

Also published as ISABE-2009-1278

Intercooled Turbofan Engine Design and Technology Research in the EU Framework 6 NEWAC Programme

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Abstract

This paper describes design studies on the high OPR intercooled aero engines in sub-programme 1 of the EU Framework 6 NEWAC programme, and rig tests and experiments in sub-programme 3 that relate to the design of efficient, compact and lightweight intercooled compression systems with enhanced operability. It summarizes the results obtained up to the third year of the project including a preliminary assessment of the new intercooled turbofan technologies in engines of 140 kN and 320 kN takeoff thrust.

Glossary

ACARE	Advisory Council of Aeronautic Research in Europe
BPR	Bypass Ratio
CLEAN	Component vaLidator of Environmentally friendly Aero eNginE
EEFAE	Efficient & Environmentally Friendly Aero-Engine
FP6	Framework Programme 6
HP	High Pressure
IP	Intermediate Pressure
IRA	Intercooled and Recuperated Aeroengine
LDI	Lean Direct Injection
LP	Low Pressure
NEWAC	NEW Aero engine Core concepts
NOx	Oxides of Nitrogen
OPR	Overall Pressure Ratio
SFC	Specific Fuel Consumption
TERA	Technoeconomic and Environmental Risk Analysis
TET	Turbine Entry Temperature

Relevant NEWAC Sub-Programmes

SP1 Whole engine integration
SP3 Intercooled compression system
SP6 Lean combustion

Introduction

As engine designers increase OPR to improve thermal efficiency, intercooling becomes increasingly attractive because it enables lower HP compressor delivery and turbine cooling air temperatures, and tends to reduce NOx emissions. Some industrial and marine gas turbines already use intercooling.

In a three-shaft intercooled aero engine the flow exiting the IP compressor will be cooled before it enters the HP compressor, using air taken from the bypass duct as shown in figure 1.

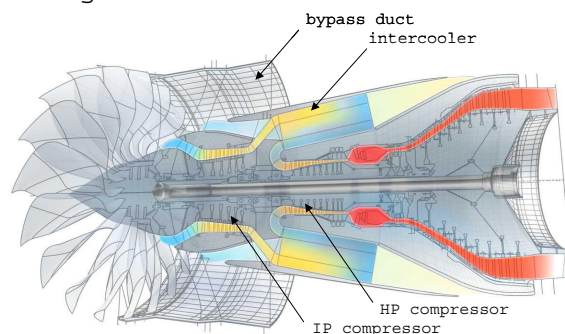


Fig. 1. High OPR Intercooled Engine

Intercooling has the potential to reduce SFC and fuel burn by increasing OPR beyond the levels achievable in conventional cycle engines. However, without new design technology the potential

improvements in core cycle thermal efficiency could be limited by pressure losses in the intercooler and its associated ducting, and by reduced component efficiencies associated with the smaller core size that comes with increased OPR and specific power. Improvements in SFC could also be offset by any increases in powerplant weight or nacelle diameter and drag.

In order to be competitive with more conventional engines an intercooled aero engine should have good operability, better fuel burn and emissions, an acceptable first cost, long service intervals and lower overall life cycle costs. The NEWAC project objectives for the intercooled engine are a 4% SFC improvement and a 16% NO_x reduction from a combination of intercooling, cooler turbine cooling air, lean combustion and core compressor efficiency improvements.

This paper describes the NEWAC programme studies aimed at seeing if the above design objectives can be realized. It starts with an overview of the programme, with emphasis on those parts relevant to intercooling. Then it discusses some whole engine design issues. This is followed by descriptions of the key technologies and research projects relating to intercooled engines. Finally it notes some preliminary conclusions.

Intercooled Engines in NEWAC

The European Union FP6 NEWAC programme is coordinated by MTU and was launched in May 2006. The website www.newac.eu gives details of this integrated programme and describes four new engine concepts offering potential for step changes in core thermal efficiency and reduced emissions. The overall research programme has forty partners and it includes whole engine design studies and major rig tests to validate the new component technologies [1].

