ON THE DEVELOPMENT OF COMBUSTION SYSTEMS AND THEIR DESIGN METHODOLOGIES FOR THE REDUCTION OF POLLUTANT EMISSIONS FROM AERO-ENGINES

- THE EUROPEAN PROJECT INTELLECT D.M.[1] –

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Abstract

The European target for 80% NOx and 50% CO_2 emission reduction in aeronautics has been set by the Advisory Council for Aeronautics Research in Europe (ACARE). Whilst the CO_2 emissions and the fuel burn can be reduced by increasing the thermal cycle and propulsive efficiency, tackling the NOx emissions requires the application of highly sophisticated combustion system technology in aero-engine combustors [1].

The required NOx emission reduction can only be implemented by the introduction of lean pre-mix fuel injection systems. Lean burn systems have inherent problems with operability, weak extinction, turn-down-ratio, fuel staging, thermo-acoustics and mechanical complexity.

Lean combustion of kerosene fuel takes place in an air-kerosene mixture with excess air such that the combustion of kerosene occurs at relatively low temperatures. The lower the combustion temperature the lower the NOx emissions. It is generally accepted that the application of lean burn systems such as lean pre-mix injectors is inevitable to achieve the target of 80% NOx reduction.

Safe and stable flame conditions are of tremendous importance during transient aircraft manoeuvering. Rain and hail can be ingested by the jet engine and could increase the hazard of flame extinction, when the aircraft flies through adverse weather.

Combustion oscillations associated with high-pressure amplitudes are a significant challenge, which can very quickly and severely damage the combustor, the injector hardware and aero-engine.

Lean burn combustion systems are susceptible to both, lean flame extinction and combustion oscillation.

Therefore it is mandatory to accelerate the design process and to derive new design rules for low emissions combustors, which take these constraints in consideration.

INTELLECT D.M. is taking up this challenge through a number of work packages on automated, knowledge-based design methodologies, flame light-up, light-across and light-around, flame stability and weak extinction, aerothermal dynamics and flame tube cooling.

By the end of this project there will be significantly contribution to the mitigation of these combustion issues, will have extended the existing knowledge base and have contributed to the implementation of the ACARE targets.

[1] Specifically Targeted REsearch Project: Integrated Lean Low Emission Combustor - Design Methodology, co-funded by the European Commission, www.intellect-dm.org

1. Introduction

The objective is to develop a design methodology for lean burn low emission combustors to achieve sufficient operability over the entire range of aero-engine operating conditions whilst maintaining low NOx emission capability. Knowledge-based design systems will form the framework to capture existing lean burn combustor design knowledge and further knowledge obtained in this project. Through the pressing demand for emission reduction, very ambitious future NOx reduction targets of 80% by 2020 have been set, which are driving research into novel combustion systems with geometries that are quite different from current systems. Existing design rules, for conventional combustion systems, cannot be applied for lean low emission combustors.

It is therefore important to have a design system in which:

• new design rules can be embodied quickly

• new technology can be incorporated faster.

The objective of this project is to create the first building blocks of integrated combustor design systems. These systems will incorporate preliminary design tools,

• to make first estimates of the arrangement of lean burn combustion systems, which meet

• operability, external aerodynamics, cooling and emissions needs.

Tools that are used during subsequent design phases, will also be linked into this knowledge-based system, so that design iterations can be done more quickly.

Furthermore, many design iterations are required for combustors based on new low emission technology since emissions and stability are very sensitive to small design changes. Therefore, it is essential that design iterations are performed much faster. In addition, a knowledge-based development system will support the reduction of the development process, to be able to react faster on changing market requirements. Up to now, knowledge-based systems are not yet available within the combustion design system.

For a successful application of such a knowledge-based system it is crucial that the system contains sufficient knowledge of all important aspects of low emission combustors. To this end a large part of the project will be devoted to obtaining this knowledge. Knowledge with respect to external aerodynamics (around the combustor) and pre-diffusers, design of staged fuel spray nozzles with main and pilot injection and cooling will be acquired, and a large part of the project will focus on operability, such as ignition and lean blow out aspects of low emission combustors.

This project exploits the development work and achievements of previous European research programmes, which have mainly addressed low NOx technology at specific operating conditions, and this project is seeking solutions for known drawbacks of low emissions technology, which have not been addressed in any research projects before. This work is essential to prove the technological feasibility of low NOx combustion technology towards its application into an aero-engine environment.

Whilst it is crucial to introduce highly complex low emissions technology, there is a very high risk that complex combustion systems will fail to gain market acceptance and would negatively affect the competitiveness of European aero-gas-turbine manufacturers. The effort to work on the operability of low NOx combustors is therefore targeting design simplicity.

2. Objectives

The main objective of this project is to provide some of the vital building blocks and subsequently to develop a knowledge-based low-emission combustor design system. To ensure the delivered product satisfies the customer requirements and is fit for purpose, whilst minimising overall module cost and reducing the design project timescale to less than 2 years, it is important to maintain maximum design flexibility, especially during early phases of the design.
To realise this ambitious objective the most advanced CFD tools, test rigs and diagnostic apparatus will be applied.

The work programme is split into 6 engineering work packages as shown in Fig.1. Work package one in one is on project management and administration.

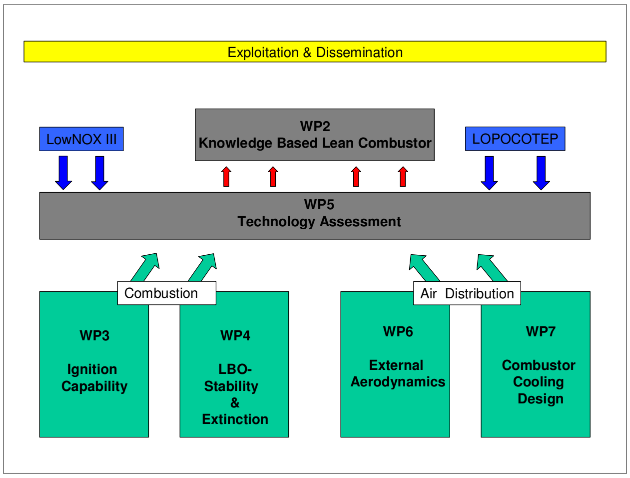


Fig.1: Overview of work packages

The Knowledge Based Engineering (KBE) tool developed under work package two will become the cornerstone for capture and application of future lean low NOx design methodology. This will provide the industrial partners with an integrated environment, linked with design guidelines and predictive tools, to support efficient application of the combustor design process.

Work package three concentrates on ignition capability enhancements. Injectors operating with an excess of air in a single annular combustor configuration can be prone to ignition problems. Ignition is a major concern of lean combustion, as sufficiently fuel rich conditions and a suitable flow field have to be achieved in the vicinity of the igniter tip. For piloted lean injectors with an integrated pilot atomiser in the lean module, the spark providing the initial ignition energy has to ignite the kernel in the middle of the injector, both on the ground and at high altitude.

Ignition investigations concentrate on the light-across and light-around capability of the injectors. Even if injectors located at the ignition sources light-up satisfactorily, the lean operating injector modules could hamper the light-across to adjacent fuel injectors and the subsequent light-around within the annulus.

The rig test programme covers ignition tests at sub-atmospheric, ambient and low power operating range conditions. The experimental work is supported by advanced CFD modelling based on two-phase combustion LES.

