New Environmental Friendly Aero Engine Core Concepts

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Abstract

Large investments have already been made in Europe and the US through R&T programmes and collaborations to reduce the negative environmental effects of aircraft use. Research is therefore providing the technologies to improve the performance of existing engine components.

However, even if these technologies improve noise and pollution emissions, their existing limitations will not allow the industry to reach the goals set in the field of aeronautics research in the Vision 2020 report made by ACARE Strategic Research Agenda (SRA).

A first step to reach these 2020 objectives has been set-up through the technology projects targeting noise, NO_X and CO_2 emission reductions. The EU integrated project VITAL /1/ is focusing on technologies for low pressure system improvements to reduce CO_2 and noise. There is however, complementary research to be performed on combustor technologies and introduction of new engine core configurations to reduce NO_X emissions and further reduce CO_2 to achieve the SRA 2020 objectives.

Alternative engine configurations consequently need to be investigated in order to find a more significant and durable reduction of pollution. This will be developed within the EU integrated programme for **NEW** **A**ero engine **C**ore concepts (NEWAC).

The main result of this programme will be validated new technologies enabling a 6% reduction in CO_2 emissions and a further 16% reduction in NO_X. This paper describes the content of the programme and presents first results of concept work already preformed.

Abbreviations

ACARE	Advisory Council of Aeronautic Research in Europe
ACC	Active clearance control
ASC	Active surge control
AEROHEX	Advanced Exhaust Gas Recuperator Technology for Aero-Engine Applications
BPR	Bypass Ratio
CLEAN	Component Validator of Environmentally Friendly Aero-Engine
EEFAE	Efficient & Environmentally Friendly Aero-Engine
HPC	High Pressure Compressor
NEWAC	New Aero Engine Core Concepts
EIMG	Engine Industry Management Group
FP	Framework Programme
IRA	Intercooled Recuperative Aero engine
LDI	Lean Direct Injection
LPP	Lean Premixed Prevaporized
OPR	Overall Pressure Ratio
PERM	Partial Evaporation & Rapid Mixing
SAC	Single annular combustor
SILENCER	Significantly Lower Community Exposure to Aircraft Noise
SRA	Strategic Research Agenda
TERA	Technoeconomic and Environmental Risk Analysis
VITAL	Environmentally Friendly Engine

Introduction

Global air traffic is forecast to grow at an average annual rate of around 5% in the next 20 years. This high level of growth makes the need to address the environmental penalties of air traffic all the more urgent. As a result Europe's aviation industry faces a massive challenge to satisfy this demand for increased air travel in an economic and safe way. Therefore alternative engine configurations need to be researched in order to find a significant and permanent reduction of pollution.

The Advisory Council of Aeronautical Research in Europe (ACARE) identified the research needs for the aeronautics industry for 2020. The engine has to contribute to the overall ACARE targets with a 20% reduction in CO_2 emissions per passenger-kilometre, 10 dB noise reduction per certification point and a 80% reduction in NO_X emissions. The existing technology programmes have already identified concepts and technologies to contribute to these goals.

NEWAC is a new European-level programme – under the leadership of MTU Aero Engines in which major European engine manufacturers, assisted by universities, research institutes and enterprises – 40 partners in all - focus on new core engine concepts. NEWAC will develop and validate novel core engine technologies to further close the gap between the current emissions and the ACARE targets. NEWAC is a 71 million Euro programme of which 40 million Euro is funded by the EC.

Four core concepts will be investigated:

- **Intercooled Recuperative Core** for the intercooled recuperative aero engine concept (IRA) operated at low OPR and using a LP(P) combustor concept.
- **Intercooled Core** for a high OPR engine concept based on a 3 shaft direct drive turbo fan (DDTF) with a LDI combustor
- **Active Core** with active systems applicable for a geared turbo fan (GTF) using a PERM combustor.
- **Flow Controlled Core** for the counter rotating turbo fan (CRTF) using a PERM or a LDI combustor

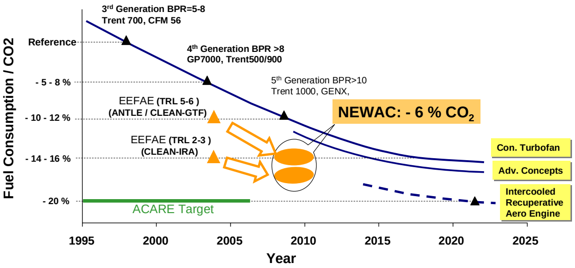

Fig. 1: Target for CO_2 reduction

The main NEWAC result will be fully validated novel technologies enabling a 6% reduction in CO_2 emissions (Fig. 1) and a further 16% reduction in NO_X (Fig. 2).

