STRATEGY FOR EVIRONMENTALLY FRIENDLY LOW EMISSIONS COMBUSTION DEVELOPMENT IN EUROPEAN AERONAUTICS

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Abstract

The European key aero-engine manufacturers in ELECT-AE[1] [1, p.37] are developing a strategy for the environmentally friendly combustion system.
The development of this joint research strategy involves complex interactions. However, it is believed that advanced low NOx technology is required and will be successful in the end.

The vision for 2020 as formulated by ACARE[2] sets ambitious targets; especially the demand for 80% NOx and 50% CO_2 emissions reduction from aviation with reference to the year 2000, requires focused and balanced research and technology initiatives for the near future. The aero-engines are committed to contribute 15 to 20 %-points to the CO_2 emission target, other contributors being the air-framers (20-25%), operations and air traffic management (5-10%).

The technology for a new generation of aero-engine combustors has to be prepared on a pre-competitive level of close cooperation and thus generating economic and ecological benefits for the European and the global Society.

Targets have been developed, designed to support the establishment of a pre-competitive research strategy consisting of actual measures and actions in the context of combustion system technology for low emissions of pollutants:

- *Strategy on technology development*
- *Integration & strengthening of the European Research Area*
- *Enhancement of exploitation in Europe*
- *Dissemination of European research results and exchange of information in Europe*
- *Search and identification of Small-Medium Size Enterprises and new research partners in the EU25.*

The conclusion is that the optimisation of the combustion process is an essential means to reducing NOx production from aero-engines. It has to be noted that advanced low NOx combustion technology contributes to fuel burn reduction by enabling cycles with higher pressures and bypass ratios, with higher turbine entry temperatures and by reducing cooling air and combustor pressure losses. Research on highly innovative architectures has to be carried out to reduce complexity, size and weight of ultra-low NOx combustion systems.

Due to the extremely complex nature of this technological field and the fact that the development of ultra-low NOx technology has by far not yet reached production readiness level, it will not be possible to down-select the successful combustion technology in the near future.

[1] European Low Emission Combustion Technology in Aero Engines, see for details: www.elect-ae.org
[2] Advisory Council for Aeronautics Research in Europe, see for details: www.acare4europe.org

1 Introduction

The objectives are very challenging. ACARE's "Vision 2020" has been established by a group of personalities representing the European aviation industry. A holistic implementation of the objectives set is required to build a sustainable world with low impact on the environment and allowing economic growth.

A wide range of technological strategies has been investigated and a lot of effort has been spent since the beginning of low NOx combustion research. These efforts were very successful in identifying and assessing the potential of low emission combustion.

Further research on combustion requirements such as operability, thermal management, coking, soot, sprays, flame stability (lean blow-out and weak extinction), pressure oscillations, ignition, relight and alternative hydrocarbon fuels is needed.

A research strategy to close the gap between the extremely challenging ACARE and EC Work Programme on one side and the research projects on the other side is required to determine future strategies on advanced ultra-low NOx combustion technology development. The ELECT-AE consortium will close this gap.

2 Objectives

The specific research on low emissions combustion for application in aero-engines, which is carried out in the frame of the European Community's Framework Programme targets low technology readiness levels.
The perspective is 10 to 20 years until entry into service and on long-term technology goals.
Such technology matures at an intermittent rate of progress. Actual feed-in of technology is not certain and risks are inherent. This research is pre-competitive.

3 Project Consortium

The consortium is bringing together the European key aero-engine manufacturers with interests in low emissions combustion and the German and French aerospace research establishments (DLR and ONERA).

Fig.1: The ELECT-AE consortium

Rolls-Royce Deutschland coordinates ELECT-AE. VOLVO Aero Corp. supports the project and its future research initiatives.