The fourth work package is focused on combustor lean blow out stability improvements. The integration of a pilot atomiser into a lean burn module is a solution that would reduce combustor complexity and improve lean injector stability. This implementation can be critical for the overall NOx reduction performance of the injection system.

The key issue of this work package is on the interdependence of pilot flame and main lean combustion zone with respect to fuel placement and homogeneity of fuel-air mixing.
The stability margin and weak extinction requirements of an aero-engine combustor, which are required for aircraft manoeuvres, exceed by far the steady state air-fuel ratios defined by the typical operating range between engine start-up, idle, take-off and cruising at altitude.

Within the fifth work package the impact of achievements of all technical work packages is assessed and is used to formulate design guidelines, which are transferred to the knowledge-based engineering system where applicable. The results of ignition and stability issues for low emission technology are assessed, based on the stability and ignition improvements obtained.

Also answers to the question whether it is feasible to achieve sufficient stability while maintaining low NOx emissions within single annular combustors, which has already been demonstrated for axially staged and double annular combustors, is assessed.

Work package six is devoted to external aero-dynamics and aero-design where CFD methods are assessed, optimised and validated to predict combustor pressure losses accurately. A novel 3-D shaped pre-diffuser will be designed, tested and optimised for lean burn fuel injectors that take up to 70% of the air flow. In addition a parametric model of the external aero-dynamical geometry linked to a CFD solver will be controlled by an optimiser.

In work package seven, combustor cooling aspects are assessed in detail. To maximise the amount of air flowing to the lean burn injectors, the air required for cooling of the combustor walls has to be minimized. Detailed experimental and numerical analysis of impingement and effusion cooling systems are performed, to formulate design rules for optimised cooling devices, which are captured in the knowledge-based engineering systems.

3. Project Consortium

The consortium comprises 17 European partners from France, Germany, Italy, Poland, Sweden and the United Kingdom. The project is coordinated by Rolls-Royce Deutschland.

Rolls-Royce Deutschland
AVIO
Rolls-Royce UK
SNECMA
Turbomeca
Office National d'Etudes et de Recherches Aerospacial ONERA
Deutsches Zentrum für Luft- und Raumfahrt DLR
Centre Européen pour la Recherche et la Formation Avancee en Calculs Scientifiques CERFACS
Centre National de la Recherche Scientifique CNRS
Universitet Lunds
Universität der Bundeswehr München
University of Czestochowa
Imperial College London
Università degli studi di Firenze
Loughborough University
University of Cambridge
Universität Karlsruhe

Table 1: Partner Organisations

The workpackage coordinators are Turbomeca, Universitet Lunds, Rolls-Royce Deutschland, Rolls-Royce UK, Loughborough University and AVIO.

4 Strategy Orientation

The reduction of NOx emissions is of paramount importance for the development of gas turbine combustors. Ecological requirements [2] necessitate the application of low emission technology to meet today's and future legislative requirements and thus customer expectations. Economic and market boundary conditions require substantial improvement of design methodologies to reduce development cost and time.

4.1 Strengthening the competitiveness of European aero-engine manufacturers

Strengthening the competitiveness of European aero-engine manufacturers by reducing the short and long-term development costs by 20% and 50% respectively may be approached, by generation of knowledge-based combustor design systems. Such knowledge-based systems will contain knowledge of low emissions combustor design, to enable new combustion systems to be developed, following design rules to estimate potential impact of choices made in the early design process.

Within these preliminary design systems, tools will be embedded to make estimates of weight, cost, emissions performance, cooling requirements, altitude relight, pressure loss and to define the scantlings of the combustor at a very early stage of the design process.

A large part of the project is devoted to obtaining and capturing knowledge of pre-diffuser design, ignition, flame stability and cooling. To prevent the loss of information in the various design phases, the applied methods and tools will all be linked to the same database.

To speed up the design process, design iterations need to be fully automated; methods are aiming to automatically generate analysis models (i.e. automatic mesh generation). Within the optimisation process parameters have to be adapted without the need to set the numerical models again.
Furthermore, to be able to apply new numerical methods, e.g. LES modelling, to the design process it is important to assess the applicability of these methods. It is important to define requirements for these CFD methods so that future development programmes can target these objectives.
The competitiveness of European aero-engine manufacturers will be strengthened by focussing on issues of low emission combustors, which are hindering the introduction of this technology into products.

4.2 Improving the environmental impact with regards to emissions

Improving the environmental impact with regards to emissions is to be achieved in the long term by reducing NOx emissions by 80% in the landing and take-off cycle relative to the ICAO standard and via an Emissions Index of NOx of 5 g per kg of fuel burnt at cruise. These very ambitious objectives are tackled throughout the entire project and by all work packages.
The reduction of NOx emissions is of paramount importance for the development of gas turbine combustors. The CAEP/2[2] emission regulations have been followed in 2004 by CAEP/4 lowering the limits for NOx emissions by 16% and in 2008 the CAEP/6 standard will become effective requiring a further reduction of 12%.
Whereas actual CAEP regulations (and airport charges) concentrate on the local impact of aviation on air quality, the upcoming discussion of cruise emission regulations considers the impact on the

[2] Committee on Aviation Environmental Protection http://www.icao.int/icao/en/env/caep.htm

global climate. For both local and global impacts, NOx and soot emissions are especially of interest.

Combustion technology suitable for controlling NOx emissions at the emission points defined by the ICAO landing and take-off cycle for certification is in general also able to reduce NOx emissions at cruise conditions.

As the timescales for aero-engine development are long there must be a clear vision and forecast of environmental needs in the future. To follow the ambitious “Vision 2020” targets of 80% reduction of total NOx produced demands the implementation of a new generation of aero-engine combustors.

Low NOx combustion technology development for small, medium, and large engine applications has especially been the aim of LowNOx III[3] and LOPOCOTEP[4] programmes. The NOx reduction targets of these programmes have been progressively refined to provide fuel preparation and fuel injection technologies able to meet the targets for the overall NOx reduction target “Vision 2020”.

New combustion processes based on lean combustion concepts such as LPP (lean premix pre-vaporised) or LDI (lean direct injection) already proved their potential for achieving these aggressive NOx reduction targets. In their current state, these technologies have not yet reached the stage of being easily converted into a concept offering the reliability and safety for an aero-engine application.

Moreover, these concepts additionally have to gain customer and market acceptance to be fully competitive. As long as there are no answers to principle questions concerning the operability and airworthiness of low NOx combustors there is no sense in defining more aggressive and hence unrealistic goals for low NOx combustion techniques. ‘Operability’ as emphasised in the reference ACARE report ‘The Challenge of the Environment’ [3 p.30] is a generic term mainly comprising ignition, stability against flame extinction and flash-back during all flight and ground running phases, at all relevant altitudes and for all relevant weather conditions.

Concepts offering the potential for both, certification and market acceptance have to be developed based on the NOx reduction know-how. As a consequence, European research and technology development has to tackle operability to allow safe and stable operation of low emission combustors.

’Cooling’ was highlighted in the ACARE report. It is an important aspect to achieve low NOx emissions; if less air is used for wall cooling, then more air can be used for lean combustion. The cooling efficiency of the combustor walls can be improved via enabling technology to satisfy the future demand for radical thermal cycle parameters (higher compressor outlet temperature) and for very high by-pass ratios.