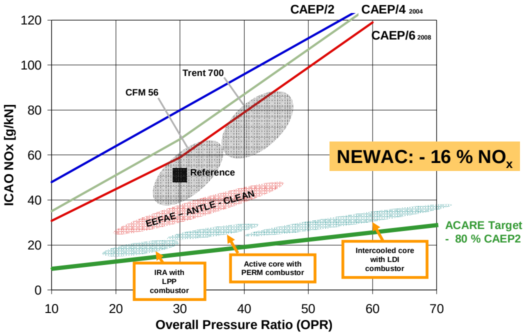

Fig. 2: Target for NO_X reduction

All new configurations investigated in NEWAC will be specified in detail, compared, assessed and ranked regarding their benefits and contributions to the global project targets. As a result, NEWAC will identify the technology routes to environmentally friendly and economic propulsion solutions. The developed components will further result in optimised engine designs based on the NEWAC technologies but also in combination with the results of the EEFAE, SILENCER and VITAL programmes.

New Core Concepts

While the focus of VITAL /1/ is on propulsion efficiency to reduce CO_2 and noise, NEWAC will address innovative core engine concepts to improve the thermal efficiency.

For a conventional gas turbine cycle the thermal efficiency is mainly a function of the overall pressure ratio and the turbine entry temperature. A further increase of overall pressure ratio and turbine entry temperature is limited by maximum material temperatures and increasing NO_X-emissions. But the thermal efficiency of gas turbine cycles can be effectively increased, if heat transfers between flows are managed, which is already widely applied in ground based applications. Figure 3 shows the thermal efficiency of such advanced gas turbine cycles in comparison with the conventional gas turbine:

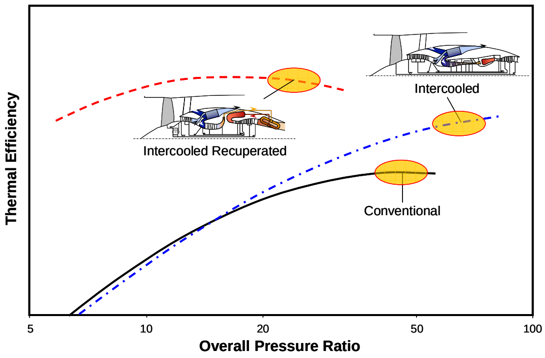

Fig. 3: Thermal efficiency of different gas turbine cycles

- **Intercooled Core**

  The introduction of an intercooler to a core configuration is an enabler for very high overall pressure ratios. It leads to fuel burn improvements by reducing the compression work.

- **Intercooled Recuperated Core**

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

Both the intercooled recuperated and the intercooled core will provide a breakthrough in thermal efficiency, however, at the expense of higher complexity especially for the intercooled recuperated core.

Beside the implementation of new engine cycles the improvement of the component efficiencies will continue to help to reduce fuel consumption as shown in Figure 4.

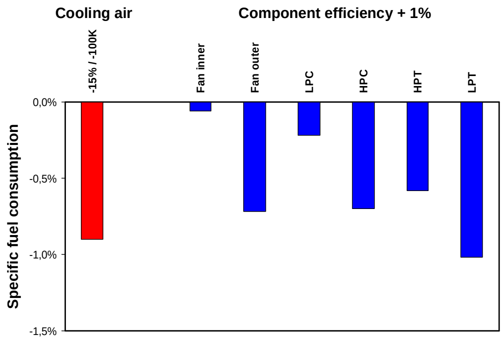

Fig. 4: Impact of component efficiency and cooling air on specific fuel consumption

Figure 4 highlights yet another potential improvement. As up to 30% of the compressor air is used for cooling purposes a reduction of the cooling air mass flow by use of cooled cooling air opens up a new possibility for improved fuel consumption.

In order to realize higher component efficiency NEWAC will adopt active systems and flow control elements to the core:

- **Active Core**

  Aero engines are operated in very different operating conditions during their flight mission. As an actively controlled core can be adapted to each operating condition, a breakthrough is expected regarding fuel burn and operability. Furthermore, active systems open up additional degrees of freedom in the design, as the core need not any more be designed on a worst case basis. Finally, loss of efficiency due to deterioration and design margins can be compensated to a certain degree by adjusting the core to the actual conditions. In NEWAC active systems will be applied to the HP compressor and a cooling air cooling system.

