Project Final Report

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Name and organisation of the scientific representative of the project coordinator:

Dr. Ruud Eggels, Rolls-Royce Deutschland Ltd & Co KG
Eschenweg 11, Dahlewitz, 15827 Blankenfelde-Mahlow, Germany
Phone: +49 (0) 33708 6 1145
e-mail: Ruud.Eggels@rolls-royce.com

Project website address: http://www.impact-ae.eu/

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1.1 Executive summary

The expected annual growth rates of air traffic with about 3% for the next two decades are only sustainable if the environmental footprint of engines for aviation is minimised. Besides the progressing stringency of legislative requirements for noise and NOx emissions, customer requirements and thus the market competition are increasingly focussing on the environmental friendliness of aero-engines.

In this context, IMPACT-AE directly supports the target reduction of NOx by 80% set by the Advisory Council for Aeronautics Research and Innovation in Europe (ACARE) for 2020. The environmental benefits of low emissions lean burn technology in reducing NOx emissions can only be effective when these are deployed to a large range of new aero-engine applications. While integrating and developing low emission combustion design rules, IMPACT-AE has delivered novel combustor design methodologies for advanced engine architectures and thermodynamic cycles. It supports European engine manufacturers picking up and keeping pace with the US competitors, who are already able to exploit their new low emission combustion technology to various engine applications with short turn-around times.

A key element of the project was the development and validation of design methods for low emissions combustors to reduce NOx and CO emissions by an optimization of the combustor aero-design process. Preliminary combustor design tools were coupled with advanced parameterisation and automation tools. Improved heat transfer and NOx models increased the accuracy of the numerical prediction. The advanced representation of low emission combustors and the capability to investigate combustor scaling effects aim at an efficient optimisation of future combustors targeting a cut of combustor development time by 50%.

IMPACT-AE was split into four technical work packages:

- WP1 'Smart design methodologies for clean combustion' as central WP to deliver the new methodology for combustor design,
- WP2 'Modelling and design of advanced combustor wall cooling concepts' for combustor liner design definition as key technology area,
- WP3 'Technology validation by detailed flame diagnostics' to substantiate fuel injector design rules implemented into the design methodology and
- WP4 'Design methodology demonstration for efficient low NOx combustors' to validate the combustor design.

The consortium consisted of all major aero-engine manufactures in Europe, 7 universities and 3 research establishments with recognised experience in low emission combustion research and 2 SMEs.

1.2 Project context and main objectives

The main objective of the IMPACT-AE project was to develop and validate smart design systems for low NOx, highly efficient aero-engine combustors. Specifically, IMPACT-AE pursued the following scientific objectives:

- Automation of the combustion aero-design process, including coupling of different levels of combustor preliminary design tools starting from simple 1D combustor sizing models up to full 3D-CFD combustor simulations;
- Improved parameterisation of the whole combustion system allowing scaling of the combustor module;
- Increased accuracy of simulation tools through improved combustor wall cooling and NOx models;
- Design and experimental validation of new combustor cooling schemes suitable for low emission combustion;
- Generation of improved combustor designs based on optimisation techniques and improved knowledge based design rules for low NOx & high combustion efficiency;
- Establishment of rapid-prototype design processes to allow a faster validation of new combustor designs; and
- Generation of comprehensive design rules for low emission high efficient combustion via detailed non-intrusive and intrusive measurements inside the combustors as well as multi-sector and full-annular combustor tests to validate the design methods.

Based on these objectives the IMPACT-AE project was structured in four technical work packages, namely 'smart design systems for clean combustion' (WP1), 'modelling and design of advanced combustor wall cooling concepts' (WP2), 'technology validation by detailed flame diagnostics' (WP3) and 'design methodology demonstration for efficient low NOx combustion' (WP4). The objectives of these technical work packages are briefly described below.

**WP1 – Smart Design Methodologies for Clean Combustion**

The central objective within IMPACT-AE is the development of intelligent combustor design methodologies towards low emission and high efficiency combustors. Hence, KBE based tools and processes have been developed and optimised by the aero-engine manufacturers Snecma (SNM), Turbomeca (TM), Rolls-Royce Deutschland (RRD), GE AVIO and Rolls-Royce UK (RRUK) supported by universities, research establishments and SMEs. The tasks cover integrated design prototype and validate methodologies for low emission combustor liners, KBE methods including more detailed parameterisation and optimisation of the combustion system, improvement of the LES-based emissions predictive capability and the generation of a more accurate NOx prediction tool.

Specifically, this work package aims at reducing the time necessary to develop a combustion chamber:

- Automation of the activities done by the engineers without added value (geometric parametrization, grid generation, CFD launching and post processing);
- Development of the thermal correlation in order to get correct thermal behaviour of the combustor and to optimize it without experiments;
- Development or improvement of combustion models in order to improve the numerical prediction and the optimisation of the pollutant emission generated by the combustion chambers.

A dedicated technology assessment task led by the WP leader reviews the technical progress within WP1.
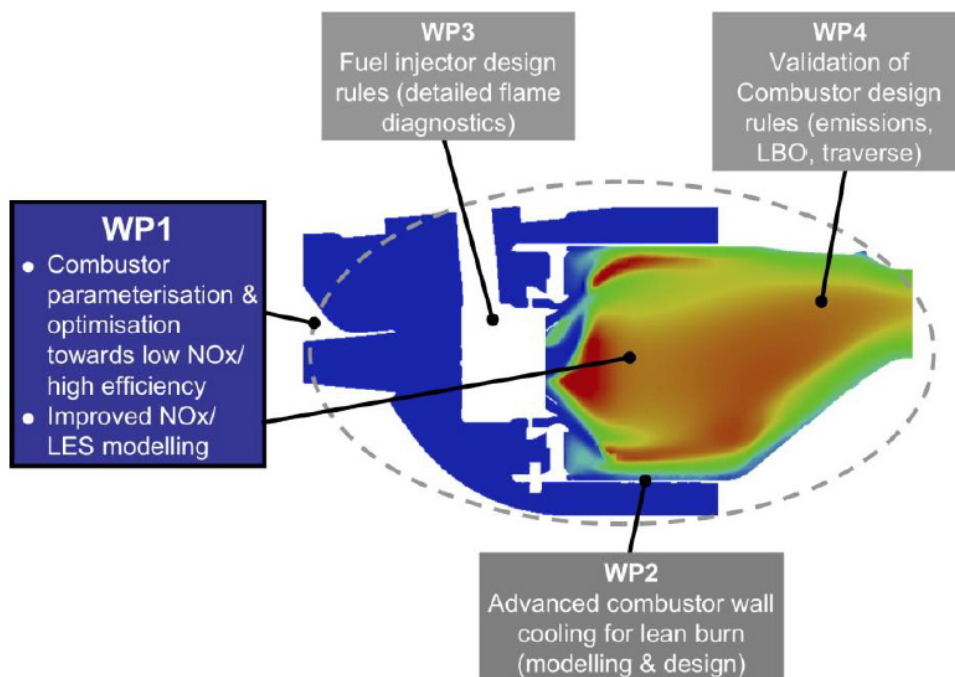
Figure 1: IMPACT-AE work package thematic network

WP2 – Modelling and design of advanced combustor wall cooling concepts

Previous combustion research demonstrated that appropriate modelling and optimisation of the combustor wall cooling is essential to further develop lean burn combustion systems. This challenge is driven by a significant reduction of the combustor air flow available for wall cooling and significant interaction between the heat release zones and the cooling flow influencing emission and combustion efficiency. Therefore, the objective of the work in WP2 was to increase accuracy and reliability of models that predict the behaviour of cooling system devices for low NOx combustors. The approach proposed within WP2 is to analyse the cooling system effect both by numerical simulation and by experiments. Numerical models considering 3D unsteady effects on wall heat load in combustors are investigated. Specific models for wall heat transfer are tested in LES/URANS methods for aero-engine combustors. A new design procedure is investigated to take into consideration the effect of air mixing and combustion radiation and to speed up design by exploring innovative cooling system configurations obtained by rapid prototyping. A technology assessment is carried out, led by the WP leader to review the technical progress within WP2.