NEWAC is complementary to VITAL, another EU FP6 programme, which aims to improve propulsive efficiency and reduce noise. The technologies from these programmes will help us to meet the ACARE targets for new engines in 2020.

One of the baseline advanced core engine concepts in NEWAC is a high OPR intercooled turbofan with a direct-drive fan, and another is the intercooled and recuperated aero engine (IRA), scaled up from the IRA engine in the EEFAC CLEAN programme [2]. In both these engine types the IP compressor exit air is cooled before it enters the HP compressor, and this cooling is achieved using air taken from their bypass ducts. However the proposed NEWAC engine designs differ in several other respects as shown schematically in figure 2.

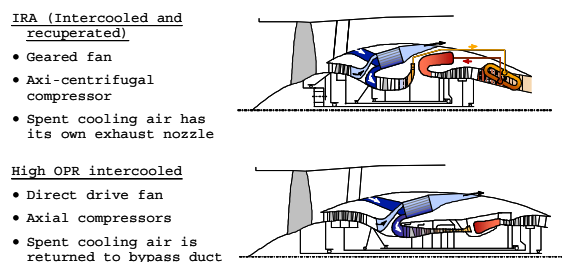


Fig. 2. Engines with Intercooling

Within NEWAC sub-programme SP1 the various baseline engine designs integrate the new technologies that are being researched in the other NEWAC sub-programmes. These engine designs will be updated with the results from those sub-programmes and used to assess pros and cons of the new technologies, which include intercooling alone and intercooling with recuperation. The NEWAC SP1 assessment of intercooled engines will be more detailed than those previously reported [3, 4, 5].

The "Intercooled Core" sub-programme SP3 is researching the key technologies needed for an intercooled turbofan to meet the specifications set in SP1. The

component technologies include an effective, compact and lightweight low-loss intercooler, low-loss inlet and outlet ducting systems for the intercooler, stiff engine and intercase structures to support the intercooler modules and to maintain rotor tip clearances, and new systems and blading designs to maintain compressor efficiency and operability in these higher OPR intercooled engine cycles.

Some SP3 technologies are also applicable to conventional engines and the IRA concept. For example the intercooler designs, ducting and installations are potentially applicable to the IRA, though that engine concept has axi-centrifugal rather than axial compressors.

Reducing NO_x emissions is a NEWAC objective, so lean combustion is researched in SP6 and assessed together with intercooling.

Figure 3 lists all the partners in NEWAC and highlights those that are active in SP1, SP3 and SP6. The remaining partners are active in other sub-programmes.

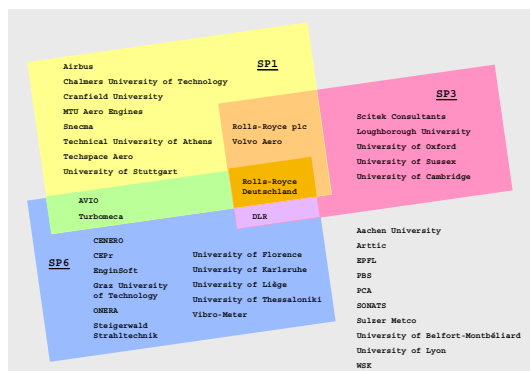


Fig. 3. NEWAC Partners

SP1 and SP3 are led by Rolls-Royce in the UK, which has also undertaken performance modelling and mechanical design studies for two sizes of intercooled engines.

In a parallel activity, the SP1 group of European Universities is developing a suite of aircraft, engine and environment modelling tools known as TERA2020. Each University works on the software and also models some baseline NEWAC

engines. Cranfield and Chalmers Universities have been modelling the intercooled engines.