- **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 investigated in NEWAC, which help in the specific field of very high aerodynamic loaded HPC to strongly increase efficiency and stall margin.

Based on these ideas four NEWAC core configurations – shown in figure 5 – were derived aiming at different applications concerning thrust and mission. For each configuration the most critical key elements will be investigated in NEWAC.

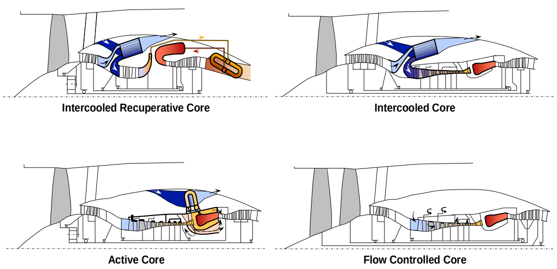

Fig. 5: NEWAC core concepts

Intercooled Recuperative Core Concept

One potential core engine configuration to achieve ACARE 2020 objectives is the concept of the Intercooled Recuperative Aero-Engine IRA. The proposed IRA cycle, already established in EEFAE CLEAN /2/, /3/, will use significant benefits from a further increase in propulsive and thermal efficiency with a potential of up to 20% fuel consumption / CO_2-emission reduction.

The significantly lower OPR of a typical IRA cycle compared to a conventional approach for a highly efficient high OPR engine cycle will by itself support ultra low NO_x combustor conditions: highly efficient IRA-cycles with OPR<30 may enable the additional application of ultra low NO_x combustor technologies, not applicable to high OPR engines.

Fig. 5 shows a functional scheme of NEWAC IRA and Fig. 6 a potential scheme of IRA integration in a conventional nacelle and underwing configuration.

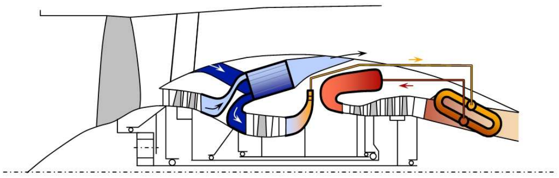

Fig. 6: Functional scheme of Intercooled Recuperative Core Concept for IRA

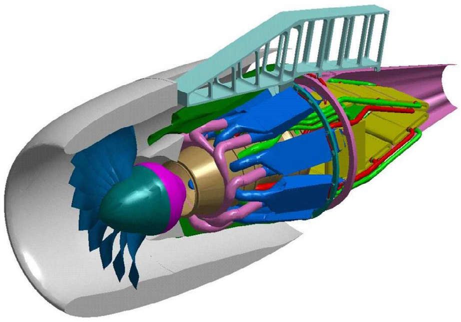

Fig. 7: IRA integrated in conventional nacelle and underwing configuration

Based on the results of EEFAE CLEAN and AEROHEX, NEWAC will investigate key components of the IRA core concept in more detail: Firstly, the recuperator and its optimal arrangement in the exit duct (the intercooler will be investigated in the Sub-Program Intercooled Core Configuration). Secondly, the centrifugal compressor is identified as most suitable to support the overall concept transferring the flow to the piping system. As the specification of the IRA HPC is outside of today's experience, a centrifugal HPC complying with the requirements of the IRA engine application will be investigated and validated. Finally, the advanced LPP combustor, which is well suited for the low OPR IRA cycle, will support further NO_X reduction of this concept and will be validated within the innovative combustor work.

The objective is to demonstrate an improvement of 0.8 % efficiency and 10 % lower weight of the compressor and 15 % lower pressure losses in the recuperator.

To fully meet the environmental goals and the market requirements and to address potential shortfalls of the main core concepts under investigation in NEWAC, additional effort on selected "more innovative core configurations" is planned to allow and initiate a discussion to even further challenge engine-targets beyond the ACARE 2020 objectives. The system studies will cover:

- variable core cycles
- innovative combustion
- contra rotating core
- unconventional heat management system

Intercooled Core Concept

Intercooled and recuperated cycles have the potential for lower SFC, but intercooling alone still offers benefits and may be more cost effective as it avoids the weight and complexity of a recuperator /4/ (Fig. 8).

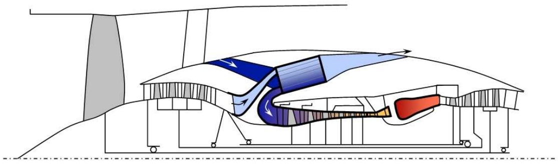

Fig. 8: Schematic of engine with intercooled core

The concept developed in NEWAC is the high OPR intercooled turbofan engine, which uses part of the bypass duct airflow for intercooling.

