Summary

The research performed under NEWAC will lead to novel technologies that help to reduce the environmental impact of air traffic. By focusing the efforts on the core engine, NEWAC complements research performed under the VITAL program and will contribute to reaching the ACARE "Vision for 2020" goals.

In SP4, the focus lies in the development and evaluation of active systems, such as active clearance control, active surge control and active cooling air cooling. These technologies are currently being evaluated and first results are already available. The next step will then be to finalize designs and test all technologies. Several large scale rig tests are planned for 2009 with results being available in 2010. These tests are expected to verify a 4% reduction in CO_2 and will help to pave the way for the next generation of environmentally friendly aero engines.

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