Industrial aero-engine technology projects co-funded by the Commission of the European Union are co-ordinated by the "Engine Industry Management Group" (EIMG). This group was formed in 1990 in response to a request from the Commission and consists of one representative from each of the 12 European aero-engine companies. Recently two new members from Czechia and from Poland (PSS and WSK) have joined. EIMG has the following objectives:

- To provide a European aero-engine industry view on the commission's aeronautic initiatives on research and technology
- To provide support to the Commission in preparing its relevant research programs
- To initiate any additional actions by the aero-engine industry which may be considered necessary to support these objectives
- To facilitate the research and technology activities of the parties and to improve or increase the results of those activities

The EIMG coordinates a number of technology working groups, all of which are supporting the ACARE objectives:

-Advanced Materials

-Turbo-Machinery (Turbine & Compressor)

-Manufacturing & Overhaul

-Aero-Engine Noise

-Integration / Whole Engine

-Mechatronics

-Mechanical Systems

-Low Emission Combustion

The Low Emissions Combustion working group initiated the ELECT-AE project and is driving the low emission combustion technology development on the European level.

4 RTD Strategy Orientation

A research strategy workshop was carried out in 2006 in Bois du Lys near Paris. The ELECT-AE consortium brought together aero-engine manufacturers, research establishments and leading universities in the field in Europe. The follow-on strategy workshop is planned for September 2007.

4.1 Strategic drivers

The following strategic drivers represent the key motivations for research:

• Environmentally friendly engine and sustainable air transport

• Economic benefits / growth

• Reduced lifecycle costs

• Reduced development time and costs

• Reduced weight (parts count / complexity)

• Airworthiness / safety / certification

• Competitiveness on a global scale

• Customer demands

Research and Technology Development (RTD), which results in advanced technology and innovation has stimulating effects on economic growth and finally on wealth.
It has to be noted that an advantage in advanced knowledge and economic wealth is essential and that these advantages will steadily erode if the efforts are reduced.
Consequently, there is no choice for Europe but to avoid fragmentation and to increase efforts in order to remain competitive.

4.2 Research and Technology Development

Medium and long-term research goals to pro-actively support the ACARE target of 80% reduction of NOx emissions can be identified:

• Combustion Technology

Lean-burn technology is essential to achieve the low NOx targets and the existing concepts have to be driven towards higher technology readiness. The development of lean combustion systems, featuring lean injection systems and single-annular combustor architecture has to be intensified.
The understanding of a number of physical processes like fuel-air mixture preparation, spray generation, particulate matter/soot formation and pressure oscillations driven by combustion instability has to be improved. Therefore, advanced models for the prediction of fuel atomisation, cooling and thermo-acoustics need to be developed.

New combustor concepts (10 years):

- internally piloted lean injection
- optimisation of lean staged combustors
- fuel-air mixing at low and high power
- better understanding of conventional ignition
- develop alternative ignition devices (LASER)
- design for fuel efficient engines with high pressure and ultra-high bypass ratio

Radical combustor concepts (20 years):

- alternative combustion concepts
- porous combustor concepts
- actively cooled (liquid/steam/gas) combustor
- no-external aerodynamics combustor
- convective cooling
- catalytic combustion, ignition and flame stabilisation
- explore the influence and benefits of advanced cycle engines

New injectors (10 years):

- mixture optimisation
- fuel atomisation, dispersion, placement
- optimise thermal management (coking)
- ensure injector scalability

Radically new injection (20 years):

- circumferential array, multi-point injection with discrete jets
- explore external pre-vaporisation
- identify improved concepts for advanced internal staging
- water injection during take-off and climb

• CFD Methods, Design Methodology and Life Prediction

Design methodologies and rules for lean combustion systems and lean injection systems focusing on operability and emission performance are urgently required.

The fundamental knowledge base and the understanding of processes concerning the fuel-air mixture preparation (fuel film / droplet break-up), particulate matter (soot) formation and pressure oscillations driven by combustion instabilities have to be improved.

Design tools have to comprise multi-physics incorporating heat-transfer and coupling with thermo-acoustics. Mechanical stress and lifing methods have to be integrated to better predict failure modes such as crack initiation and propagation.

• Diagnostics & Test Rigs

Diagnostics and test rigs have to enhance capability at realistic engine operation conditions. Optical access and the application of advanced LASER techniques are the main issues for large scale testing of combustion devices.
Simultaneous multi-parameter measurements and the development of new techniques to explore optically dense regions of sprays and the gases in high pressure combustion environments must have high priority to reduce test time, costs and to increase testing value.

• Alternative Fuels

Alternative fuels can play an important part in reducing emissions. Safety of supply and costs are decisive.
Liquid hydrogen is not applicable in aero-engines of the existing fleet and requires a new, globally available infrastructure.