Intercooling reduces the work required to achieve a given OPR, or enables OPR to be increased for the same work. It also reduces HP compressor delivery temperature relative to a simple cycle gas turbine. This means that the combustor temperature rise is bigger for a given TET and the turbine cooling air is cooler so that less cooling air mass flow is required. These effects increase the specific power of the core, so that core size and mass flow are reduced and bypass ratio is increased for an engine of given thrust and fan diameter.

The above effects all improve thermodynamic efficiency, but this improvement is offset by pressure losses in the heat exchanger and ducting systems. To make intercooling viable these pressure losses and the cost, weight and volume of the intercooler must be minimised.

Because intercooled engine cycles have lower flame temperatures for a given TET they also have fundamentally reduced NO_x emissions.

The cross-section of a typical intercooled turbofan is shown figure 9, and figure 10 shows one way of arranging a number of intercooler modules around the core of such an engine.

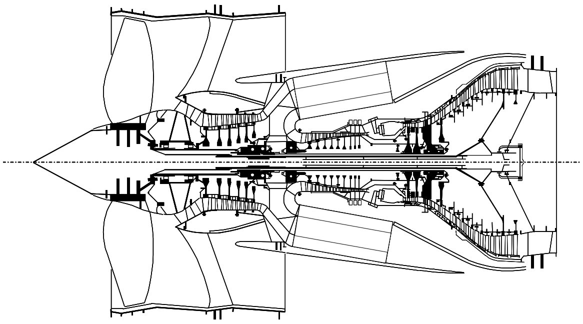

Fig. 9: Typical Intercooled 3-Shaft Engine with Direct Drive Fan

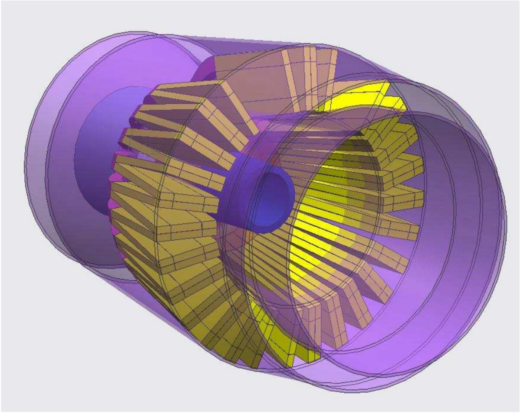

Fig. 10: Intercooler Modules Arranged Around the Core of an Engine

NEWAC will research the technologies required to realize an efficient intercooled aero engine.

Activities include the preliminary design of a high OPR intercooled compression system, the aerodynamic design and testing of high pressure and low pressure ducts to take air to and from intercooler modules, the mechanical design and analysis of an advanced intercase structure incorporating the new high pressure ducts, the design optimisation of a very compact and lightweight cross-corrugated heat exchanger module and the manufacture and testing of heat exchanger components.

It also includes the design and rig testing of a high pressure compressor and some associated technologies to enable compressor efficiency to be maintained and improved at the smaller core sizes and higher pressure ratios required for the intercooled aero engine.

The objective is to demonstrate the potential for a 4% SFC improvement and a 16% NO_x reduction from a combination of intercooling, cooler turbine cooling air and compressor efficiency improvements.

Active Core Concept

Aero engines are operated in very different operating conditions during their flight mission. As an actively controlled core can be adapted to each operating condition, significant operating advantages can be achieved and additional degrees of freedom are offered in the design phase as the core does not have to be designed for the worst case operating point. In NEWAC the two most promising areas for active systems in a core engine will be investigated (Fig. 11).

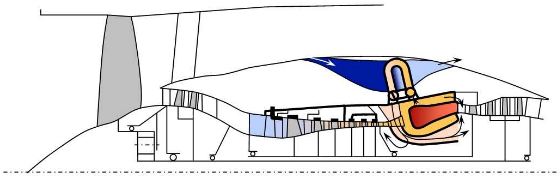

Fig. 11: Schematic of engine with active core elements

The first one is an active cooling system which offers an enormous improvement potential. It lowers the temperature of the cooling air for the HPT and for other cooled parts. In modern core engines a fixed amount of 20% to 30% of the air delivered by the HPC is used for cooling the HPT, thus “bypassing” the cycle and having further detrimental effects on the core.