Intercooled Engine Performance

In a conventional turbofan engine the thermal efficiency is increased by increasing OPR and optimizing TET. In an intercooled engine thermal efficiency is also improved by reducing the work required for compression, but this benefit is outweighed at low OPR by pressure losses in the intercooler and its associated ducting systems. Increasing OPR and taking advantage of a reduced HP compressor delivery temperature to increase combustor temperature rise reduces the core mass-flow and further increases the thermal efficiency. In contrast, the thermal efficiency for the IRA cycle peaks at a lower OPR, which is a function of the effectiveness of the recuperator. Figure 4 compares the thermal efficiencies of these three engine cycles.

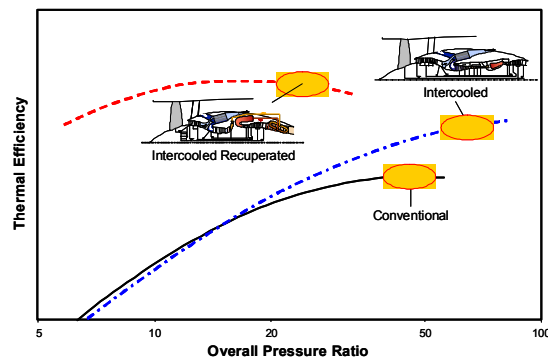


Fig. 4. Performance Comparison

In principle it would be more efficient to use fuel as the heat sink, but so long as the fuel is a hydrocarbon like kerosene it will have too little thermal capacity. Bypass duct air provides the most practical heat sink.

For these advanced cycles the energy rejected as heat from the core to the bypass duct airflow is partly recovered from an increased bypass duct exit jet velocity, but thermodynamically it is best only

to reject low-grade heat, so the intercooler is placed fairly early in the compression system. For the larger, high OPR intercooled engine the HP compressor pressure ratio is about 12 for an OPR of 80 at top of climb and optimum effectiveness for the intercooler is 60-70%. If the effectiveness is increased any more than this then the intercooler size and weight becomes excessive.

Airbus has set typical thrust requirements for the NEWAC and VITAL programmes, at climb, cruise and takeoff, for both larger and smaller engines, for long-range and short-range aircraft respectively.

The intercooled engine cycles are modelled with a new performance program that takes full account of intercooler off-design performance, the extra duct losses, and thrust recovery from the spent cooling air mixed back into the bypass duct.

Intercooled Engine Architecture

Heat Exchanger Installation:

The general arrangement of a typical three-shaft intercooled turbofan is shown in figure 1 and figure 5 shows the layout of the intercooled compression system, which has an array of intercooler modules around the core of the engine and inboard of the bypass duct. Ducts to connect the modules to the IP and HP compressors and the bypass duct.

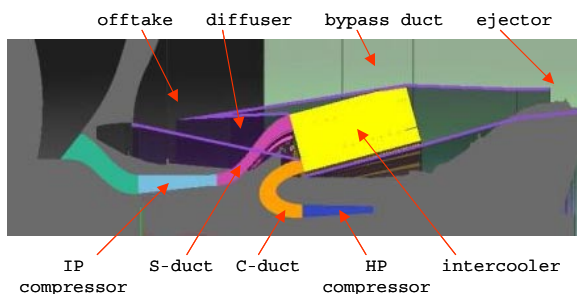


Fig. 5. Intercooling System Layout

A bypass duct offtake and a separate diffusing duct are needed to diffuse the cooling air before

it gets to the intercooler to avoid high pressure losses and since the cooling air mass flow is comparable with the core mass flow, a fully annular offtake is preferred. The IP compressor exit air also needs to be diffused upstream of the intercooler.

The intercooler inlet ducts need a certain length to diffuse the flow efficiently and to recover static pressure. Also, since it is hard to diffuse and turn a flow at the same time, the diffusing ducts need to be fairly straight. These considerations effectively fix the intercooler location. The design of the inlet duct to the HP compressor has accelerating flow that can more easily be turned through nearly 180° to bring it round to the HP compressor inlet.