To reduce NOx emissions, the combustor’s external aero-design and aerodynamics -as covered by the ACARE report- including pre-diffuser must be optimised for application to lean burn combustors with lean injectors that require a large proportion of the combustion air. The objective is to reduce air-flow losses, to improve air distribution and to maximize pressure recovery.

5 Research and Technology Development

Knowledge Based Engineering: The tools developed will become the cornerstone for capture and application of future lean low NOx design methodologies. This will provide the industrial partners with an integrated environment [4, 5, 6, 7], linked by design guidelines and 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.

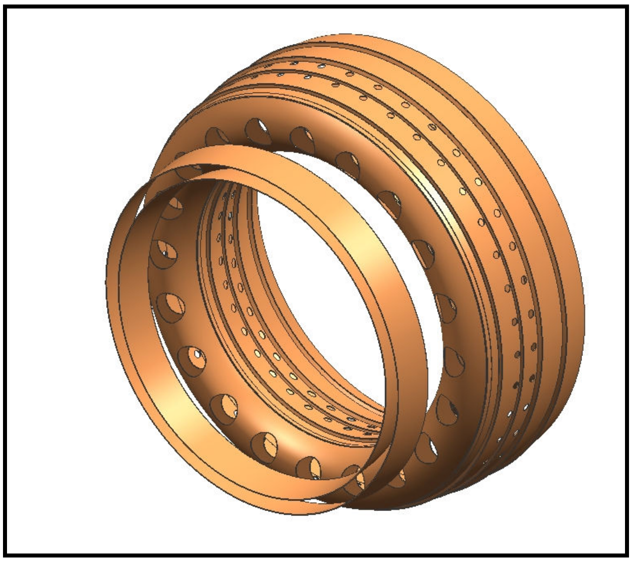


Figure 2: CAD model of geometrical parameters

The generic CAD model provides a very good baseline in terms of setting up a fully automated preliminary combustor design system.

[3] FP4: Low Emission Combustor Technology Programme
[4] FP5: Low Pollutant Combustor Programme

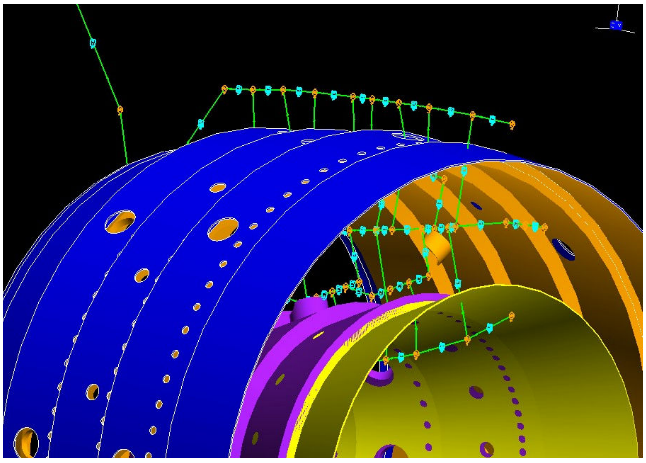


Fig. 3: 1-D network modelling and 3-D geometry

A KBE system's parametric geometry enables automatic generation of a 3-D model of a flame-tube, as shown in Fig. 3.

The system developed is now being enhanced to include automatic CFD mesh blocking capability for automatic optimisation. Another area that will be investigated in the next few months is how to develop the system to be able to analyse geometries that have been originally created outside the system. Eventually, availability of this integrated design system will allow investigation of the application of optimisation techniques for design filtering.

Recent enhancements of the tool for automatic chain optimization [8, 9, 10, 11] for low NOx injection system and combustor module concern its ability to handle several objective functions.

When dealing with combustor optimisation, designers often need to optimise many criteria.

However, a design can yield an improved objective function while degrading another one. To perform multi-objective optimisations, a Pareto front approach has been implemented and coupled with the existing surrogate based algorithm. After testing the resulting method on several analytical test cases, it was applied on a 2D configuration that models a 3D helicopter combustor (Fig. 4).

In this problem, a set of solutions that yield the best combustion efficiency as well as the lowest value of the temperature maximum at the exit of the chamber were evaluated.

The optimisation parameters selected for this case are the axial positions of the two primary jets.

In parallel to these developments an industrial configuration was optimised for a suitable temperature profile at the exit of the chamber as well as an optimum (i.e. high) combustion efficiency when controlling the axial position of the primary jets, the air mass flow in the swirl-generator and the balance of air mass flow between internal and external multi-perforation.

The parallel mesh deformer satisfies the geometrical requirements and has been improved. It allows large mesh deformations while conserving the CAD features such as the periodicity of the initial geometry.

Preliminary computations point to objective functions that do not seem very sensitive to the optimisation parameters. More detailed studies with respect to the operating conditions are needed to improve the search domain. Developments concerning the ability of automatic local and global re-meshing of the configurations under investigation, allowing large geometrical changes, are needed. Finally, the introduction of a suitable parametric CAD design concept is of interest.

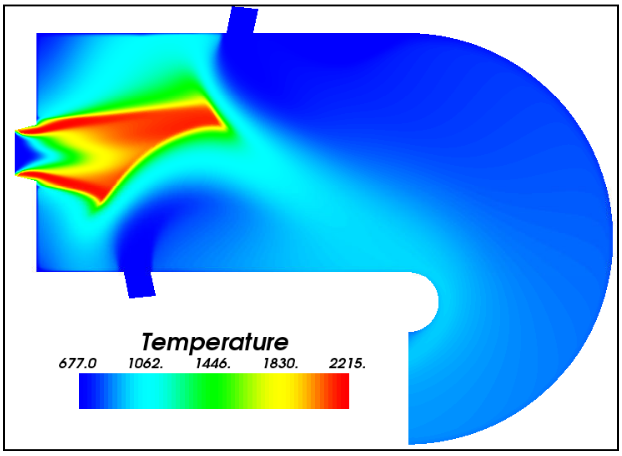
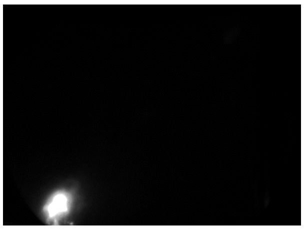


Figure 4: 2D model of a combustion chamber

Ignition Capability: a first set of experiments observing ignition of the LP(P)4 duct (pilot only) in a high pressure rig have been performed. The entire ignition process was observed by imaging chemiluminescent emission from the flame with a high-speed framing camera. In addition, OH was imaged in a planar arrangement using a multi-pulse dye laser system. The experiments showed that ignition is a stochastic process dependent on local air/fuel ratio and local flow around the spark igniter. Both Jet-A1 and a Fischer-Tropsch-based synthetic fuel were investigated.