Cooling air cooling has been identified in /5/ and /6/ for enabling high pressure cycles with high turbine exit temperatures. Nevertheless, the potential for medium OPR cycles is significant as well, as the needed amount of cooling air can be reduced. In the known studies, cooled cooling air is provided only to the turbine blades, and the amount and temperature of the cooled air is fixed. These systems promise only a moderate SFC reduction. In NEWAC a new, highly advanced cooling air system will be investigated for which, not only the rotor blades, but also the stator vanes, the rotor disk and the liners are supplied with cooled cooling air. In addition, the cooling air temperature is actively controlled depending on the mission point. This will reduce the necessary amount of cooling air to a minimum.

Furthermore, as another positive implication of the availability of cooled compressor air, the use of cooled air for cooling the HPC rear cone will be investigated. This component is critical concerning temperature levels and related material stresses and opens up new manufacturing options.

The second area of research within the Active Core are active systems in the HPC itself. The technologies addressed in NEWAC are an active clearance control system (ACC) and an active surge control system (ASC) (Fig. 12).

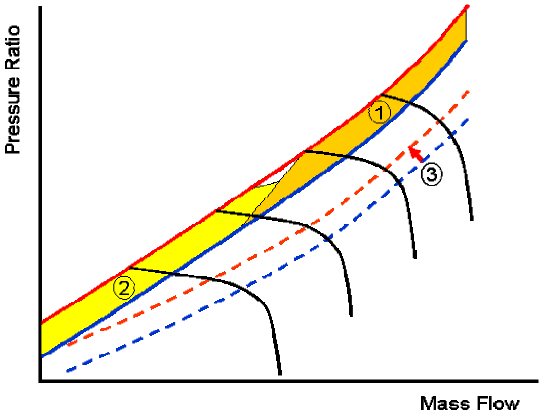

Fig. 12: Compressor map showing surge margin gain of ACC (1) and ASC (2) and the resulting benefit of lifting the operating line (3)

These two technologies should be validated in a core engine test allowing for realistic transient operation, vibrations and temperature levels.

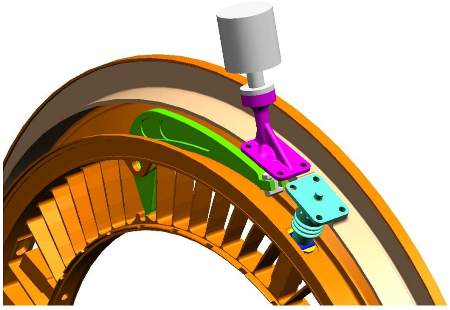

Fig. 13: Example for an active clearance control system

Casing integrated ACC for compressor rear stages provides significantly better efficiency and increased full speed surge margin. Deterioration of radial clearances can be eliminated, thus providing additional efficiency and surge margin for engines in service. Within NEWAC, two types of ACC – a thermal and a very ambitious mechanical approach – will be studied and compared with alternative technologies for tip clearance improvement (Fig. 13).

In addition to active clearance control, active surge control (ASC) for compressor front stages via air injection enhances the operability of the engine at part speed conditions. Together with a rear stage ACC, an optimum operation can be achieved over the full flight envelope as shown in Fig. 12. The technology enables a design for normal flight operation by eliminating the worst case requirements in part power conditions. Currently no ASC systems are in aircraft use. However, several demonstrators and research compressors exist, which show the system's potential /7/ /8/ /9/ /10/.

In NEWAC, the benefits of ACC and ASC will be investigated and compared with the passive alternative, a multi stage casing treatment. To achieve this target, highly advanced casing treatments will be developed and rig tested to provide a benchmark for the effectiveness of these active systems.

The chosen combination of active and/or passive technologies will then be tested in a core engine at realistic conditions. The key issues for all these systems - flight safety, weight, system complexity and cost – can then be properly evaluated. The objective is to validate a 4 % SFC increase and 1 % propulsion system weight reduction.

Flow Controlled Core Concept

In order to meet the ACARE 2020 objectives, strong improvements on engine component efficiencies are required in addition to new engine architectures. The VITAL program evaluates new high BPR architectures (such as CRTF, see Fig. 14) involving limited pressure ratio from the booster (low speed) and resulting in very demanding pressure ratio requirements from the core engine to reach a high OPR.