Having several small modules, rather than one big intercooler, eases maintainability and helps minimize overall weight and volume.

In the proposed configuration each module has two cross-flow matrix units, like car radiators, but angled to the cooling flow to minimize frontal area and arranged in a V-shape. Cross-flow matrices make manufacturing and manifold connection easier. Figure 6 shows the V-shaped arrangement.

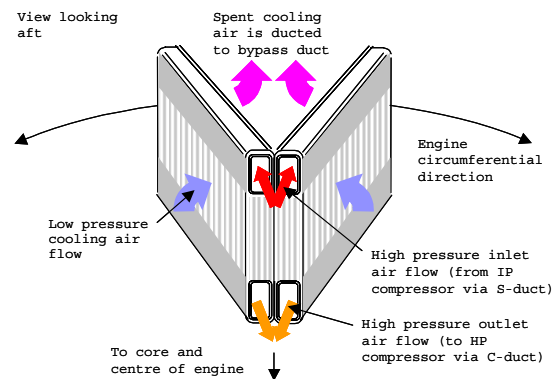


Fig. 6. V-shape Intercooler Module

In current intercooled engine designs the 20 or 24 modules are arranged in 4 groups leaving gaps at the top and bottom and sides of the engine core to improve core

access as shown in figure 7. For comparison the IRA proposal has 8 larger intercooler modules.

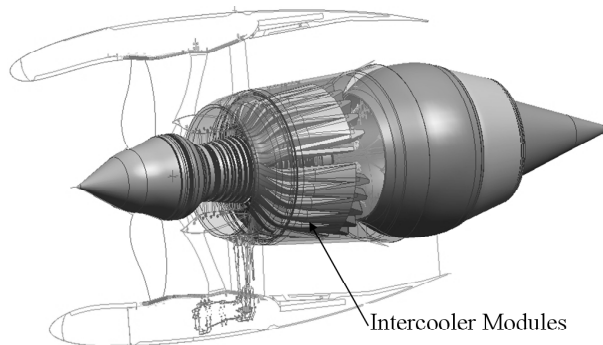


Fig. 7. Intercooler Arrangement

Compressor and Turbine Designs:

Preliminary compressor designs have been generated for the long-range and short-range intercooled engines and their efficiencies have been assessed. The IP compressors have lower pressure ratios and fewer stages and the HP compressors have higher pressure ratios and more stages than existing 3-shaft Trent engine designs. This is to optimize the IP/HP work split for the intercooled cycle. Both core compressors are axial, but the outlet guide vanes for the IP compressors are angled to help turn the exit flow away from the engine axis and they do not take all of the swirl out of the flow.

The IP/HP work-split requires new turbine designs. Consideration has been given to both one and two stage HP and IP turbines and to the optimum number of low pressure turbine stages. Typically the higher bypass ratios of the intercooled engines require one extra low pressure turbine stage.

Research Activity in SP3 and SP6

Heat Exchanger Ducting:

The aerodynamic design of the HP ducting has been a three-way collaboration between Rolls-Royce,

Volvo Aero and Loughborough University.

Ducting has been designed for the 320 kN long-range intercooled engine and near full scale models have been tested at Loughborough behind a single stage compressor generating inlet conditions that represent IP compressor exit. The diffusing S-ducts take advantage of the inlet swirl to help distribute the air between the unevenly spaced intercooler modules [6].

The HP ducts rig is shown in cross-section in figure 8 and fully built up for testing in figure 9.