Fischer-Tropsch synthetic kerosenes, which can be produced from natural gas, coal or biomass, and blends thereof with Jet-A1 or JP-8 kerosene, are in the focus of interest. At present these kerosenes are regarded as the only realistic alternative aviation fuel, because these synthetic fuels fulfill the kerosene specifications (e.g. Defence Standard 91-91).

The assessment of the combustion, emission performance, controls and whole engine impact of Fischer-Tropsch kerosene has been initiated.
Research is required not just on ‘drop-in’ kerosene replacement fuels but also on how to define the specification of new ‘ideal’ fuels to further reduce emissions.

It has to be noted that SASOL of South Africa has a semi-synthetic fuel certified for civil application. Their semi-synthetic fuel is a blend, which comprises 50% of Jet-A1 and 50% Fischer-Tropsch fuel. This synthetic kerosene originates from gasified coal (CTL = coal to liquid).

A number of aero-engine manufacturers are involved in the certification of a 100% synthetic CTL kerosene produced by SASOL, including Pratt & Whitney, General Electric, Honeywell of the USA and Rolls-Royce from the UK.

In the long term an increased use of biomass derived Fischer-Tropsch kerosene is expected.

Generally, there is concern that the extensive use of biomass for the production of fuel (e.g. transportation, heating, electricity etc.) can lead to an ethical issue. The agricultural land that is transferred to the production of biomass for fuel is not available for the production of food.

The results were reported to [2] ICAO's Task Group on Long-Term Technology Goals during their review meeting on 20 to 24 March at UK's Department of Trade and Industry, London, to [3] the Aeronautics Days 2006 in Vienna, by an advertorial in Parliament Magazine [4], to AERONET III [4] and to the ICAS 2006 [5].

5 Future Research and Technology Initiatives

The gaps of knowledge identified will be used to align and to focus future European research and development initiatives.

A European research and technology strategy on low emissions combustion in aero engines was initiated. Perspectives were developed covering combustion technology, CFD methods, design methodologies, diagnostics and test rigs and alternative fuels.

Lean combustion systems (single annular architecture) with lean injectors were identified as the only viable approach for the time being with some rather radical technologies slowly emerging.

The lean burn technology development has to be strongly supported by enhanced capabilities in the field of CFD methods & design methodologies and diagnostics and test rigs.

5.1 Targets in FP7

The FP7 work programme in Aeronautics is focused on the following items:

- Greening of air transport

Reduction of emissions and noise disturbance, incorporating work on engines and alternative fuels, structures and new aircraft designs, airport operations and air traffic management

- Improving cost efficiency

Reduction of costs associated with product development, manufacturing and operating costs focusing on the zero maintenance aircraft and the increased use of automation and simulation.

- Pioneering the air transport of the future

Addressing the long-term challenges of aviation with more radical, environmentally efficient and innovative combinations of technologies, which would lead to significant steps forward in air transport.

5.2 Technology Enhancement in FP7

The proposal **TECC-AE** Technologies Enhancement for Clean Combustion in Aero-Engines represents the efforts of the ELECT-AE consortium to implement the RTD strategy.

Topics with high priority have been selected:

- Enhanced operability for staged lean injection

  - Identification of parameters limiting ignition
  - CFD development to predict extinction and ignition probability
  - Optimisation of combustor geometry regarding ignition and weak extinction
  - Determination of the impact of swirl distribution on flame stability
  - Quantification of fuel flow split impact on pollutant emissions

- Thermal management optimisation
  - Methodology validation for liner cooling testing at scaled conditions
  - Identification of basic phenomena leading to cooling film breakdown
  - Refinement of criteria for coke formation
  - Design tool for fuel injection and for minimisation of fuel coking
  - Optimisation of internal geometries and fuel splits to avoid coking

- Sensitivity of wall cooling to unsteady flow features
  - Investigation of the acoustic behaviour of lean burn combustion systems
  - Characterisation of cooling films under moderate pressure oscillations
  - Assessment of the sensitivity of the combustor external aerodynamics to acoustic pressure fluctuations
  - Reduction of acoustic instabilities by facilitating cooling film dampers

- Innovative technologies
  - Development of innovative technologies for conventional fuel (Jet-A1) combustors
  - Characterisation of compact ultra-low NOx injection systems
  - Validation of innovative ultra-low NOx injection systems
  - Assessment of the feasibility of purely convectively cooled combustor
  - Investigation of new combustor architecture equipped with simplified injection system

The TECC-AE proposal was submitted to the first Call of FP7. At the time of writing of this paper no information about the potential success or failure of the proposal was available.