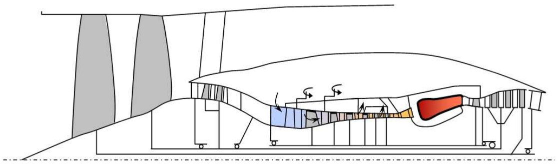

Fig. 14: Schematic of engine with flow controlled core in CRTF architecture

The Flow Controlled Core approach focuses on the compressor module by developing and integrating innovative technologies, providing a significant increase of efficiency and stall margin in the highly loaded HPC.

The strategy is based on the implementation of innovative concepts capable of local control of the compressor flow field. The optimised design of the compressor in association with the integration of these aero-oriented technologies leads to a global benefit. The Flow Controlled Core can also be applied to more conventional high BPR turbofans.

More precisely, these new and significant progresses in the field of highly loaded compressors will be made possible through the combination of several approaches.

Implementation of breakthrough technologies able to control the flow locally, either near the operating line or near the stall line, associated with an adapted and suited advanced aerodynamic design for both improved efficiency and stall margin. Among these technologies, advanced casing treatment specifically designed for HPC will be considered, as well as other more prospective concepts such as casing aspiration or air injection. Aspiration will be evaluated both on casing walls and blades profiles where innovation is a lot higher and can lead to new perspectives (see Fig. 15) /11/. The objective will be to integrate and link as much as possible these different technologies of flow control, through the idea of aspiration concept, to the engine air system.

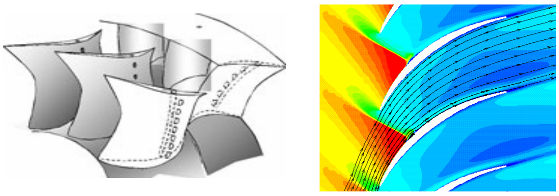

Fig. 15: Aspirated blade concept

Design advanced 3D aero suited to flow control devices: Taking into account past experience, multistage 3D CFD codes will permit implementation of 3D shapes and local optimisation such as non axi-symmetric inner end wall profiling, specific tip shape or local design of the outer flow path like trenches. The aim will be higher efficiency, stability and lower sensitivity to clearance opening.

Continue maturation of the stall active control system initially tested with success in the EEFAE-CLEAN program. The specific goal will be to integrate and optimise stall active control system, such as fast-opening bleed valves, into a real-engine environment for full benefit.

Blade casing rub management for tight tip clearances will also be addressed; the objective is to enable soft rub between blade and casing, free of secondary effects such as clearance opening due to unwanted rub-induced dynamic phenomenon or material transfer between abradable and blade. The development of sophisticated abradable and blade/casing contact modelling will lead to design guideline, Fig. 16. In parallel, the development of an improved abradable material more tolerant to contact will be carried out.

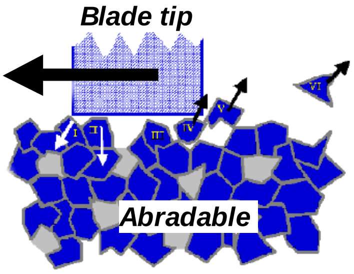

Fig. 16: Blade/casing rub advanced modelling

At last the integration of all the above technologies will be optimised in a consistent design for a “flow controlled core” concept.

The FCC focuses deeply on innovative HPC technologies, with the objective to increase strongly the state of the art in terms of polytropic efficiency (+2,5%), stall margin (+15%) and robustness toward degradation (–1/3).

Innovative Combustor for New Core Concepts

Lean combustion technology operates with an excess of air to significantly lower flame temperatures and consequently significantly reduce NO_X formation. Up to 70% of the total combustor air flow has to be premixed with the fuel before entering the reaction zone within the combustor module. Therefore, cooling flow has to be reduced accordingly to provide sufficient air for mixing.

Lean combustion comprises the lean direct injection of fuel, premixing with air and at least a partial pre-vaporisation of the fuel before initiating the combustion process. The optimisation of homogeneous fuel-air mixtures is the key to achieving lower flame temperatures and hence lower thermal NO_X

formation. However, this homogenisation has a strongly adverse effect on combustion lean stability, drastically narrowing the operating and stability range. To overcome these stability drawbacks while maintaining good NO_X performance, fuel staging is required.

This can be made in a staged combustor architecture by multiple rows of injectors. A staged combustor is geometrically separated into at least two zones, so that each zone can be optimised for a particular requirement (regarding different parts of the flight envelope) and could thus offer good stability at low power. Alternatively, fuel staging can be achieved using internally staged injectors in SACs, thus creating a pilot and a main combustion zone downstream of a common fuel injector as Figure 17 illustrates /12/.