The OH PLIF images indicate that the flame is intermittent; The simultaneous emission images imply that the ignition flame is a surface wrapped into a cone shape as it re-enters the core of the flow. Earlier PLIF images in the same duct (acquired during LOPOCOTEP experiments) indicate that combustion is quite different after a steady flame has been established. The LOPOCOTEP images were taken at the LP(P)4 injector exit while the INTELLECT images were acquired at the igniter. Details are reported in [12] and about the LP(P)4 burner development in [13].


t = 0,5 ms


t = 10,7 ms

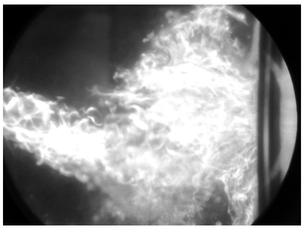

t = 13,4 ms

Fig. 5: Ignition of synthetic jet fuel at an operating condition of 3,14 bar(a)

They can therefore not be correlated in a conclusive way, but the LOPOCOTEP images show a steady flame that is anchored near the inner edge of the spray cone while the INTELLECT images (Fig.5) show an unsteady and intermittent flame that has not anchored itself during to the short time span of the measurements performed on the ignition process. Once the spark igniter is turned off the flame stabilises.
These experiments showed that ignition is a stochastic process depending on local air/fuel ratios and the local flow around the spark igniter. Some common features can be identified between different ignition attempts, where the main features in the dynamic pressure during ignition can be identified in the high-speed camera pictures. The results from these experiments also indicate differences between Jet-A1 and the Fischer-Tropsch-based kerosene during the ignition process.

By means of Large Eddy Simulation [14], applying the BOFFIN code, it has been demonstrated that small droplets typically present in a spray may enhance the rotational strength of coherent structures. As a consequence, these structures, which are the major cause of droplet dispersion (Fig.6), are responsible for droplet concentration and vapour fields that are highly discontinuous.
These findings may be of use in combustion chamber design; atomiser diameter and fuel inflow directions may be tailored to minimise segregation effects and thus non-vaporised and unburnt liquid fuel.

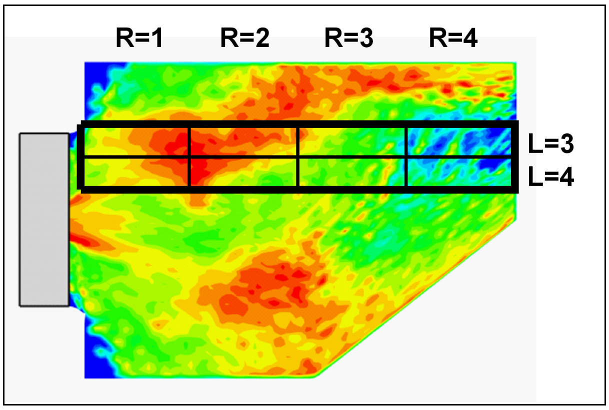


Fig.6: Location of selected regions for droplet diameter evaluation

The investigation of light-across configurations is related to an industrial 3-sector combustor (Fig.7) for which computational meshes have been prepared.

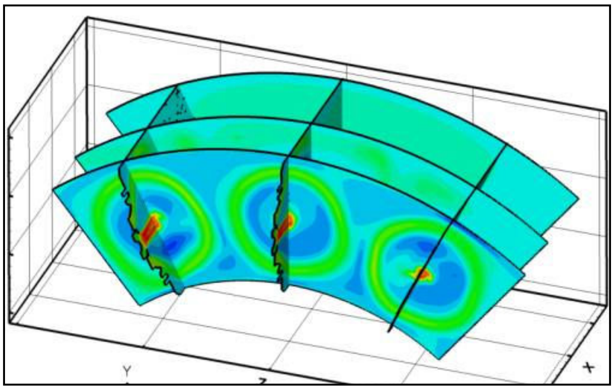


Fig.7: CFD results of 3-sector combustor

The LPX fuel injectors were tested in a two-sector combustion rig under simulated (sub-atmospheric) altitude conditions (Fig.8). With the pilot fuel injector modified from a pressure atomizer (LPX1) to an air blast type (LPX2), the fuel preparation and distribution was significantly changed. In one of the tested configurations the V-shroud flame stabiliser was modified to reduce interaction between pilot and main air stream. Test conditions were similar to the set up of previously tested lean burn systems.

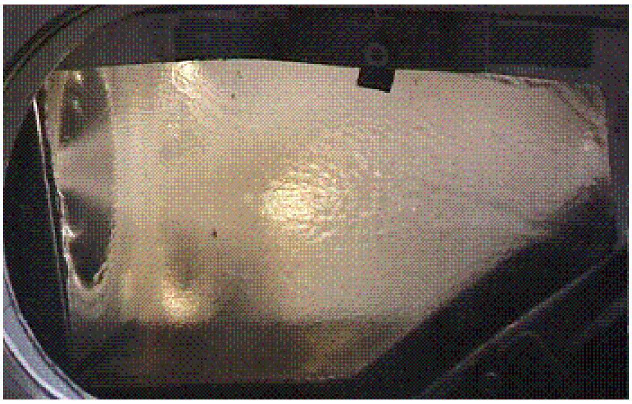


Fig. 8a: Spray injection before ignition

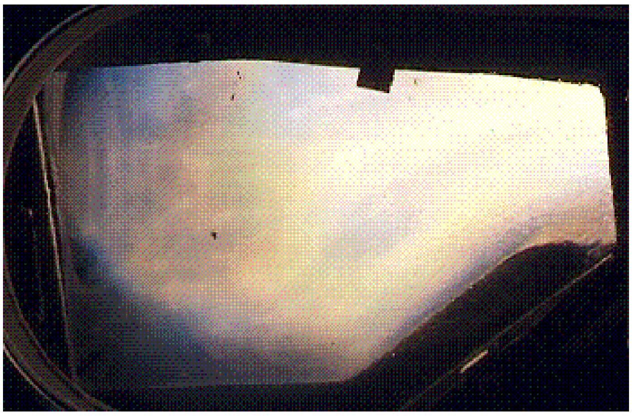


Fig. 8b: Light-up at rich conditions

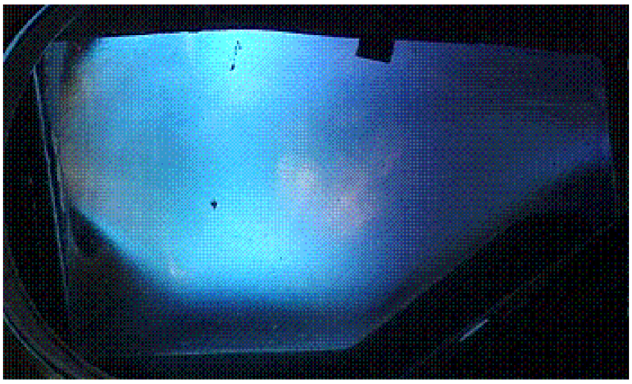


Fig. 8b: Flame close to weak-extinction

In this particular case the relight capability was limited to rather low air velocities and low-pressure differentials. The objective of the modification was not achieved. The design needed to be improved. Consequently, the design of the next generation of lean modules (LNB = low NOx burner) was initiated.

Stabilisation and Extinction: The lean premixing (LP) modules were tested in a high-pressure single-sector test rig and characterised in an optically accessible atmospheric glass combustor.

The lean module design concept for an extended range of operability, was derived from a number of pre-existing concepts. The pre-existing technology base comprised the well-know LP(P) modules from LOPOCOTEP and other lean burn concepts with pilot fuel injection, all of these representing a lean combustion approach with internal fuel staging. This pre-existing knowledge base was exploited for this purpose. The new generic burner types were the LPX and then the LNB fuel injectors.

Airfoil profiled guide vanes and the V-shroud flame stabiliser (both LP(P)5 features [15], technology developed in LOPOCOTEP) have been implemented here.