6 Networks (European Research Area)

ELECT-AE is a forum where information, experience and views can be exchanged between the organisations inside and from outside. It supports the forging of future RTD initiatives, strategies and help to integrate and to strengthen the European Research Area. It assesses and disseminates results from its linked RTD projects to acquaint the public and the aeronautics community with the latest achievements in low emission technology in aero-engines.

6.1 RTD projects

The coordinators of on-going low-NOx relevant RTD programmes (including FP5 and FP6) are linked to ELECT-AE. The coordinators are represented in the so-called Project Liaison-Support Team.
During FP6 four EIMG led projects were approved by the EC. Two are mainly dealing with technology development and design methodologies (INTELLECT D.M. and TLC), the third one is focused on combustion prediction methods (TimeCop-AE). The fourth project is devoted to the development of remote emissions sensing techniques (AEROTEST).

- FP6 C1: INTELLECT D.M.

This project is focused on operability (e.g. flame stability & weak extinction in adverse weather conditions), ignition capability (cold start, light across and light around), external aerodynamics and combustor cooling design. Design rules and guidelines will be fed through an assessment process into knowledge based engineering tools for parametric and inverse design. The NOx objective agrees with the ACARE goals, which requires a reduction of 80% relative to CAEP/2 by 2020.

The Knowledge Based Engineering (KBE) tools will become the corner stones for capture and application of future lean low NOx design methodology. This will provide an integrated environment, linked with design guidelines, predictive tools, to support efficient application of the combustor design process. Key design parameters and the models to be integrated have been identified, as well as the way they fit into the preliminary design process.

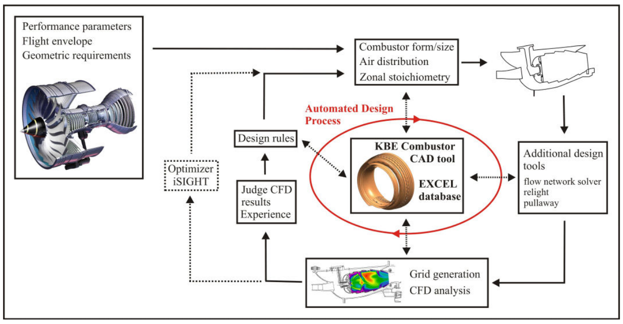

Fig. 2: Preliminary Combustor Design Scheme

Variations concerning the liner lengths, the mixing holes distribution and size, the injector diameter etc. can be performed. The combustor volume required to guarantee combustion efficiency is calculated automatically, changing the overall combustor lengths. The pre-diffuser and dump gap layout is also performed automatically based on simplified correlations.

Highly efficient cooling technologies are now becoming very important because of the air-feed requirements of the lean burn modules, where the fraction of combustor air flowing through the lean module has to be maximised.

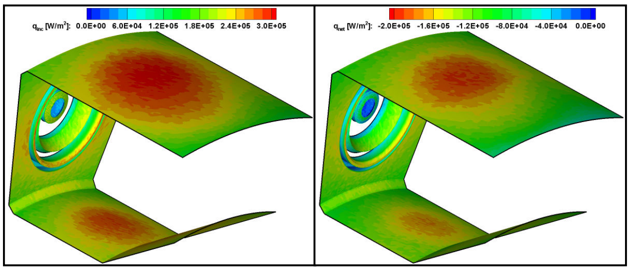

Fig. 3: Incident and net radiative heat flux

Due to the positive achievements, INTELLECT D.M. [7] will continue until the end of 2008.

- FP6 C1: AEROTEST

The aim is to achieve a high level of confidence in aircraft engine emission measurements by non-intrusive methods, with a view to using the remote optical technique for engine emissions certification.
Two major objectives will allow to meet the engine manufacturers' needs:

- address the standardisation issues, the ultimate aim being to promote non-intrusive techniques to ICAO for engine emission certification;
- develop validated techniques for gas turbine monitoring, using emission data to be used routinely by engine manufacturers, both in development tests and engine health monitoring.