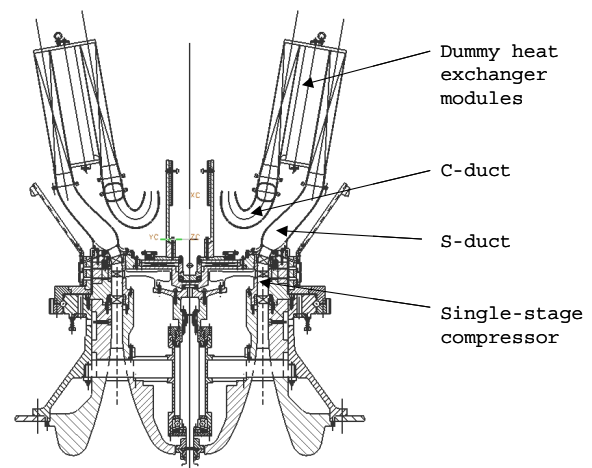


Fig. 8. HP Duct Rig Cross-section

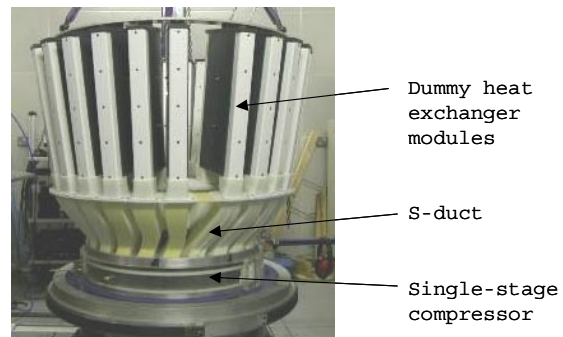


Fig. 9. Fully Assembled HP Rig

The test programme is now complete with S-duct and C-duct test results in line with CFD predictions. The conclusion from these studies is that the target performance can be met provided the S-duct splitters are not too fat

and the velocity profile at inlet to the C-duct is controlled.

For the low pressure ducting, the studies have concentrated on the annular offtake from the bypass duct and the downstream diffuser. A second fully annular test rig has been commissioned at Loughborough University to conduct a flexible series of experiments in different builds exploring different offtake and diffuser geometries and various area and mass flow ratios. The diffusion occurs both upstream and downstream of the offtake.

The rig has a single-stage compressor that is custom designed to simulate a fan and its outlet guide vane. To avoid testing at a very small scale, a cropped fan and a bypass duct of a reduced bypass ratio are modelled. This makes best use of the available airflow for the rig.

Figure 10 shows a half-section through the rig configuration for build 4, which has a diffusing duct together with representative S-duct blockage modelled down-stream of the splitter. These experiments continue through 2009.

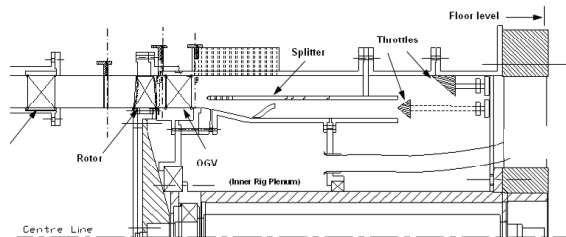
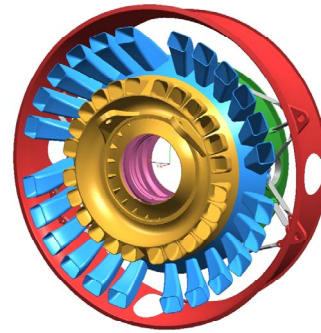


Fig. 10. LP Duct Rig Cross-section

Intercase Design:

The intercase or frame between the IP and HP compressors is a main structural component of the engine and critical to maintaining carcass stiffness. The mechanical design is more complex in the intercooled engine because it must accommodate the S-duct and C-duct, so Volvo Aero is working-up the large engine intercase design in detail. Figure 11 shows the current arrangement.