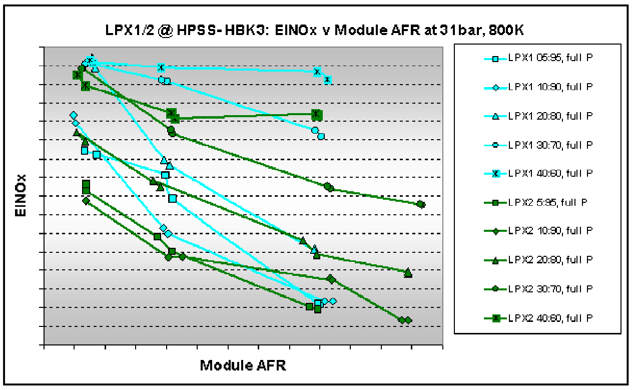


Fig.9: NOx emission result at high-pressure conds.

In Fig. 9 the EINOx performance versus module AFR is shown for the LPX1 and LPX2 modules. At all fuel splits the LPX2 fuel injector configuration shows slightly lower EINOx values compared with the LPX1 configuration. At lower AFR values (e.g. richer flame conditions) the difference between the measured NOx emissions increases.
Although the achieved results show NOx levels within the target region it is believed that further reduction is needed to increase the margin required to account for future engine cycle deterioration.

With regard to investigation of stabilisation mechanisms and fuel distribution, a series of screening tests of several burner configurations was carried out in an optically accessible single-sector combustor. The screening experiments comprised video recordings and planar Mie scattering for the visualisation of liquid fuel distributions in a plane parallel to the burner faceplate at 5 mm distance, with varying operating parameters and injector geometries.

For the first configuration, the LPX1, which is based on a pressure swirl pilot and a pre-filmer main stage, a series of parameter variations at a constant pressure loss was performed.

Fig.10 shows examples of results for three operating conditions, which have been selected to illustrate the overall performance of the injector, and in particular the effects of a variation of pilot/main split and temperature.

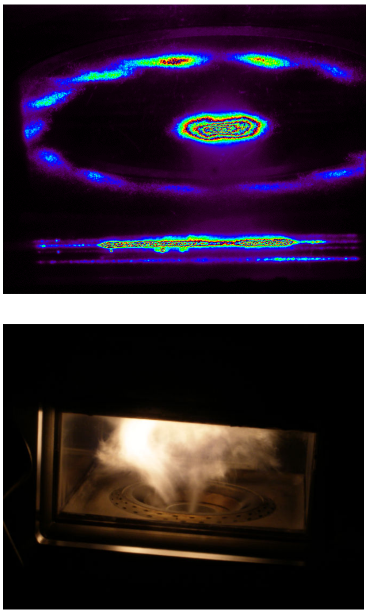


Fig.10: Planar Mie scattering of liquid kerosene in a plane parallel to the burner faceplate at 5 mm distance (LPX1 burner)

Lean Premixing systems are susceptible to self-excited combustion oscillations, caused by coupling of unsteady combustion and acoustic waves. Small fluctuations in pressure and velocity, which develop in air and fuel lines, can lead to considerable fluctuations in the instantaneous equivalence ratio and heat release, triggering unsteady combustion.

Experiments devoted to the simultaneous imaging of OH-PLIF and 3D-PIV in the reacting flow of a laboratory scale burner have been concluded [16, 17]. The resulting images have been analysed, delivering high quality data of the oscillating flow field and combustion field within it.

Figure 11 is a chemiluminescence image taken just before the onset of flame transition from stable to increasingly unstable combustion, terminating in weak extinction. These experiments revealed that the fuel mass flow at which weak extinction occurs can vary substantially while all other flow parameters are kept constant. The same applies to the weak extinction process itself. There is no way to predict if combustion develops instability, i.e. oscillations or intermittent flame-outs of several microseconds duration with subsequent continuation of the reaction, or if the combustion seizes without any previous warning signals of an imminent flame out.

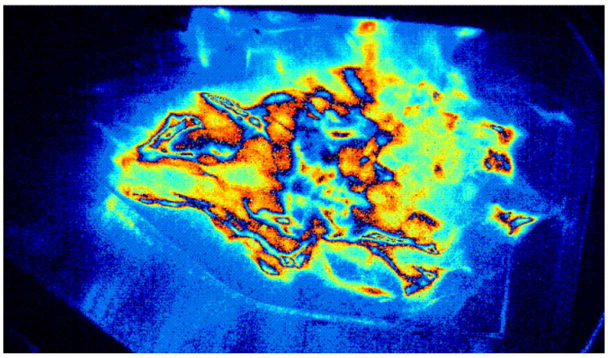


Fig.11: Chemilumincescence image of the flame in the sub-atmospheric relight test rig at the onset of combustion instability, approx. 1.5 s before weak extinction at sub-atmospheric pressure

Two-phase flow combustion LES-CFD investigations of stability at lean operating conditions were performed.
The preliminary computations of the flow and evaporating droplets were performed using the BOFFIN code with the spray code implemented [18]. The simulations were performed for ground ignition condition. The physical property parameters for the kerosene were generic. It was assumed that at the preliminary stage the droplets will be injected over a cylindrical area located close to the pilot injector and the unmodified Rosin-Rammler relation was used for definition of the drop size distribution at the injection area.

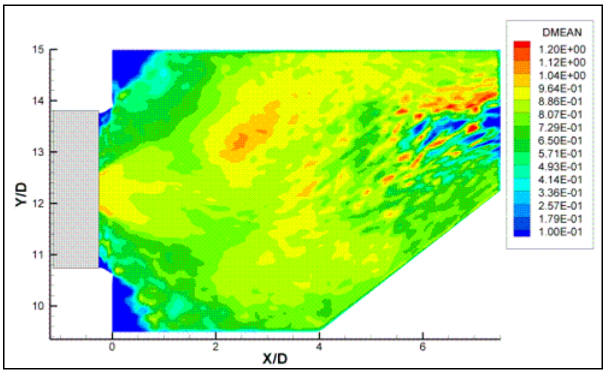


Fig.12: Normalized droplet diameters

The spray velocities at the injection area were assumed to be relatively small (usually also assumed in RANS simulations). The droplet velocity components were computed as a superposition of the constant values and random fluctuations. The results were obtained assuming a non-zero value for the longitudinal velocity component and the addition of some random fluctuations in the radial and longitudinal directions.

Technology Assessment: Emissions reduction was assessed on the basis of LP(P)5 results. The LP(P)5 technology, which was developed within the frame of LOPOCOTEP, is producing by far the lowest pressure oscillations and it will be used in the future for benchmarking. The LP(P)5 burner was tested in a high-pressure test rig for comparison with the newly developed LPX and LNB burners.
The conclusion is that the features of the LP(P)5 technology responsible for low noise have to be integrated into the lean premix modules. The intention is to combine the positive features of both module families.
The results of these high-pressure emissions measurements were fed into a flight mission study [19, 20 and 21]. In the ICAO LTO cycle about 80% NOx reduction can be achieved when advanced low NOx combustion technology (Fig.12) can be introduced into advanced engine concepts for improved airframes.