Two non-intrusive techniques have been improved and evaluated:

- FTIR (Fourier Transform Infrared spectroscopy) equipment linked to a multi-pass mirror system (White Cell) and the
- LII system (Laser Induced Incandescence).

Some of the major achievements obtained during the last period are:

- FTIR calibration method,
- calibration of the LII system (soot)
- study of pollutant emissions correlations that could be used for engine health monitoring,
- development of method that allows fault diagnosis from emissions concentrations;

Fig. 4: Large engine test bed with equipment

Several measurement campaigns have been done on different aero-engines and one industrial gas-turbine. A comparison between intrusive and non-intrusive techniques has been performed for an aero-engine. An extended campaign is planned this summer in a large RR test bed, to obtain a database from different engines.

- FP6 C2: Towards Lean Combustion (TLC)

The TLC project will permit to achieve maturity in the development and design of lean injection systems with fuel staging for single annular combustors.
Evaluation of various concepts, use of design optimisation procedures, large number of tests, development and application of advanced experimental diagnosis for realistic combustor conditions, strong support of numerical diagnosis with the latest European CFD tools, will contribute to this goal.

The committed objective that has been set is to achieve a NOx target of between 60 to 70 % reduction relative to CAEP/2 regulations for medium and large turbofan engines.

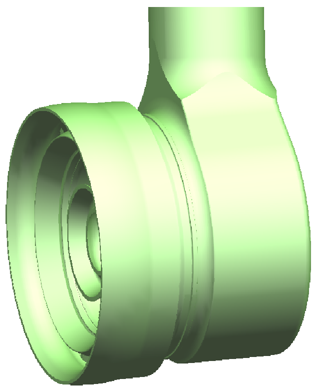

Fig. 5: Lean direct injection burner

From the technological point of view, two essential features of TLC will be:

1) The aero-engine manufacturers will explore lean combustion applied to single annular combustor architecture,
2) both NOx and particulate matter emissions in the landing and take-off flight cycle and at cruise conditions will be considered. Moreover, the trade with CO and UHC and operability will be addressed.

An important result was achieved in the experimental parametric studies on partially pre-vaporised lean spray flames: The degree of pre-vaporization was identified as having the most significant impact on the emissions and the lean extinction limit.

- FP6 C3: TimeCop-AE

The main objective is to advance LES methods into combusting two-phase flows for gas turbine applications.

Existing numerical models, which are key elements for Large Eddy Simulation (LES) capabilities will be improved. This are two phase flow models (Euler/Euler and Euler/Lagrange descriptions, injection models) and detailed chemistry (use of detailed reaction mechanisms developed in previous EU projects for the development of reduced schemes, which are suitable to model the combustion process within a wide range of operating conditions for the application in Reynolds-Averaged-Navier-Stokes (RANS) solvers and LES codes.
The 2-phase flow models will be extended to kerosene evaporation, micro-mixing and improved turbulence-droplet interaction. Kerosene chemistry (reduced schemes and turbulence coupling) will be experimentally validated and implemented.

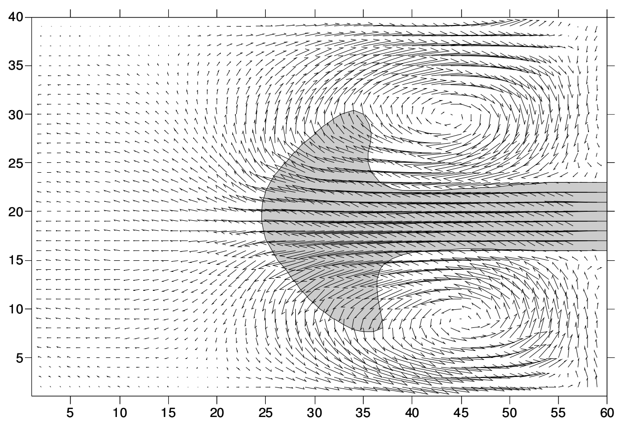

Fig. 6: multi-phase simulations of the breaking dam problem and jet injection

Experiments will be carried out to obtain measurements for the validation of LES tools and for model development.
Two sets of experiments are retained to facilitate the comprehension of fundamentals and their potential implications in complex geometry applications: generic academic-like experiments and complex geometries experiments gathering data similar to that of real aero-engine conditions.