WP3 – Technology validation by detailed flame diagnostics

Within WP3 advanced non-intrusive measurement techniques are applied to assess the low emission combustors developed in WP1. The major objective is to generate clear design rules regarding optimised pilot/main flame interaction during fuel-staged operation and with respect to flame/wall cooling interaction. The experimental data generated within this work package allow detailed validation of CFD optimisation tools. Additionally, understanding of how fuel temperature affects spray and vaporization is improved via detailed measurements. A novel emission sampling technique allows fast measurements of lean burn combustor at combustor exit to gain improved understanding of lean burn combustion processes and to support the improvement of emission prediction accuracy, allowing faster design development of low-emission lean burn combustors. Also in the work package a technology assessment is carried out led by the WP leader to review the major findings based on detailed measurements inside the low emission combustors, especially regarding common design rules for lean combustion.

WP4 – Design methodology demonstration for efficient low NOx combustors

WP4 provides a final demonstration of the design methodologies developed within WP1 and WP2. Full-annular combustion tests are carried out to validate the combustor performance regarding NOx-emissions, combustion efficiency, lean blow out and combustor exit temperature traverse for different fuel injection technologies. Moreover, new combustor liner cooling systems are evaluated during multi-sector test campaigns. The maturity of an innovative low-NOx compact combustor is assessed. Emission characteristics of a novel fuel injector and combustor configuration within a full-annular environment is measured and the results is used for the validation of a low emission combustion system based on KBE design rules. Another important outcome in WP4 is an improved understanding of the implementation path and design rules for introduction of cooled cooling air (CCA) into combustor external aerodynamics architecture for lean burn, low NOx combustor systems in advanced cycle engines.

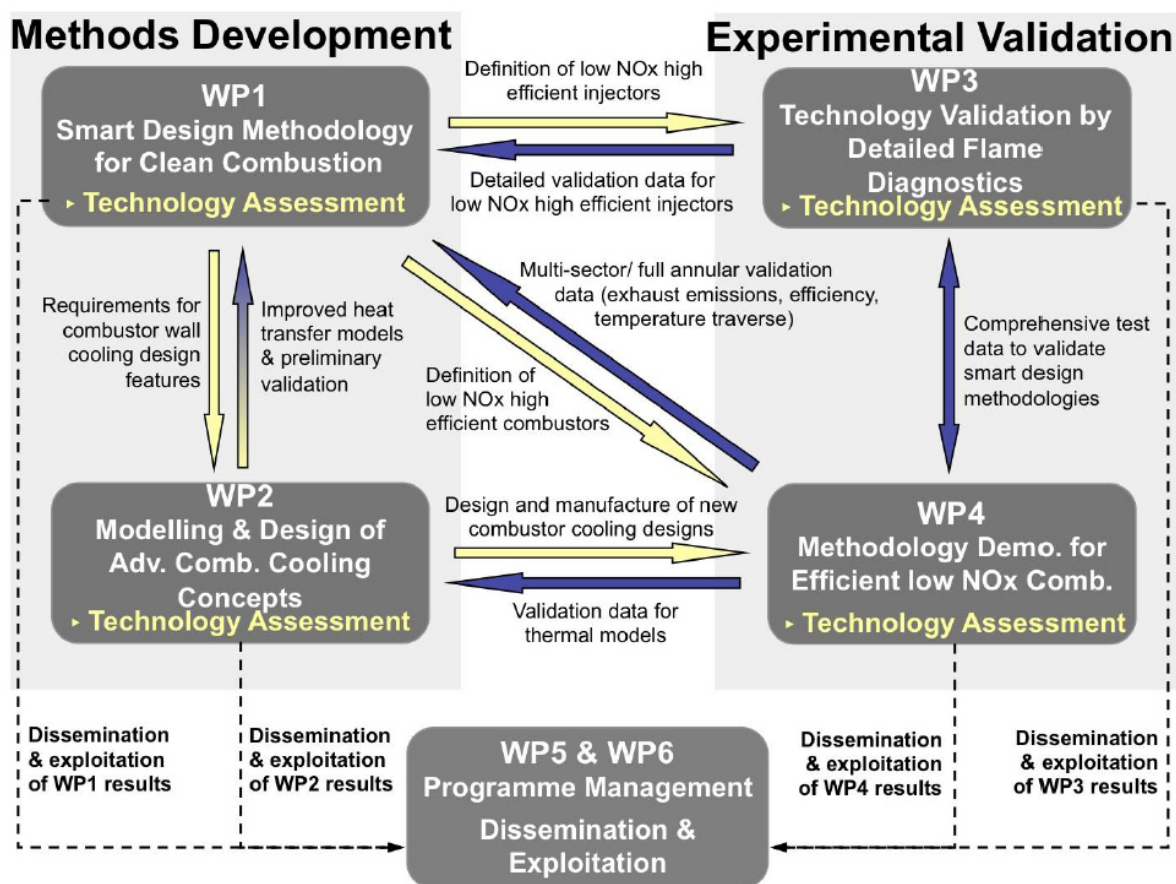The Figure below depicts the relationship between the six work packages within IMPACT-AE.

Figure 2: IMPACT-AE work package relationships

1.3 Description of the main results/foregrounds

This section describes the main results achieved in the four technical work packages of IMPACT-AE.

WP1 – Smart Design Methodologies for Clean Combustion

All the different objectives in WP1 have been achieved. This work package is divided in seven different tasks.

In task 1.1.1 the development of the automation of the design of a combustor has been performed through three different activities.

First, an optimization Knowledge Based Engineering (KBE) tool was developed. This tool, based on the Optimus software, modifies automatically the parameters of a parametrised CAD geometry. Then it generates the corresponding CAD and generates the mesh. The tool then launches automatically the CFD simulation and then does the post processing. The result is analysed by the tool which then modifies the parameters defined at the beginning of the optimisation loop. The whole process is described on Figure 3.
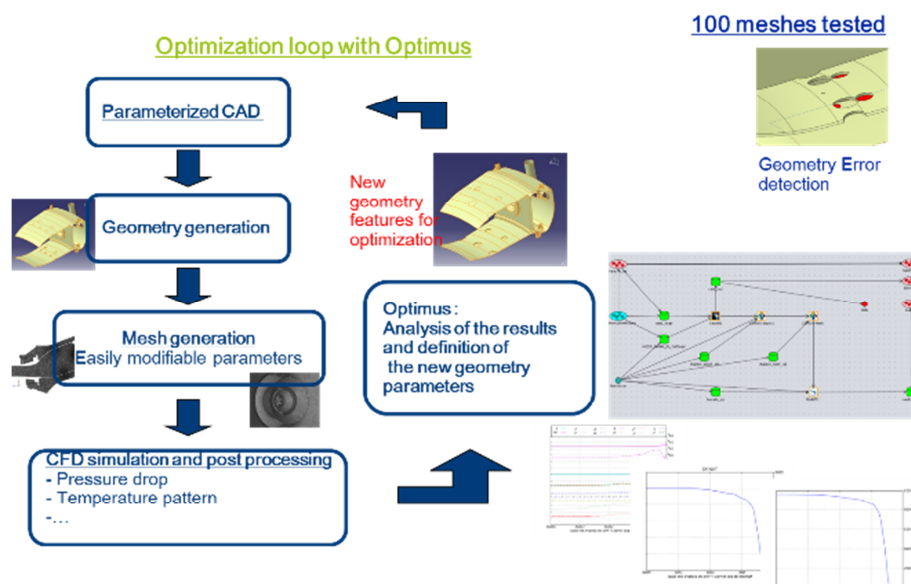