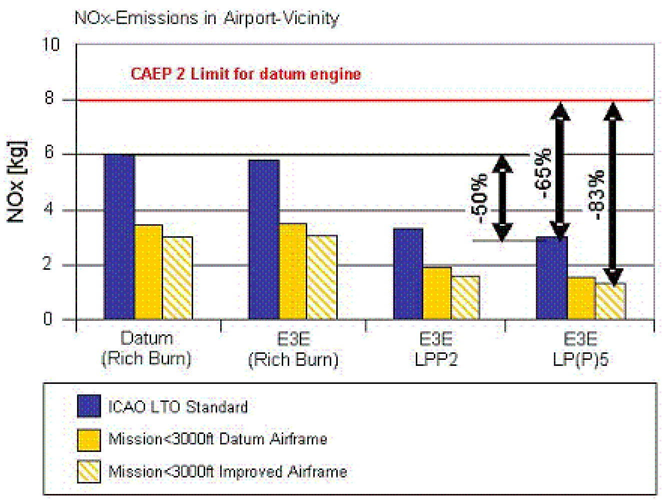


Fig.12: Reduction NOx emissions by lean burn[5]

Assessment of pre-diffuser aerodynamics: In lean burn modules 50 to 70% of the airflow usually enters the flame-tube through the fuel injector. This can lead to deeper flame-tubes, which in turn leads to sharper flow turning within the dump region. Increasing emphasis is put on controlling the fuel injector feed flow quality.
Due to the differences between a typical rich and lean burn combustor external aerodynamics, methods need to be developed and validated for prediction of both, pressure losses and the overall external aerodynamics of lean burn systems. From an overall engine point of view, an improved control of combustor external aerodynamics can lead to a shorter system with obvious benefits in weight.

[5] E3E = generic engine cycle data from the German national project E3E that was applied in CYPRESS

The result is that an integrated OGV-diffuser design has got potential for application to lean burn combustors. In particular, the OGV design, based on three parameters (lean, sweep and twist) can energise the boundary layer, hence delaying separation (Fig.13).

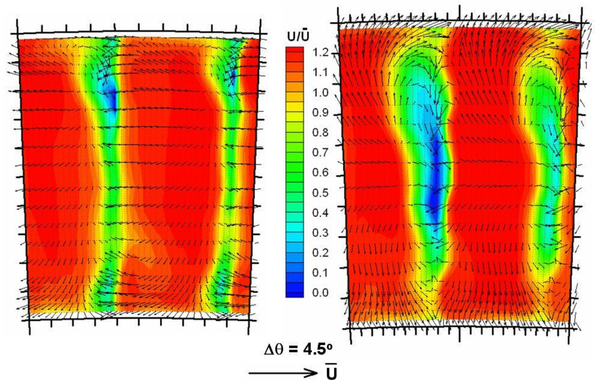


Fig.13: OGV exit axial velocity contours and secondary flow vectors:
- Conventional diffuser (left)
- Integrated OGV diffuser (right)

It can be concluded that

- increasing the flow through the fuel injector can worsen the fuel injector feed quality as well as potential compressor rotor forcing
- the design rules for low-to-moderate flows through the injector do not apply to designs based on larger fuel injector flows for a given dump gap
- the variable that needs assessing is the dump gap, although the problem could perhaps be tackled via circumferential profiling of the pre-diffuser and
- results with increased dump gap show that
  - compressor forcing can be removed
  - pre-diffuser performance remains affected.

More work in this area is required to properly evaluate the effect of dump gap optimisation.

External Aerodynamics: Preliminary results have been obtained for combustors where a larger amount of air flows through the fuel injector show that this flow split can bring about a worsening of the fuel injector feed quality and potential compressor blade forcing.

New experiments are therefore being carried out, which aim to find out whether a new design rule can be established for combustors characterised by high flows through the fuel injectors.

Experiments with the existing flame-tube and 30% cowl flow [22] and measurements with cowling/flow area variation (30, 50 and 70% flow) have been completed [23].
These test have revealed a very interesting phenomenon; when fuel injector/cowl mass flow increases to high levels, namely the possibility that the potential field induced by the suction effect of the cowl, flow penetrates upstream beyond the pre-diffuser and OGV and starts to force the rotor. This did in fact happen in the tests carried out, as seen in Fig.14.

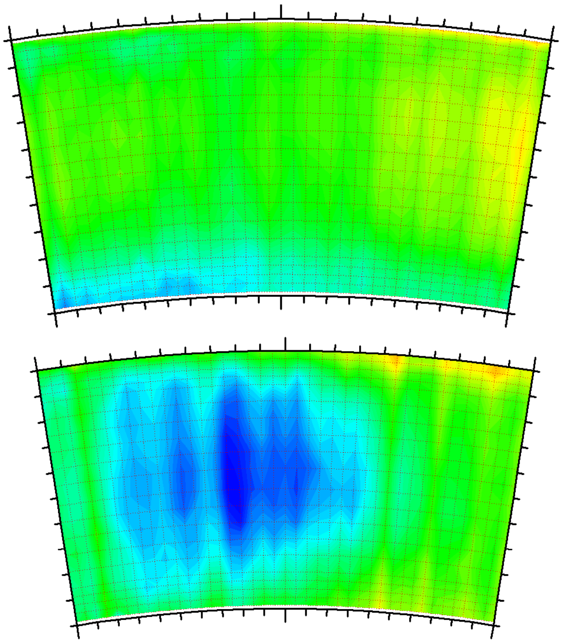


Fig. 14: Pre-diffuser exit static pressure contours (30% cowl air flow, top / 70% cowl air flow, bottom)

3D CFD calculation methodology has been setup to predict the pressure losses of the combustor. Special boundary conditions are used to impose the mass flow rate through the different boundaries; the exception is the inner air bleed boundary where the static pressure was imposed. Good agreement between experience and calculation has been achieved.
A LES calculation of the flow around a combustor has been done using the AVBP LES solver, which is a parallel CFD code for reactive unsteady flow simulations on hybrid grids. The mesh used for this calculation included the diffuser, the plenum, the injection system and the combustor itself. Some simplifications concerning the boundary conditions were necessary at the time this calculation was carried out. The effusion cooling has not been taken into account, because the corresponding LES boundary condition is under development. Also, the rotational periodicity was replaced by a symmetry condition.

The LES averaged solution has been compared to the N3S-Natur's RANS solution and the qualitative features of the mean flow are well reproduced by both solvers. The unsteady LES velocity field and the RANS mean velocity field are shown in Figs. 15 and 16.