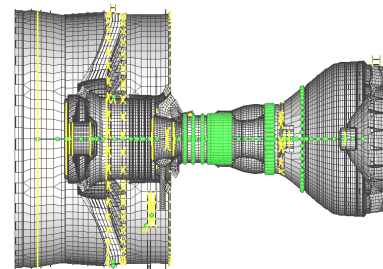
Preliminary Intercase design for 24 intercooler modules viewed from aft

Fig. 11. Intercase Assembly

Whole Engine Modelling:

A potential problem for the intercooled engines is that their smaller diameter cores may be more flexible than those of conventional engines, and under thrust loads and manoeuvre loads the HP casings may be subject to more distortion, giving a disproportionate increase in tip clearance to the now smaller HP compressor and turbine blades.

Initial whole engine mechanical modelling of the long-range engine confirmed that this hazard was real and could affect the HP compressor efficiency. Further modelling has started, using a stiffer intercase design. We expect tip clearances to be improved with little weight increase. Figure 12 shows part of the original whole engine model.



Note small diameter core in relation to fan case

Fig. 12. Whole Engine Model

An intercooled engine with its small core operated at high speeds and working at increased absolute pressures also sets challenges for

transmissions design and bearing load management. Ongoing studies are also addressing these issues.

Intercooler Design and Testing:

The intercooler is an air-air heat exchanger that operates up to around 300°C and 8 bar, which is not as challenging as recuperator designs. A wide range of materials and constructions can be used, but 300°C is too hot for conventional aluminium alloys. The challenge is to design an effective, compact, lightweight, low-loss, durable, and affordable heat exchanger that also has very good resistance to fouling and blockage. The modules must include HP inlet and outlet manifolds and attachment and sealing features.

The selected intercooler matrix configuration is a cross-flow cross-corrugated primary surface design. This type of matrix does not need to use a material of very high thermal conductivity and it also offers multiple paths to the airflow, as shown in figure 13.

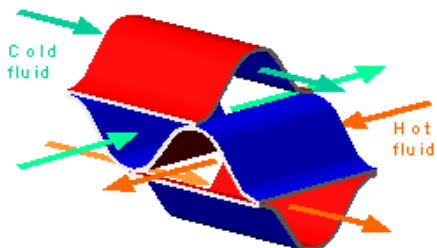


Fig. 13. Two Unit Cells of Matrix

A significant area of research concerns heat exchanger entry and exit losses. Because of the need to minimize the frontal area of the intercooler assembly, the hot and cold airflows both need to turn through nearly 90 degrees at entry to and exit from the matrix, giving high approach velocities that have the potential to produce flow mal-

distribution reducing intercooler effectiveness and increasing loss.

These design issues have been addressed by research studies at Rolls-Royce and Oxford University. Figure 14 shows an experimental configuration for rig testing at Oxford. The flow distribution on the LP side of the intercooler has been improved by modifying matrix entry and exit geometry. Work at Oxford is also quantifying effects of detail design changes on heat transfer performance and pressure loss at entry to the matrix.

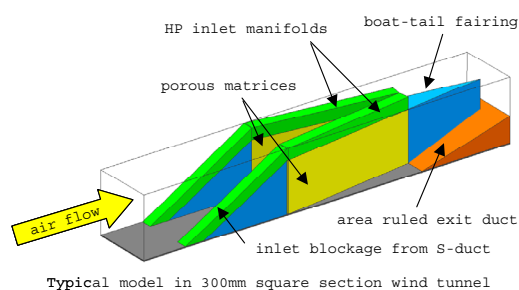


Fig. 14. Intercooler LP Aero Rig

Prototype intercoolers are being manufactured using powder bed deposition by selective laser melting. This may not be the preferred manufacturing route for production intercooler modules, but it enables new designs with complex and novel features to be made and tested relatively quickly. A cross-corrugated test piece that was produced during manufacturing trials is shown in figure 15.