Figure 3: Optimization loop of the KBE tool

Second, a KBE tool which links the predesign tool to the CFD code was developed (see Figure 4). Form the 1D predesign tool, this tool gets information about the air repartition and about the thermodynamic condition inside the combustion chamber. The tool generates the numerical parameter file, the boundary condition file and the two phase flow parameter files. Each simulation is done exactly with the same parameters which are defined manually inside the tool. Therefore, this tool simplifies the data pre-processing and increases the quality of the simulations: each set of simulations is done with the same numerical and diphasic parameters and is comparable. This tool was used in the tasks 3.2 and 4.1.
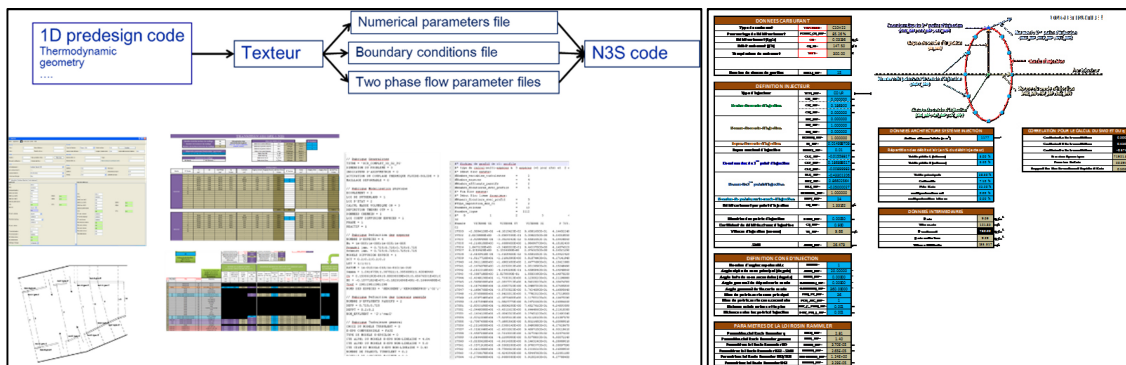
Figure 4: Principle of the KBE tool (left); Parametrisation of the Multipoint fuel injection (right)

Third, the thermal correlation about the wall cooling air developed in task 1.1.1.2 has been implemented into the 1D pre-design tool and has been used to design the annular combustor in the LEMCOTEC project (see Figure 5).
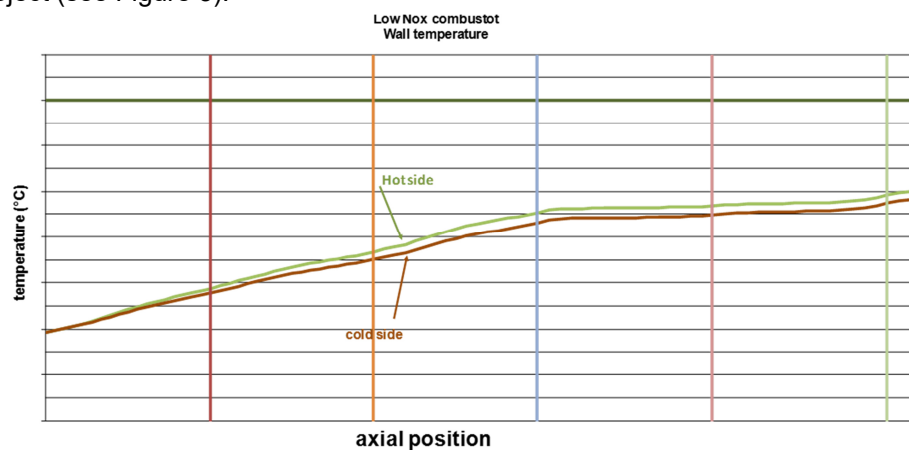
Figure 5: Result of the thermal correlation applied on the LECMOTEC combustor

In task 1.1.2 Turbomeca (TM) developed an effusion cooling model of the combustor wall based on an existing experimental database (the aero-thermal conditions and the geometry of the multi-perforated plate studied are close to the ones encountered in gas turbine combustor). This effusion cooling model was integrated into the 1D pre-design software used at TM. A limited number of tests on basic experimental data available at TM has been also carried out to validate this tool. This new tool has been used to study the thermal behavior of the low NOx annular combustor tested in task 2.3.1 (IMPACT2).

In task 1.2 Rolls-Royce Deutschland (RRD) has worked on the generation of parametric combustor CAD models using standard features. These parametric CAD models and the RR prelim design tool PreDict have been supplied to the Universität der Bundeswehr München (UBWM) for implementation in an improved combustor design process.

UBWM has developed a tool to automate the combustor design process, which includes the following processes:

- Automated UG NX CAD model parameter adjustment, using parametric CAD models from RRD;
- Automated grid generation, using the BoXer grid generator (provided by Cambridge Flow Solutions Ltd - CFS) and information from the parametric CAD models;
- Automated CFD analysis with the RR in-house solver PRECISE-UNS, using input information from the prelim design tool.

To realise an automated generation of optimal refined meshes (with BoXer tool from CFS) and optimized CFD analysis within the KBE process, additional grid refinement studies and numerical investigations have been performed. CFS has been working on the generation of high quality grid which can be created in an automated process.
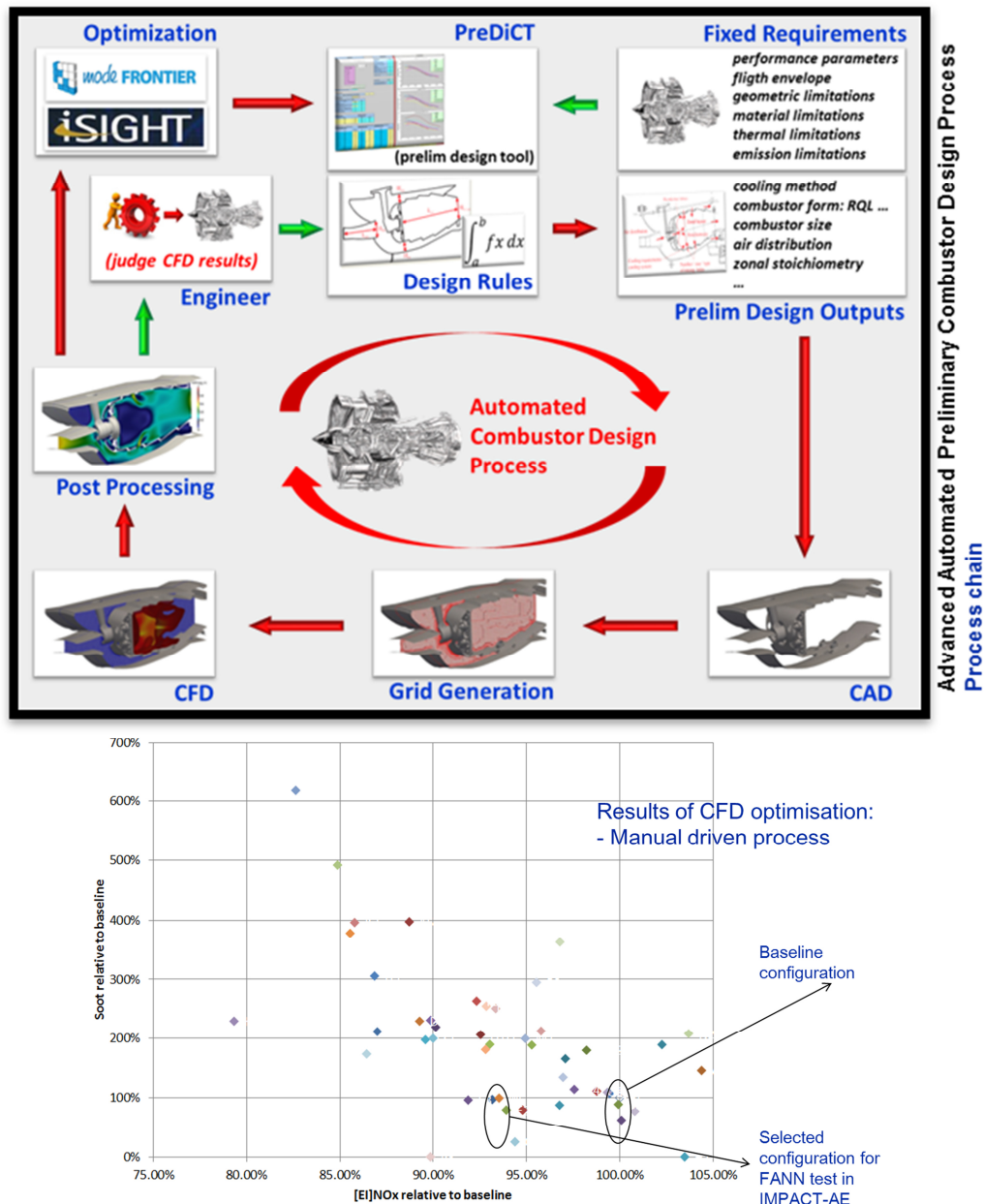