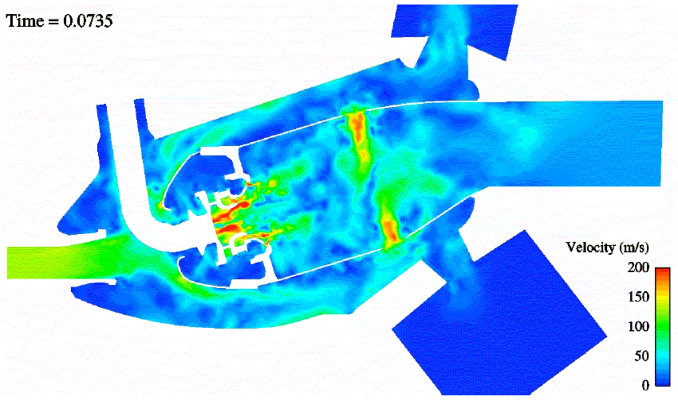


Fig. 15: Unsteady LES velocity field

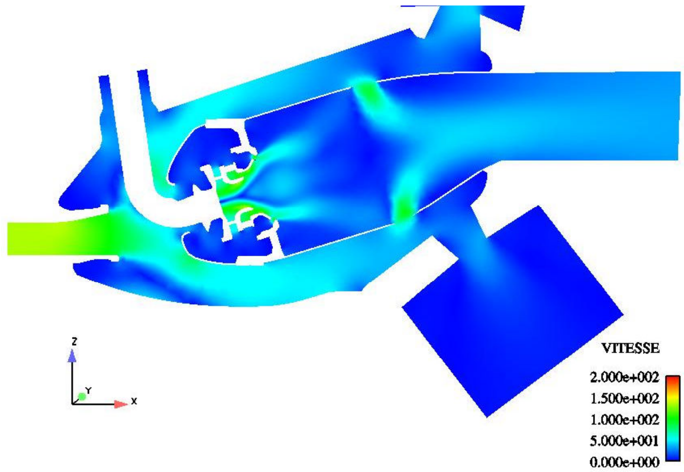


Fig. 16: Mean RANS velocity field

Application of optimisation techniques to design turbomachinery-components has been introduced a few years ago and can now be regarded as a routine activity, albeit still challenging. The main objective is to define a set of best practices for the read-across of turbo-machinery optimisation expertise to combustion optimisation problems, particularly on combustor external aerodynamics and integrated OGV-diffuser designs.

Iteration is required for optimisation; optimisation is not possible if the iterations cannot be run quickly enough. The simulation codes need to be linked together and be capable of batch running; more crucially, they need to run in parallel on a computing cluster. Ultimately, the optimisation process needs to satisfy the project requirements of accuracy and timeliness.

The design optimisation system comprises the following processes:

- Parametric geometry construction
- Automatic rapid mesh generation
- Robust and accurate CFD solver
- Post-processing data extraction
- Optimisation algorithm
- Dedicated computing cluster.

At the core of the shape optimisation is the ability to change the geometry in a flexible and general manner. The geometry parameterisation is a critical factor enabling efficient exploration of the design space and time-effective optimisation.

Combustor Cooling Design: Cooling device optimisation studies have been carried out. Validation of CFD tools has been performed. A Monte-Carlo method, radiative discrete transfer method and six-flux method have been implemented in CFD proprietary and commercial codes.
Several numerical simulations have been carried out and comparison with experiments performed [24]. A significant effort has been made to simulate the effusion cooling by means of CFD. Detailed experimental data have been provided for numerical tool validation.
The numerical results obtained show good agreement with available experimental data coming from other projects. Some effusion hole geometries have been selected for testing. The manufacturing of such configurations is partially finished. As far as other cooling devices are concerned, experiments showed that impingement cooling combined with ribs can be considered the final (i.e. most effective) choice for combustor design.

Effusion cooling is a cooling system where holes are drilled through the liner of the gas turbines combustion chambers to inject cool air into the chamber. For each hole of the perforated wall, a micro-jet of air is generated.
Due to constraints in computational power, a truly perforated wall, with thousands of holes, cannot be computed in typical full-scale 3D CFD simulations.
As a consequence, new wall boundary conditions accounting for effusion cooling in full-scale CFD computations are needed. Detailed data about effusion cooling is then necessary to support this modeling effort.

The CFD simulation of effusion cooling using Direct Numerical Simulation DNS [25] and wall-resolved LES were performed for isothermal [26] and non-isothermal [27] cases. The numerical data has been used to establish an appropriate effusion boundary condition model for RANS simulations. The objective of the approach is to simulate a small number of holes, with periodic boundary conditions reproducing the geometry of an infinite effusion-cooled wall (Fig.17).

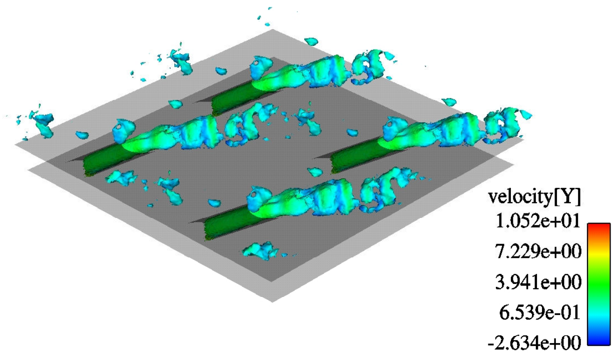


Fig. 17: 3D instantaneous solution: iso-surface of velocity modulus coloured by the velocity (m/s) normal to the wall (y direction).

Comparisons between numerical and experimental results provided to show the ability of periodic LES to reproduce a typical effusion flow [26, 27].

The numerical data obtained from these computations show that an appropriate model for effusion cooling should at least account for the non-viscous suction/injection of cooling fluid through the plate, which is the first-order effect in effusion cooling.

A thermal prediction of a multi-perforated wall has been performed. This simulation has been done using the new effusion cooling boundary condition implemented in the RANS code, N3S-Natur, at the initial stages of the INTELLECT-DM project.
The boundary condition uses conservative jump conditions through the effusion cooled wall, combined with a boundary layer analysis and constitutes an upgrade of an “adiabatic porosity boundary condition” in the N3S-Natur solver.

The original boundary condition was sufficient to accurately predict the pressure losses through the effusion-cooled liner. The new effusion boundary condition takes wall friction (through a wall law) and non-adiabatic walls into account.

The boundary condition model has been applied to a single-annular combustor. Several iterations between thermal solver (ABAQUS) and the RANS solver are needed for convergence. The final, converged solution of the 3D thermal map of the combustor liner is shown in Fig.18.

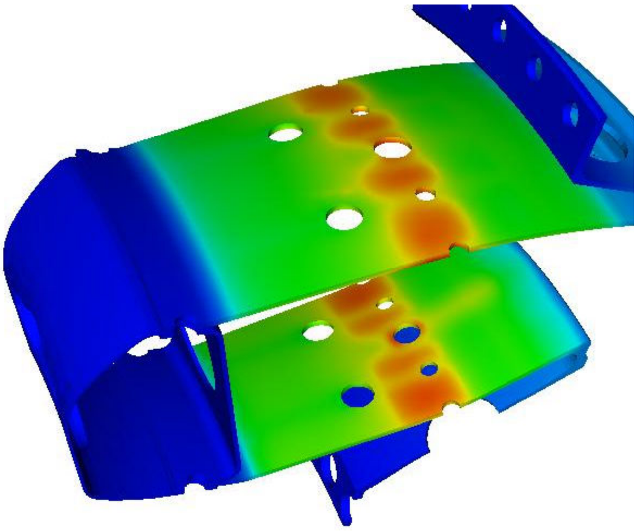


Fig. 18: Wall temperature distribution

Wall temperature predictions considering radiative heat transfer have been carried out. A 2-step reaction mechanism for Jet-A1 kerosene was applied. Turbulent combustion was modeled by a standard Eddy Dissipation Concept approach.

The turbulent combustion model has been linked to a Lagrangian two-phase model, in order to properly describe the non-negligible fraction of pilot fuel, which is injected in the liquid state into standard LPP combustors.

A generic tubular combustor was selected as a test-case for comparison of CFD results with measurements. A 3D mesh was set-up. Results are shown in Fig.19. The definition of soot models has begun to apply properly the Discrete Transfer Method for radiative heat transfer to predict and compare liner wall temperatures.

To verify the accuracy of the soot model with respect to experimental data, a kerosene jet-flame will be selected from literature as an additional test-case.