Improved and newly developed models will be integrated into the advanced CFD codes, in order to obtain 2-phase reactive CFD capability that will resolve the unsteady behavior that is natural to turbulent flow. To ensure the proper implementation of these new models validations are first performed on academic experiments. Once validated, the advanced CFD methods will be applied and tested on complex 3D geometries.
A link to the automotive spray combustion community has been established.

7 Patent Awards

ELECT-AE is promoting the development of European technologies supporting and enabling low and ultra-low NOx combustion in aero-engines.

The objective of the Patent Awards is to award individuals or teams for their outstanding contribution in the field of low and ultra-low NOx combustion covering advancements in the development of combustion technology, fuel preparation, mixing, combustion, cooling, fundamental knowledge, theoretical and experimental methods, modeling and design methodologies.

Individuals and teams from all partner organisations actively participating in low NOx combustion related specific targeted research projects from Framework 5, 6 and 7 directly linked to ELECT-AE are entitled to submit applications. The patent and its know-how must have been generated in a work-package, task or subtask in one of these projects.

The awarding ceremony will take place during the Final Meeting of ELECT-AE in autumn 2008.

The evaluation of submitted applications will consider the following items:

- Topicality and creativity
- Degree of innovation, competitiveness and spin-off effects
- Applicability (license, prototype, series)
- Potential contribution to growth
- Sustainability

The submitted patent application has to be filed to at least one National Patent Office of one of the member states of the European Union (EU25) or to the European Patent Office.
Supportive work on administration and selection will be provided by RRD's patent bureau.

8 Conclusions

ELECT-AE is supporting the implementation of the ACARE objectives (80% NOx reduction).

Aero-engine manufacturers, research establishments and leading universities in the field in Europe were brought together. The following important fields have been identified for further initiatives:

- Combustion Technology
- CFD Methods, Design Methodology and Life Prediction
- Diagnostics & Test Rigs
- Alternative Hydro-Carbon Fuels

Lean-burn technology is essential to achieve the low NOx targets and has to be driven towards higher technology readiness.
The development of lean combustion systems, featuring lean injection systems and single-

annular combustor architecture has to be intensified and efforts have to be increased.

The work and the objectives of the EIMG, ACARE and ICAO's Working Group 3's Task Group on Long Term Technology Goals are supported.

Regular communication and exchanges of information between ELECT and the directly linked EC co-funded research projects has been established and is applied for information exchange.

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References

[1] Ed. Schavan, A., Success through research – Germany's contribution to European research projects, CORDIS focus – thematic supplement, iss. 24, June 2007, EU Publications Office, Luxemburg

[2] von der Bank, R. European Research and Technology Strategy on Low Emissions Combustion in Aero-Engines for the 21st Century, presentation, ICAO, WG3, Task Group on Long Term Technology Goals Review Meeting 20 - 23 March 2006, Department of Trade and Industry / United Kingdom

[3] von der Bank, R., Berat C., Cazalens M., Harding S., European Research and Technology Strategy on Low Emissions Combustion in Aero-Engines, presentation, Aeronautics Days 2006, 19-21 June 2006, Vienna, Austria

[4] von der Bank, R., European Research and Technology Strategy on Low Emissions Combustion in Aero-Engines for the 21st Century, advertorial point of view, Parliament Magazine, p.56, iss 220, 20 March 2006, Brussels, Belgium

[5] von der Bank, R., European Low Emissions Combustion Technology in Aero-Engines, presentation, workshop AERONET III, 24-25 January 2006, DLR-Office, Brussels, Belgium

[6] von der Bank R., Berat C., Cazalens M., Harding S., Organisation of European Aeronautic Ultra-Low NOx Combustion Research, 25th International Congress of the Aeronautical Sciences, ICAS 2006, 3-8 September 2006, Hamburg, Germany

[7] von der Bank R., Savary N., Aldèn M., Zedda M., McGuirk J., Cinque G., On the development of combustion systems and their design methodologies for the reduction of pollutant emissions from aer-engines – the European project INTELLECT D.M.,1st European Air and Space Conference & Deutscher Luft- und Raumfahrtkongress 2007, 10-13 September 2007, Berlin, Germany