Figure 6: Principle of the KBE tool (top);
Result of the manual optimisation done with the KBE tool (bottom)

The design tools have been provided to RRD and implemented in the design process of RRD. Next, the tools have been used to optimise an aero engine combustor. The parameters were linked to geometrical properties of the dilution holes. The optimised output parameters were the NOx and soot emissions. In the end, one configuration has been selected, for which hardware has been manufactured and tested in a Full Annular test.

In task 1.3.1. GE AVIO developed a QRDV methodology. It aims to create guidelines that allow to speed-up the design conformity of the parts with the product requirements through a direct design-to-prototype method, and substantiate it through experimental investigations. This effect is further enhanced by the selection of the rapid prototyping in the manufacturing phase that reduces time and cost of the product development process.

Samples hardware was manufactured and tested. Data gathered were used to tune the models representative of the part, including the uncertainty on the real dimensions, and therefore on the performance, due to the process capability (see Figure 7). All data were analysed to populate a database of corrective parameters that can be exploited for modifying any kind of geometry, also different from the ones of the present study.
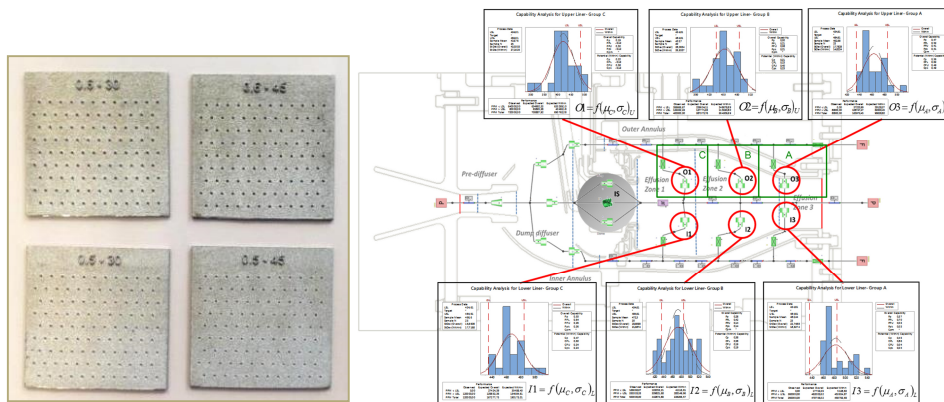

Figure 7: Tested sample (left); Model representative of the part (right)

In task 1.3.2, the University of Florence (UNIFI) focused on the thermal medialisation of the walls of the combustion chamber. The existing design methodology (Therm1D) relies on the 1D approach proposed by Lefebvre and it is based on correlation to characterize convective and radiative heat loads. As pointed out in recent studies, this approach fails to predict the actual conditions within the flame-tube when applied to modern aero-engine combustors with strong recirculation zones.

To overcome this issue and provide high-fidelity estimates of the heat loads, 3D CFD is required. An innovative design methodology (Therm3D) was hence developed in ANSYS CFX by UNIFI to perform a sequential solution of 3D CFD, 3D radiation and 3D heat conduction, with the aim of allowing outstanding improvements in the fidelity of the metal temperature prediction (see Figure 8, left). Significant efforts were made to define the strategy exploiting the best trade-off between computational cost and accuracy.

An application was carried out on NEWAC combustor to validate the new approach (see Figure 8, right).
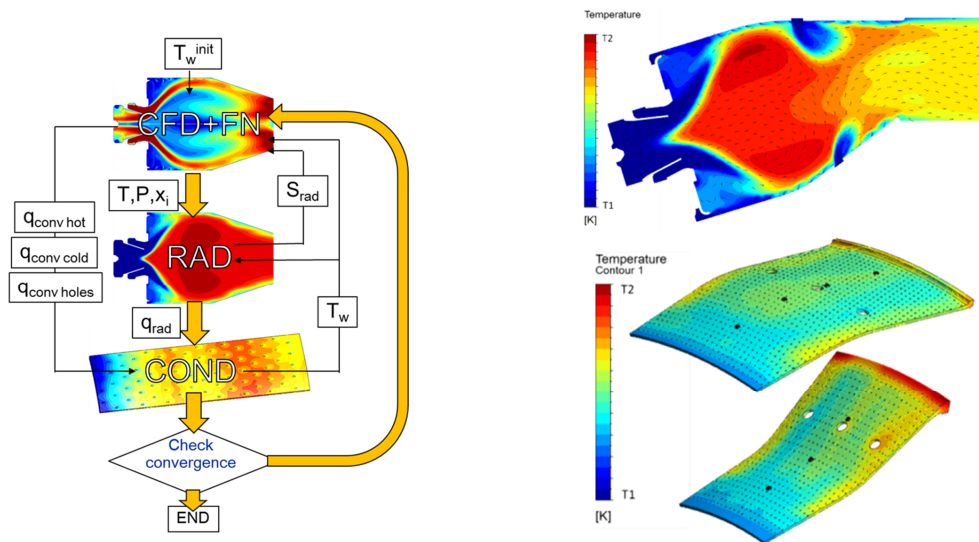
Figure 8: Principle pf the Therm3D methodology (left);
Validation on the NEWAC combustor (right)

In task 1.4, a typical lean burn combustion system was parameterised. This was done based on Siemens NX CAD representation, using a sketchbook approach. An Open C++ method was then used to enable automatic feature recognition that was relied on to tag surfaces, which in turn is necessary to set up CFD boundary conditions. The feature recognition capability was read across from an existing rich burn KBE system, which applies to a different combustor topology and size. Model generation rules were implemented into the system to allow automatic creation of a Flownet network for the lean burn combustion system. The network model is used to work out pressure loss and flow distribution for the entire system.

Furthermore, the Boxer grid generation tool was tested and CFD predictions based on Boxer generated grids compared against results obtained using ICEM-CFD for a lean burn injector. The version tested incorporated the CFS-developed in-plane feature capture functionality. Meshing rules were embedded into the system to enable automatic generation of CFD grids. Setting up of the boundary conditions was automated as well.