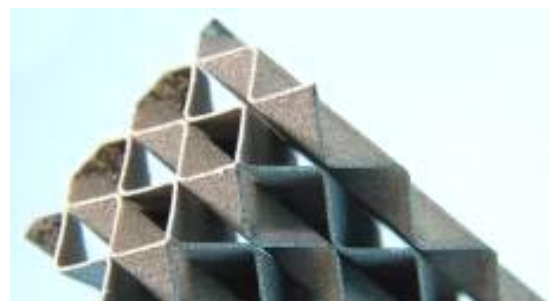


Fig. 15. Matrix Test Piece

The first metal prototype was delivered for testing in April 2009, but it does not incorporate all the lessons learned from the installation studies. A second prototype design is expected to demonstrate improved performance. The prototype designs represent just part of a V-shape module, as shown in figure 16.

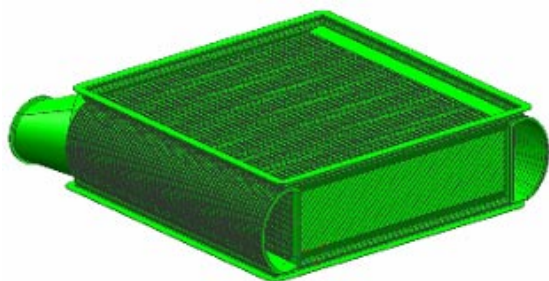


Fig. 16. Prototype Intercooler

The test rig for the prototype heat exchanger units was built and commissioned by Scitek Consultants.

Compressor Research in SP3:

Introducing intercooling to a 3-shaft engine design creates additional challenges for the core compressors. The high OPR proposed to maximize the cycle efficiency gains must be achieved without compromising component efficiencies or compressor operability. The IP/HP work split and the compressor working lines are significantly different to conventional designs, increasing demands for off-design handling capability. Also the small core size puts extra pressure on maintaining competitive tip clearances, which become limited by some mechanical and manufacturing constraints that do not scale.

With these challenges in mind a substantial element of the work in SP3 has been aimed at the design of highly efficient and operable core compressors. The three main areas of research are, (1) advanced blading design, (2) stability enhancement, and (3) tip clearance improvement. As these technologies

are to a large degree also relevant to conventional engine cycles with increased OPR (that are foreseen in the medium term) this research is expected to contribute to improved efficiency and reduced SFC for both engine types. These technologies are demonstrated on low-speed rigs and by HP compressor rig testing.

The latest parallel 2D/3D blade CFD design methods are applied throughout the compressor and they include optimizing leading edge shapes and camber distributions to minimize secondary losses. A particular design aim has been to desensitize compressor performance to tip clearances such that any potential deficit due to the reduced core size will have less effect on compressor efficiency and operability. This work has been carried out by Rolls-Royce aero teams in the UK and Germany. The new blading is shown in figure 17.



Fig. 17. HP Compressor Blading

The final design is to be tested on a high-speed rig at the AneCom Aerotest facility. The test campaign is underway in April 2009 and involves overall performance characterization as well as detailed flow measurements that will be used to validate CFD tools. Figure 18 shows the rig.

Methods of enhancing the stability of the compressors are being investigated in Rolls-Royce Deutschland and at the University of Cambridge. These are focussing on re-energizing the tip flow via recirculation of a small portion of the core mass flow.

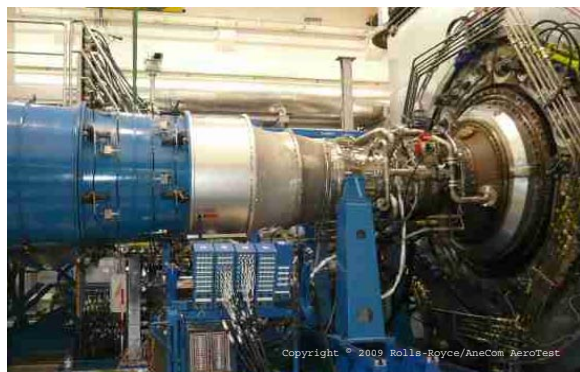


Fig. 18. HP Compressor Rig

Rolls-Royce has developed a tip recirculation system utilizing air from rear stages of the compressor, which is injected through casing slots over the front rotor stages as illustrated in figure 19. The effectiveness of the system in extending the operating range of the compressor has already been demonstrated in low-speed tests (carried out prior to NEWAC) and refined through steady and unsteady CFD calculation. It will now be validated as part of the planned NEWAC SP3 high-speed rig test.