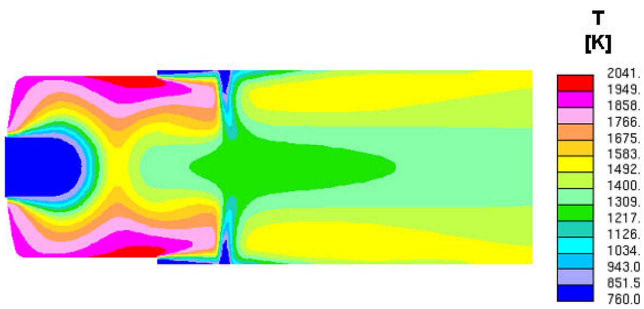


Fig. 19: Temperature contour plot of the generic tubular aero-engine combustor

A radiative heat transfer model was coupled with the reactive flow equations to evaluate the combustor wall temperature by CFD simulations with conjugate heat transfer. The soot model, which is based on flamelet-theory and was developed within CFD4C[6], has been used to increase of radiative heat load due to soot emissivity.

A thermal conduction model has also been implemented in the code to refine the wall temperature evaluation. Several numerical analyses have been carried out for a combustor, which was designed, manufactured and tested in the CLEAN[7] project.
Detailed measurements of wall temperatures at different points have been used to compare numerical results with experimental data available from a test campaign with the CLEAN combustor at high-pressure [29]. Fig. 20 shows a qualitative comparison of simulation and measurements.

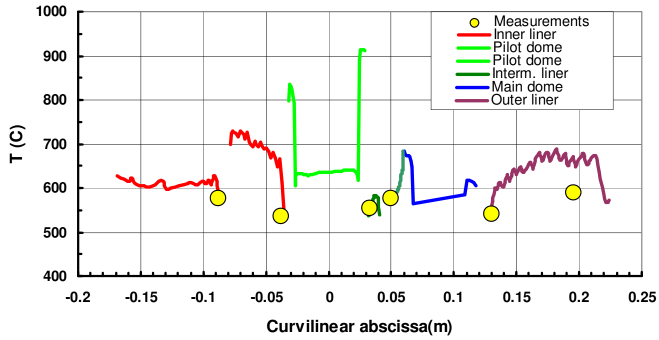


Fig. 20: Wall temperature in the main plane at take-off engine condition

A Monte Carlo radiation module has been developed and the module has been implemented in a commercial CFD-code. The module is tested for a set of academic cases, which are: radiative heat exchange between black/grey walls with and without a participating medium as well as wall heat flux prediction in box and cylindrical shape furnaces with given temperature distribution and radiative properties. To reduce the computational time during the solution of the radiative transfer, a mesh coarsening algorithm has been developed and tested for the academic test cases. The resulting solutions on coarse meshes are in good agreement to solutions obtained on the original fine meshes. At the current state of development, the module is restricted to structured meshes.

[6] FP5: Computational Fluid Dynamics for Combustion
[7] FP5: Component vaLidator for Environmentally friendly Aero eNgines (demonstration platform)

To demonstrate the predictability of the developed Monte-Carlo radiation code, the radiative emission of a luminous, enclosed propane jet-flame has been determined.

Fig. 21 shows a comparison of calculated (top) and measured (bottom) temperature distribution. Herein, the calculated and measured temperatures are in qualitatively good agreement, concerning the absolute value and the position of the maximum flame temperature. A detailed summary and models of the simulations can be found in [30, 31].

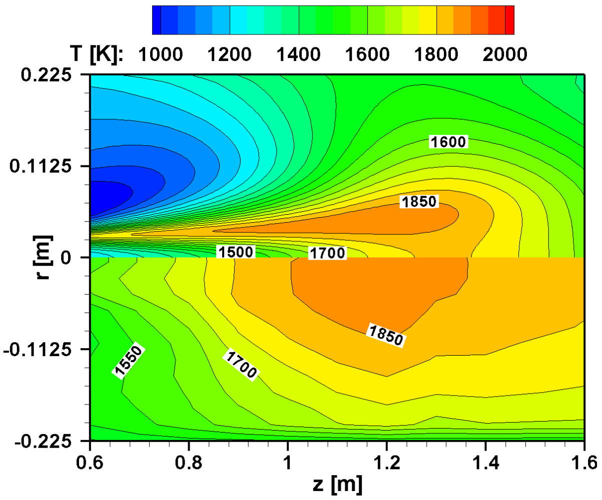


Fig. 21: Calculated (top) and measured (bottom) temperature distributions of investigated propane flame.

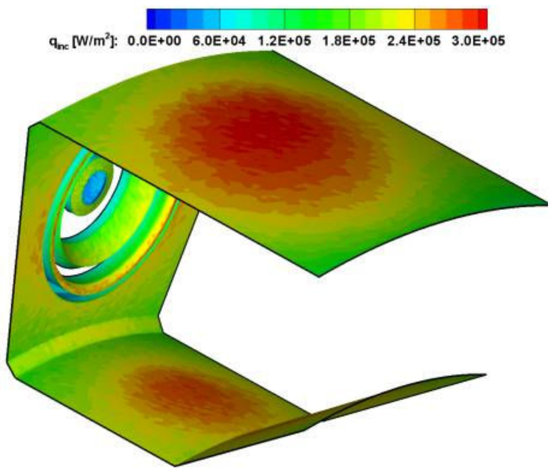


Fig. 22: Incident radiative heat flux of a lean-burn kerosene flame in a sector combustor

The effect of radiation in a generic combustor with lean burn injector has been simulated applying operating conditions taken from CYPRESS[8]. The radiative heat flux distribution is shown in Fig.22.

8 Conclusions

The question that needs to be answered was on how much design complexity of the combustor is really required to achieve the ambitious NOx reduction targets?

To sustain competitiveness the answer on the potential time requirement for a combustion system being designed has to be found.

INTELLECT D.M. is driving the technology development to help to generate the required answers.

The major scientific and engineering subjects approached were:

- combustor design methodology based on knowledge based engineering systems,
- design guidelines for ignition, cooling, external aerodynamics and lean blow-out performance of lean burn systems
- approaches for the flame stabilisation of lean injection system combustion by incorporation of a piloting flame into low NOx fuel injectors
- assessment of the impact of low NOx technology on combustor operability and achievable emission levels
- optimisation of pre-diffuser design for lean burn combustors and
- analysis and definition of requirements of effusion and impingement cooling for lean burn combustors.

Progress was enhanced by generating a high degree of synergies within the project by

- close European cooperation of academic and industrial partners,
- application of highly sophisticated CFD models and by
- introduction of modern knowledge based engineering and artificial intelligence tools.

[8] FP5: Future Engine Cycle Prediction and Emissions Study

By concentration on single annular combustors with lean burn injectors a fundamental step change of the combustor design has been introduced in INTELLECT D.M., leading to cost reductions and improved competitiveness.

The single annular combustor with pilot flame stabilised lean burn kerosene injector has moved into the focus.

Axially staged or double annular combustor architectures have not been investigated.

The close cooperation of European industry and academia has shown to not only maintain the current high level of knowledge, but that this can improve the quality of academic and industrial research in Europe. Through the collaboration of industrial partners and research institutes the knowledge and the specific expertise which is present within the consortium of well established research institutes, universities and industrial partners was also transferred between the partners.

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