The whole system was tested successfully.
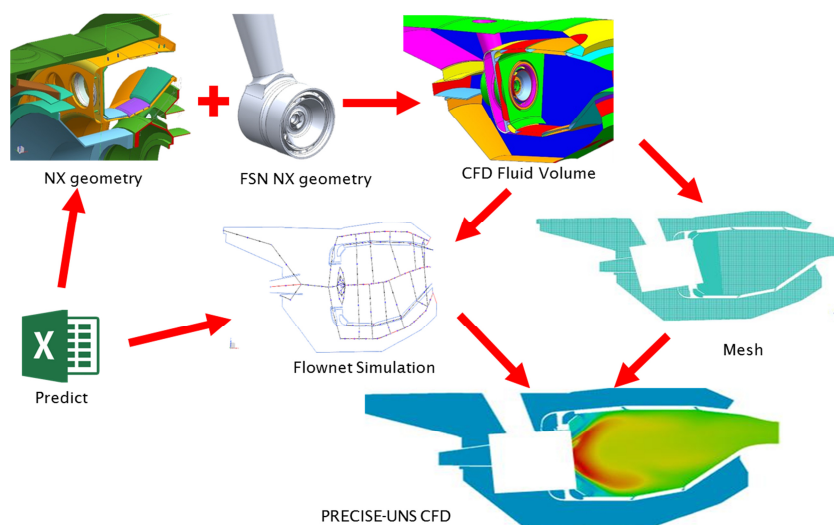
Figure 9: Principle of the RRUK KBE tool

In task 1.5, Imperial College London (IC) developed and validated on different configurations a subgrid combustion model (stochastic fields method) dedicated to the prediction of pollutant emissions.

The IC implementation of the stochastic fields method was transferred to the latest version of the RR in-house code PRECISE. The model was then used to simulate of a TIMECOP-AE test case. Comparison against pre-existing simulations run with the stochastic field approach has shown good consistency. Comparison against measured temperature has shown a reasonable tie up.

Furthermore, the stochastic fields LES model was run on a UK supercomputer (ARCHER). This exercise allowed characterising the parallel scalability of the current implementation. The testing has shown that the PRECISE-UNS CFD code scales nearly linearly up to 1000 cores. For higher number of core the scalability degrades.

The stochastic fields method with n-dodecance detailed mechanism was then used to simulate the lean burn combustor tested in task 3.4. The results were compared against the ones obtained with the FGM model and the measurements. The stochastic fields prediction of temperature traverse and NOx compared slightly better with measurements than the FGM prediction. The CO map was predicted qualitatively well but the absolute values underestimated. As expected, these LES predictions were more accurate than the RANS/SAS predictions performed as part of task 3.4 on the same geometry. Eventually, the stochastic fields method was applied to simulation of another lean burn combustor. In this case, the operating condition was pilot only. The simulation used a simple 4-step mechanism.
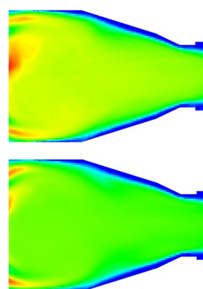
Figure 10: Simulation of the BOSS combustor with the stochastic fields method. Temperature, Upper figure, n-dodecane mechanism, lower figure 4-steps mechanism.

In task 1.6, the global objective was to enhance and industrialize NOx models that have been developed at the Institut National des Sciences Appliqués de Rouen (INSA-CORIA), Snecma (SNM) and Turbomeca (TM) for databases built in recent European projects and for realistic combustors from TM.

The NOx model developed at INSA-CORIA has been validated by successfully simulating the SANDIA flame D. This model is based on the tabulated chemistry approach and the chemical table generator has been adapted to the Luche mechanism for kerosene chemistry. The NOx model has been implemented to the YALES2 and AVBP LES codes.

NOx emissions have been computed in real industrial configurations. Two configurations are considered:

-   The first one, computed by both INSA-CORIA and TM, is a conventional TM combustion chamber;
-   The second one, computed by TM, is a low-NOx combustion chamber equipped with lean premixed injectors.

Instantaneous results, flame topology and mean distributions of thermo-chemical quantities have been studied. The flow is found to be asymmetric with regard to the pilot, which has a strong influence on the aerodynamics and on mixture fraction and NO creation process.

An overall good agreement is found between available experimental data at the combustion chamber exit and the LES predictions. Table 1 provides the results obtained for pollutant emissions for the two computed simulations (two meshes of different refinement ratios are used for computations). The
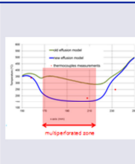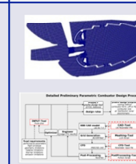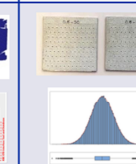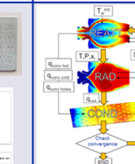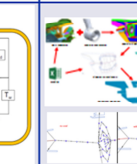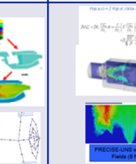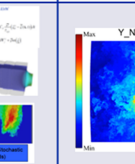
results are in good agreement with experimental data for the NOx emission index values, while a strong discrepancy arise for carbon monoxide. Without heat losses and two-phase flow modeling, CO specie could be difficult to predict with a strong level of confidence.

	Ref. Grid Relative error	Fine grid Relative error
$ieNO$	39.3%	24.3%
$ieNOx$	4.3%	-
$ieCO$	85.2%	-

Table 1: Values and relative errors with regard to experimental data for integral pollutants data.

In task 1.7 SNM performed the risk analysis and made the technological assessment of the result obtained inside the work package. The summary of the technological assessment is presented on Figure 11. All the objectives of this work package have been achieved.

T1.1.1	T1.1.2	T1.2	T1.3.1	T1.3.2	T1.4	T1.5	T1.6
SNM	TM	UBWM/CFS/RRD	GeAvio	GeAvio – UNIFI – KIT-U	RRUK	IC/RRUK	CORIA/TM
Optimization / data pre processing / Thermal correlation	Thermal correlation	KBE tool from CAD parts to CFD post processing	Additive fabrication characterization	Thermal design	KBE tool from CAD parts to CFD post processing	LES combustion model for emissions prediction	NOx Emission model
Reduction of the time necessary to design and optimize a combustor	Reduction of time necessary to get the good life cycle	Reduction of the time necessary to design and optimize a combustor	Reduction of time and cost to manufacture combustors	Reduction of time necessary to get the good life cycle	Reduction of the time necessary to design and optimize a combustor	Reduction of the time necessary to design and optimize a combustor	Reduction of the time necessary to design and optimize a combustor

Figure 11: Summary of the technological assessment

WP2 – Modelling and Design of Advanced Combustor Wall Cooling Concepts

In the design of modern combustion chambers the cooling of the combustor walls is of high importance. Since the flow field in modern combustors is very complex and unsteady, the simulations have to take this unsteadiness into account. Various approaches can be chosen in order to obtain a method exploitable in an industrial environment.

In the subtask 2.1, the Deutsches Zentrum für Luft- und Raumfahrt (DLR) developed a method to include transient effects in conjugated CFD simulations. CHT-CFD simulations combine simulations of fluid domains and solid domains in one setup. In general this is favorable compared to the coupling of two different codes.

One obstacle in the combination of those two different types of domain is that fluid simulations rely on rather small time scales with typical time steps of 10e-7s to 10e-4s in order to capture flow dynamics like turbulent fluctuations. Simulations of solid domains on the other hand are simulated with time steps around 1s or longer. This is due to the long response times of solids and also to the fact that

thermal simulations of solids are very robust because only an energy equation has to be solved. CHT-CFD simulations are often conducted in steady state because this allows to set different "time steps" or relaxation factors for the two domains. This way the convergence of the solid domain can be significantly accelerated. In unsteady simulations this option is not available.