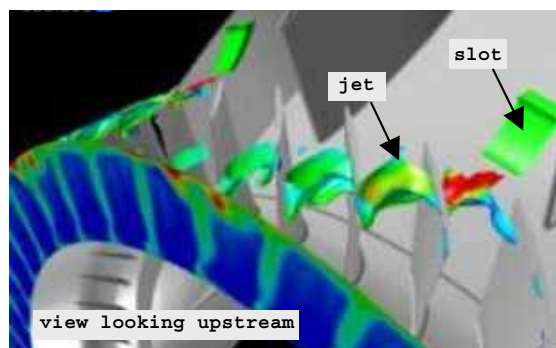


Fig. 19. Tip Blowing Jets

An alternative approach is being followed at Cambridge where the recirculation is carried out at a more local level. As figure 20 shows, air can be bled from within a given rotor stage and re-injected into the tip flow.



Fig. 20. Local Offtake Positions

Careful placement and design of the oftakes enables the system to be most active at the off-design points where the re-injected flow is most effective in extending the operating range of the stage. Low speed testing is in progress to confirm the expected behaviour and, if shown to be successful, this technology would be a candidate for the later high speed rig testing.

In an attempt to minimize the impact of the small core size and the risk of additional carcass distortions in an intercooled cycle engine, studies have been undertaken to identify casing and rotor concepts that can reduce the level of tip clearance required throughout the flight cycle. These studies have mostly focused on passive and adaptive technologies that minimize the mismatch between rotor and casing thermal responses or isolate the rotor path from the thermomechanical loads.

One of the more promising technologies being developed involves speeding up the rotor drum transient thermal response by careful use of core flow bleeds into the drum cavities combined with features that enhance the heat transfer. CFD studies and validation rig testing are being carried out at the University of Sussex, utilizing a disc heat transfer rig as shown in figure 21.

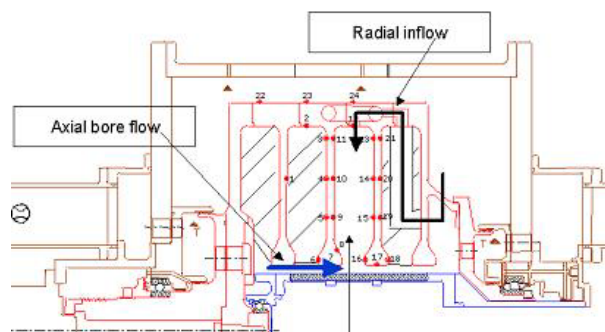


Fig. 21. Disc Heat Transfer Rig

LDI Combustor Design:

Three types of lean combustor are being researched in SP6 [1]. The lean combustion technology most suited to the higher OPR engines is Lean Direct Injection (LDI), and Rolls-Royce Deutschland has sized single annular LDI combustors for the intercooled study engines.

Preliminary estimates for the LDI combustor NOx emissions have been made, but more definitive assessments will be made following further combustor testing at higher pressures in SP6.

Intercooled Engine Assessment

SP1 is assessing the value of the new technologies in the NEWAC baseline engines, and also in some new engines that combine several different technologies from the NEWAC and VITAL programmes.

Initial assessments of the intercooled engines indicate that they could come close to meeting performance improvement targets, but might struggle to meet their weight targets. They are expected to show a significant improvement in NOx margins, particularly for the long-range intercooled engine.

Acknowledgments

The authors would like to thank Rolls-Royce plc and the other NEWAC

partners for permission to publish this paper. The authors also wish to thank the E.U. for supporting this programme - the work is part funded under E.U. contract number FP6-030876.

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