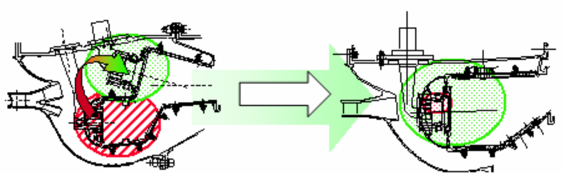

Fig. 17: Development towards a lean burn technology single annular combustor (SAC)

The SAC combustor geometries are much simpler and thus more advantageous with respect to unit cost, weight and cooling; cheaper to make, lighter and easier to cool. But even for the SAC, cost and weight reasons will demand that the total number of low emission injectors per annulus has to be minimised. As they are more complex compared to conventional air-blast fuel spray nozzles a significant proportion of the combustor cost will now be related to these advanced internally staged injectors.

In contrast to previous projects with several approaches to lean combustor architectures, NEWAC is concentrating on a SAC architecture with lean injectors.

The Ultra Low NO_X (ULN) combustor core technology is highly depending on the performance of the learn burn injection system. Air quantity needed for emission abatement is expected to be 60 to 70% of the combustion air. With this level of injector air-to fuel ratio, operability including ignition, altitude re-light, pull-away, weak extinction stability and thermo-acoustics will be a serious problem which needs to be carefully taken into consideration during ULN combustor development.

On this basis, the ULN lean premixed technology will require fuel-staging system to control the performance of the combustor through the entire engine cycle.

For the fuel injection system the current status of these techniques does not allow a down-select of injector technology. It would be too risky to make a selection before major performance parameters have been assessed and validated especially the characterisation of operability and thermo-acoustic behaviour. Thus, three different lean fuel injection systems will be investigated, based on previous EC and national funded projects:

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

They will be developed for applications in a wide range of engine OPR as shown by Figure 18.

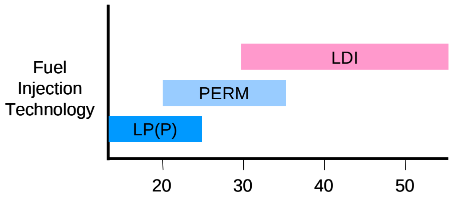

Fig. 18: Application of different fuel injector technologies depending on OPR

LP(P) injection - this concept is much more suited to low OPR engine cycles due to the fact that auto-ignition and flash-back constraints are much lower for this range of engines. It is based on the action of several air flows, one devoted to the fuel atomisation and the second dedicated to the mixing and fuel evaporation. The combination of the two acts also as a promoter for the flame stabilisation in the combustion chamber.

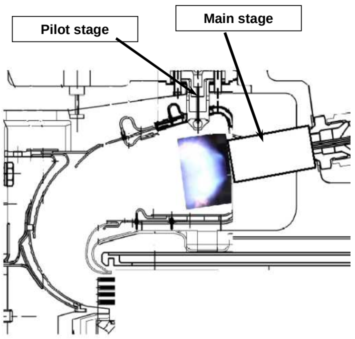

Fig. 19: LP(P) Combustor

PERM - the concept is based on swirler technology development and is addressed to achieve partial evaporation inside the inner duct and a rapid mixing within the combustor, optimising the location of the flame and the stability of the Lean System.

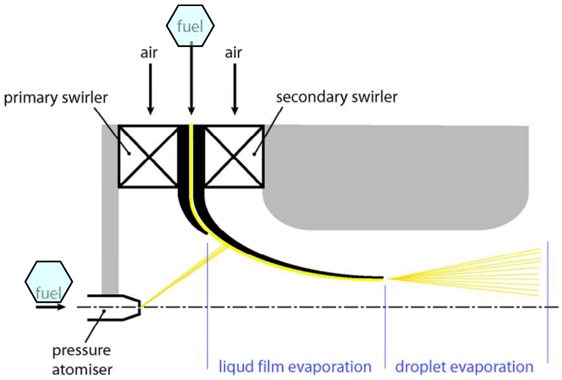

Fig. 20: PERM Combustor

LDI – This concept has a controlled premixing: concentric internally staged fuel injection with optimised pilot and main stage flame structure to control their interaction for low NOx and weak extinction stability.