Therefore the inclusion of unsteady effects is a numerically very demanding task. DLR developed a 4-equation heat transfer model to capture the effects of unsteady fluctuations on heat transfer by a model that determines the impact of the flow fluctuations on the turbulent heat diffusivity with a varying turbulent Pr number instead of a commonly used constant Pr number. This is being realised by two additional transport equations. DLR also developed an unsteady CHT method to capture transient effects in a fluid domain and to apply them in a separate simulation of the solid domain. This approach was tested and validated with the CHT-CFD simulation of a forward facing step and a channel with a rib.
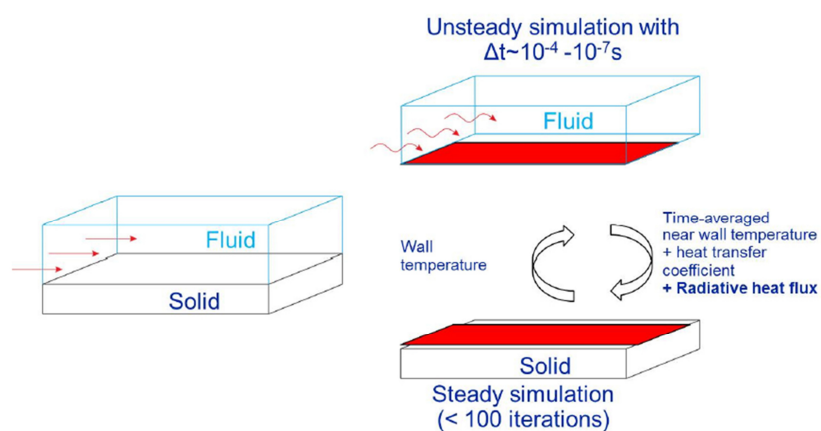
Figure 12: sketch of unsteady CHT methodology

CHT-CFD simulations was then tested by MTU Aero Engines (MTU) with a multi physics simulation of a complex combustion chamber configuration. The method was extended in order to also include radiative heat transfer in a combustion chamber: this can be realised by an additional source term in the energy equation. The test of the method showed that also in a complex setup the model runs stable. A stabilised solid temperature could be obtained faster than it is possible with the direct simulation of the CHT-CFD case.
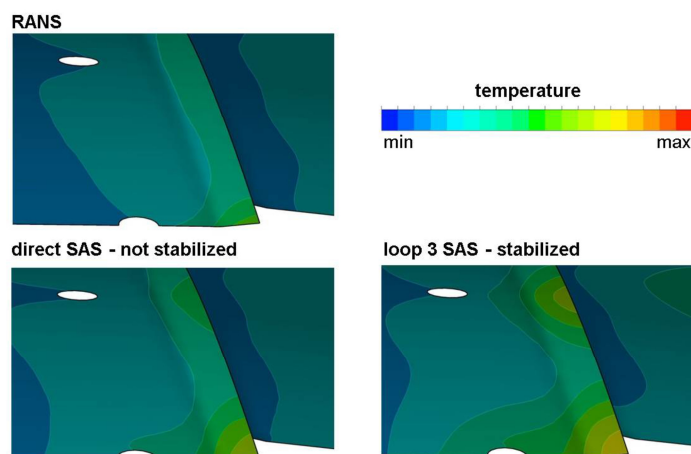
Figure 13: Solid temperature comparison of RANS, not stabilised direct SAS CHT-CFD

In the subtask 2.2 TM assessed the efficiency of effusion cooling with detailed simulations, taking into account the flow field as well as the heat transfer from the walls to the cooling air. A homogeneous model for the dynamics of the flow through a multi-perforated plate already existed in the LES code used by TM. However no models for heat transfer through this plate were tested so far. The configuration chosen was a Low-NOx combustor, in which multi-perforated plates were used to cool the walls of the combustor. The cooling efficiency as well as the composition of the mixture to be burned in the primary zone were checked before using this technique at the industrial scale. In task 2.2.1, the low-NOx combustor was simulated with a LES code and two models for the multi-perforated plates: an existing validated model, based on a homogeneous approach for the dynamics of the flow inside the cooling holes, and a new model based on a heterogeneous description of the cooling holes. The experimental data obtained on the configuration using thermocouples stations along the inner and outer liner of the combustion chamber were used to assess the validity of the coupled heat transfer simulation. The adiabatic temperature is presented in Figure 14 at walls as well as the computed plate temperature as function of the azimuth. Available experimental data points are reported in the figure. Several experimental points have two values for a given azimuthal value to give an appreciation of experimental disparity between the combustion chamber sectors.
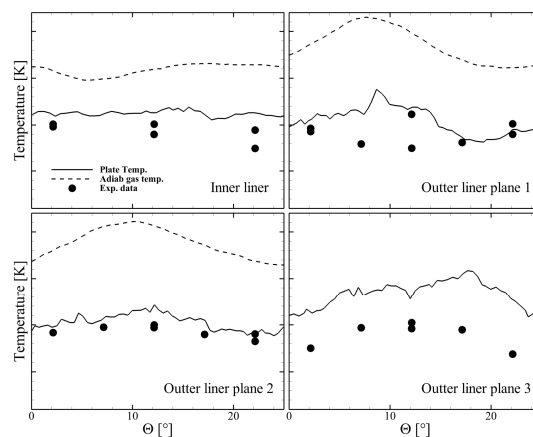
Figure 14: Comparison between simulations and experimental data

The simulations results agree well with the experimental data on the plate temperatures, even if temperature is over-predicted in the four experimental planes. Radiation inclusion is expected to enhance the capabilities of the simulations to tackle more precisely the experimental values.

These results demonstrate the capabilities of coupled LES to reproduce satisfactorily heat-transfer in the plate (and multiperforated plates) in an industrial context, with return times compatible with design offices constraints.

The aim of task 2.2.2 owned by Université de Pau et des Pays de l'Adour (UPPA) was to generate a DNS database for a jet discharging in a turbulent cross flow.

The objective was to develop its own simulation tool, AeroSol. Dealing with unstationary simulations a high order method is required. Although the geometry is relatively simple, an unstructured mesh has been applied, while the geometry includes an inclined cylindrical hole, which is not easy to mesh using a structured approach. Also, UPPA developed its code with a full compressible system. Considering its flexibility for unstructured meshes and its compatibility with the upwinding of hyperbolic fluxes, but also the fact that this method can be developed for any order of accuracy, a code based on the discontinuous Galerkin method on unstructured hybrid meshes was chosen.

The results obtained for a jet in cross flow with the compressible software code Aerosol were gathered from two configurations: without gyration, i.e. with a hole aligned with the main flow direction and with a 90° skidding of the hole with respect to the main flow.

The final database is composed of

- The value of the mean velocity on each degrees of freedom;
- The value of all the components of the Reynolds stress in all the degrees of freedom;

- The instantaneous values on a set of probes;
- The linear projection of the instantaneous flow (i.e. the projected value on each vertex of the mesh).

The UNIFI activity in task 2.2.3 deals with the development of new pre and post processing methods to be applied to an existing chemical reactor network code.

The first step in the procedure consists in the definition of regions of the domain to be clustered together and which will be represented by a single reactor. Several strategies can be followed, for the clustering refinement criteria and the resulting number of reactors in the generated network. One option is to apply a large number of reactors, creating a coarser mesh by grouping together a small number of cells. However, the drawbacks associated to such an approach are the difficult management of the network inside the chemical reactor's code, the loss of physical insight on the single reactors and relatively large solution time, compared to the proposed target of creating a fast design and pre-design tool.

Therefore, the objective of the research work consists in the definition of a reactor network where only few reactors are employed. Moreover, a physical meaning and function of the single reactor should be easily recognizable. Reactors should be related to the main aero-thermal features of the combustor. In Figure 15 the CFD mean values are compared with three solutions obtained in REACT. When no diffusion is implemented the studied flame is not correctly reproduced in the network solution. The main exchange pattern, diffusion, is neglected and the solution is wrong. Before the code revision the diffusion terms had to be artificially limited in order to reach a steady solution, otherwise convergence issues do not allow the solution of the network. After the code revision, the diffusion can be managed by the solution process and the obtained distribution in the network is definitely satisfying.
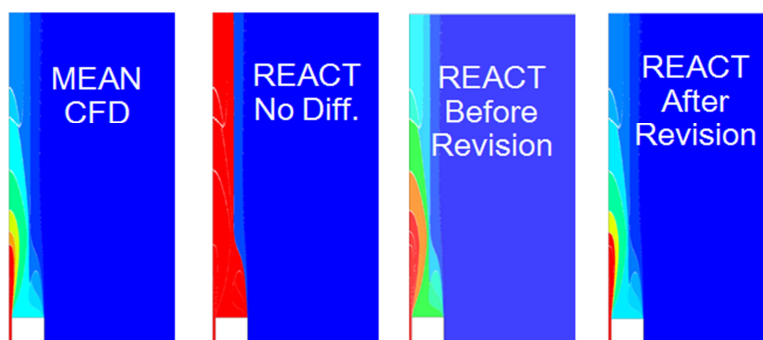
Figure 15: CFD mean values compared with three solution obtained in REACT

The Karlsruhe Institute of Technology (KIT-U) activity in this task 2.2.3 deals with the evaluation of the effect of turbulence-radiation-interaction (TRI) in an RANS/URANS-environment. For this, the spectral radiative properties of the molecules water and carbon dioxide (the main radiative species in combustion of natural gas and kerosene) in terms of emission and absorption are averaged using presumed probability density functions. The properties are calculated using narrow band parameters. For this, the correlated-k distribution method (CK approximation) was applied.

Two radiation calculations were executed taking into account TRI and a second one without taking into account TRI. These calculations were compared and evaluated (effect on the radiation field). A radiation calculation taking into account TRI was coupled to the CFD-calculations to evaluate the TRI effect on the flow field and the combustion.
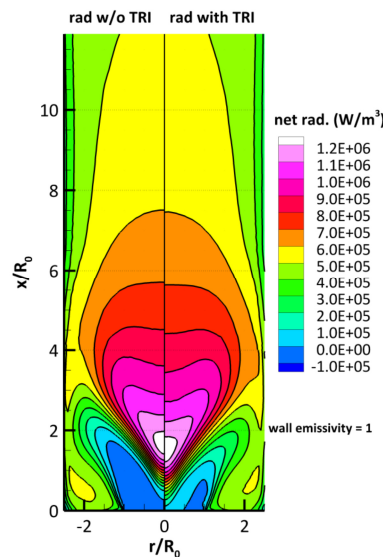
Figure 16: Impact of the TRI on the net radiative heat flux field

As a result, the TRI generally enhances the absorption and emission. The enhancement of the emission is in this combustion case stronger than of the absorption. In the vicinity of the flame (x < 0. 2 m) the emission is enhanced by ca. 5% and the absorption by ca. 3 %. The net radiative heat rate in the gas in this area is enhanced by 7%. Since the net radiative heat rate is primarily absorbed on the walls, the wall net radiative heat rate is enhanced by ca. 9-13% in the vicinity of the injector (x < 0.2 m). This amount is remarkable and has to be taken into account by the local cooling design.

Two test campaigns were carried out on the bench of the M1 Office National d'Etudes et Recherches Aérospatiales (ONERA, Palaiseau) in task 2.3. The first test campaign was performed using a NEWAC combustion chamber equipped with LP injectors (referred to as IMPACT1).

The combustor IMPACT2 is the same that the first one but with the double wall in the primary zone shortened to make the combustor lighter and less expensive to manufacture.

Pollutant emissions, gas temperatures in the exit plan of the combustor and thermal behaviour of the inner and outer liner have been recorded. Results are compared on 10 operating conditions up to 13.7 bars:

- With the IMPACT2 combustor, compared to IMPACT1, a decrease of 25% of NOx emissions produced at high Fuel/Air ratio was observed, but in return an increase of CO and unburned fuel at lower Fuel/Air ratio. The range of Fuel/Air Ratio with a good balance between NOx, CO and unburned fuel emissions was the same between IMPACT1 and IMPACT2 configurations but they are shifted to higher FAR in the case of IMPACT2.
- The thermal behaviour of the combustion chamber was analysed with 32 thermocouples distributed over the outer and inner liner. The suppression of a part of the double liner results in higher temperatures with IMPACT2 configuration (+300°), but even at the most stringent thermal conditions, the liner temperature remains below the critical temperature affecting its lifetime.

With the IMPACT2 combustion chamber, TM disposes of a low NOx combustion chamber based on the concept of lean combustion that reaches the standard CAEP8 in term of NOx emissions. The combustion chamber and LP injection system defined in the NEWAC project have been improved to obtain a good balance between pollutant emissions over a wide range of Fuel/Air Ratio and a good potential of integration.
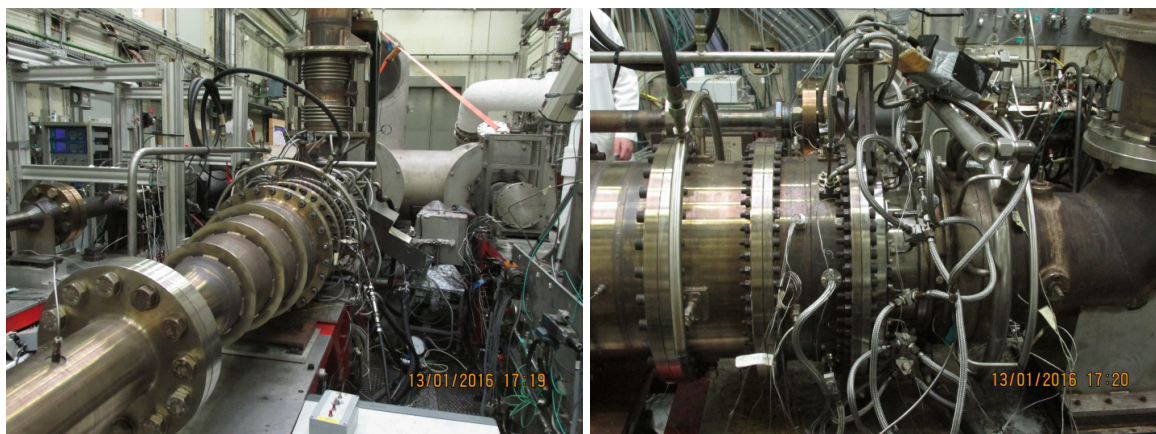
Figure 17: Views of the IMPACT2 FANN combustor test module installed in M1 ONERA test rig

In task 2.3 GE AVIO designed, manufactured and tested a three-sector combustor with different liner configurations. Innovative manufacturing capabilities (additive manufacturing) were considered in order to accelerate test preparation.

An important feature of the rig is the possibility to easily change both the outer and inner liner, allowing a rapid turn round of different configurations to study the influence of cooling holes pattern and its interaction with swirled flow. The tests results were exploited to validate advanced numerical modelling and the overall QDRV methodology based on tests carried out with real geometries (injector-injector and injector-liner interaction). In parallel, at the test site, the development of the reactive test cell in the new UNIFI laboratory was conducted, with a consolidation of the layout of the test facility according to the requirements of the experimental tests and a final layout of the fuel and main lines with the strategies to control fuel, mainstream and the cooling flow.

The manufacturing of the combustion chamber with effusion cooling holes and the swirler enabled exploiting the activities carried out in task 1.3, which allow to design a part and correct the nominal geometry in order to obtain the desired shape on the real part. The thermal behaviour of the additive parts and the validation of the methodology developed in the project was a main objective of task 1.3 using the result obtained in the test campaigns run in task 4.2.