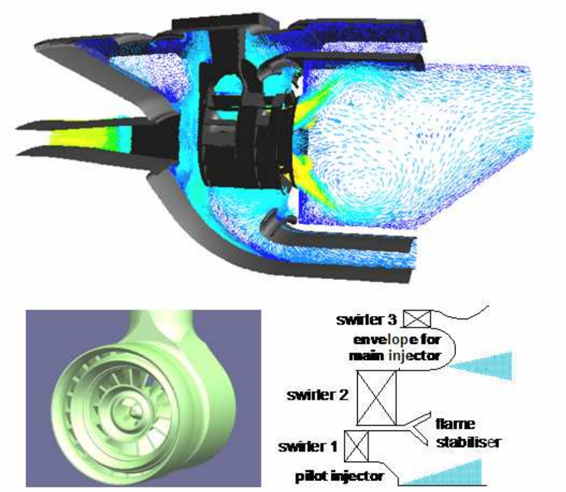

Fig. 21: LDI Combustor

Advanced measurement techniques will give insight into the fuel preparation, fuel placement, the initial combustion flame front of both pilot and main combustion zones. They support the identification of problem areas and help to define necessary modifications. The sequence of CFD, sector testing and detailed measurement campaigns will be an iteration process feeding in results into a modified fuel injector layout. Full annular testing will finally validate the new derived fuel injector technologies simulating real engine conditions within a full combustor scale.

Whole Engine Integration

For all core concepts the requirements and objectives were defined, starting with whole engine performance cycle data. The programme 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 as indicated in figure 22.

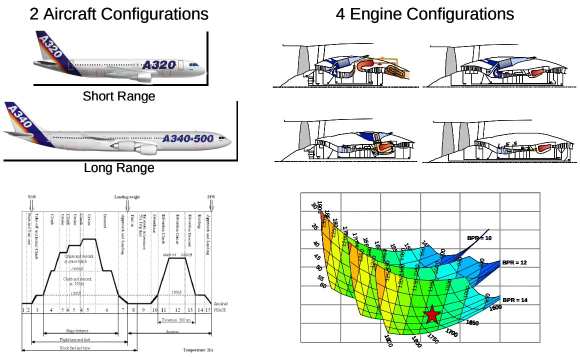

Fig. 22: Technical Approach to Whole Engine Integration

A significant work package within NEWAC will be to adapt and develop the software tool TERA (Technoeconomic and Environmental Risk Analysis), previously created in the VITAL programme, in order to compare the environmental and economic impacts of the new designs. Issues to be addressed include performance, weight, engine installation, NO_X and CO_2 emissions, noise, fuel costs, maintenance cost and aircraft flight path and altitude. The socio-economic model will identify engines with minimum global warming potential and lowest cost of ownership as shown in figure 23.

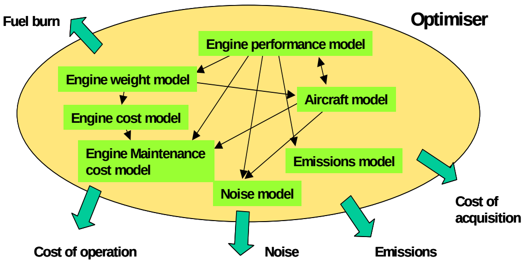

Fig. 23: Technoeconomic and Environmental Risk Assessment (TERA)

After assessing the ability of the four NEWAC engine configurations to meet ACARE 2020 objectives, the whole engine integration will combine NEWAC and VITAL technologies to generate new aero-engine configurations with optimised environmental performance and economics.

Summary

The NEWAC programme addresses the validation of new technologies necessary for the achievement of ambitious environmental objectives of future aero engines. It will provide a step change for low emission engines by introducing new innovative core configurations to strongly reduce CO_2 and NO_X emissions. This breakthrough will be achieved by developing and validating new core configurations using heat management (intercooler, cooling air cooler, recuperator), improved combustion, active systems and improved core components.

NEWAC will design and manufacture these innovative components and perform model, rig and core tests to validate the critical technologies. The core configurations include an intercooled recuperative core concept operating at low OPR, an intercooled core configuration operating at high OPR, an active core and a flow controlled core operating at medium OPR.

The main result will be fully validated new technologies enabling a 6% reduction in CO_2 emissions and a further 16% reduction in NO_X. This will deliver together with EEFAE, national programmes and expected results of VITAL, the overall CO_2 reduction of 20% and the NO_X reduction close to 80% at a technology readiness level of 5, contributing to the attainment of the ACARE targets.

NEWAC will achieve this technology breakthrough by integrating 40 actors from the European leading engine manufacturers, the engine-industry supply chain, key European research institutes and SMEs with specific expertise.

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