Figure 18: GE AVIO sector rig installed in the UNIFI facility

WP3 – Technology Validation by Detailed Flame Diagnostics

In task 3.1 (Detailed non-intrusive measurements for a low emission injection system), several planar optical diagnostic tools were applied to characterise two variants of a fuel staged lean burn fuel injector by RRD. Their only difference consisted in a modification of pilot injector aerodynamics, which had an impact on fuel placement and as a consequence, on flow field, heat release, temperature and soot formation. The tests were performed in the combustor test rig BOSS (Big Optical Single Sector), which was designed and built in a close cooperation between DLR and RRD for investigations in the primary zone of lean low emission combustors using advanced optical diagnostic techniques. The tests were performed for a range of operating conditions from low to intermediate power and were accompanied by emissions measurements using conventional probe sampling and analysis technique. The measurements provided data on flow field, fuel placement, shape and location of reaction regions, temperatures and – for pilot only operating conditions – soot formation. The resulting database is expected to improve the knowledge on factors governing combustor performance, especially with respect to smoke emissions.
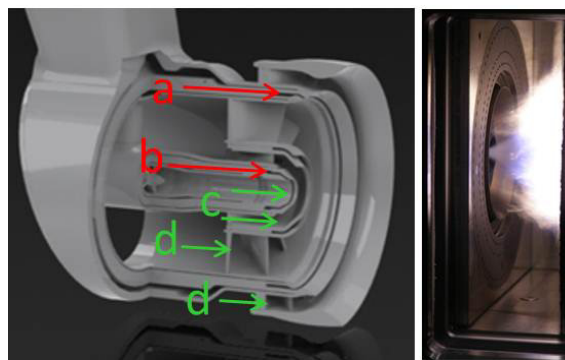
Figure 19: Basic design of a Rolls Royce LDI fuel injector with concentric arrangement; pilot injector at centre. a: main fuel flow; b: pilot fuel flow; c: pilot air flow; d: main air flow. Left: schematics; right: operation in BOSS rig.

The data obtained demonstrate a chain of consequences, initiated by a modification of pilot injector aerodynamics, on fuel scheduling, leading in turn to changes in reaction zone locations, temperature and flow field structure; and, most strikingly, in soot formation.

Task 3.2 (Pilot/main flame interactions and flame/film cooling interaction) comprised the design and manufacturing of the following devices:

- A movable injection system allows to change the combustor volume in order to study its influence on combustion properties (e.g. gas temperature, emissions).
- A cooling air system allows to study different cooling configurations and helps to better understand flowfield/chemistry interactions leading to CO formation.
- A water-cooled gas sampling probe allows to measure CO concentrations close to the walls and correlates results with those from optical measurements.
- A new injection system.

Laboratory experiments were performed in a high pressure – high temperature cell to gather spectroscopic information on CO molecules by means of laser-induced fluorescence (LIF) technique for various operating conditions. Results helped choosing the appropriate measurement strategy for subsequent experiments on the M1 test bench with real aircraft injection systems.

Imaging experiments on CO using planar laser-induced fluorescence (PLIF) technique were performed on the M1 test bench with two variants of real aircraft injection systems, namely TOSCA and LEMCOTEC D8, for various operating conditions.

Examples of spatial distributions of CO are shown in Figure 20 with both injection systems. Images are presented on the same intensity scale. For the TOSCA configuration, CO is located between the fuel region and the flame zone which are clearly separated. This flow region corresponds to the position where the fuel is oxidised due to local high temperature and subsequently forms CO. For the LEMCOTEC D8 configuration, CO is detected only at the periphery of the flame front and is not observed in the central region of the flow as opposed to the TOSCA configuration; which is probably due to the different flame and fuel repartition between both injection systems. The general trend of CO-PLIF images are in agreement with the results of gas analysis carried out at the combustor exit (see Figure 21).

(a)   (b)
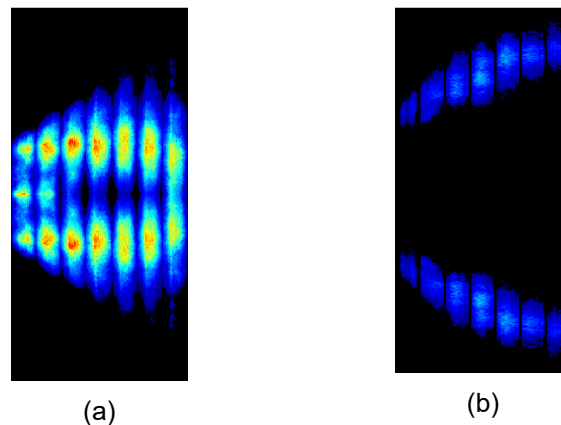
Figure 20: CO mean spatial distributions with (a) TOSCA and (b) LEMCOTEC D8 injection systems at idle condition (470 K, 4.5 bars, PHIpil/PHI=0.18/0.18).

Figure 21 shows the CO emission index (EICO) for three injection system. The minimum value is about 20% less with the LEMCOTEC D8 configuration compared to the TOSCA geometry. Comparison with the pollutant emissions measured with the TLC injection system (investigated in the eponym programme almost a decade ago) shows the progress made by the new geometries of injectors (TOSCA and LEMCOTEC D8) in this respect.
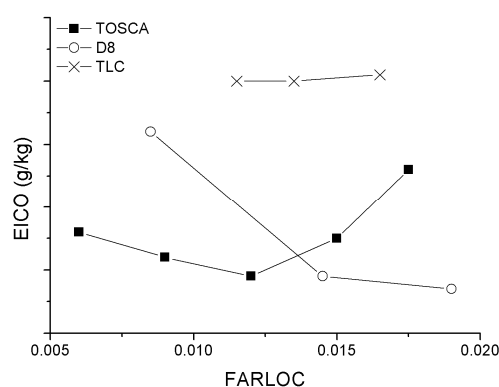
Figure 21: CO emission index at idle condition (470 K, 4.5 bars) for various equivalence ratio and three injection systems.

RANS simulations were performed and compared with experimental results. Key results achieved in task 3.2 include:

- A CO-PLIF technique has been developed for the first time at ONERA, and applied to realistic aircraft combustor under operating conditions of interest.

- Experimental work has shown the importance of injector geometry on combustion properties (spatial distributions of fuel / reaction zones / pollutant emissions). Correlations have been drawn from the joint analysis of the different measurements (optical and gas sampling) which have also been used to validate CFD simulations.
- The new injection system design allowed to reduce pollutant emissions with respect to the state-of-the-art SNM multipoint injection system at the beginning of the IMPACT-AE programme.
- New injection system designed based on the LEMCOTEC results (obtained at the beginning of the LEMCOTEC project).
- Validation of numerical simulations using experimental results.

In task 3.3 (Experimental investigation of entropy waves in liquid fuelled combustor) the following activities have been conducted:

- Experimental investigation of the non-linear behaviour of self-excited flames and analysis of multi-mode interaction at different operating conditions;
- POD analysis of OH* chemiluminescence and OH PLIF images;
- Design and manufacturing of a small-scale entropy rig;
- Experimental investigation of the propagation of the entropy waves at different operating conditions;
- CFD modelling and LES simulations of the diffusion and dispersion of entropy waves;
- Development and validation of a theoretical model for the diffusion and dispersion of entropy waves;
- Extension of the model for the investigation of real combustors; and
- Application of the theoretical model to the study of thermoacoustic instabilities and indirect noise in the context of low-order acoustic network codes (LOTAN).

Significant results achieved in task 3.3 include:

- Development of a database on thermoacoustic oscillations and new processing technique for image phase averaging in a multi-frequency problem;
- Characterization of entropy diffusion and dispersion through CFD simulations and experiments; and
- Development of a new theoretical model for the entropy transfer function (validated by experiments and CFD computations).

In task 3.4 (Fast response emissions sensor for lean burn combustors), work started from an analysis of the requirements for a fast emissions traversing system to measure CO and UHC at the exit of combustion chambers. Various spectroscopic approaches were considered and in the end Quantum Cascade laser methods were chosen measurement of CO and UHC concentrations. A concept design of the system was done and measurement error analyses performed at low TRL. The uncertainties measured were shown to be comparable to the ones affecting conventional emissions measurement methods. Formaldehyde was used as a marked for UHC. The design of the measurement system was finalised and installed onto a full annular rig.

Comparisons were carried out against conventional emissions measurement methods on a rich burn as well as a lean burn combustor in a full annular facility. 2D maps of CO, CO2, UHC and NOx were taken for the lean burn combustor and compared with maps obtained with conventional NDIR techniques. A range of different RANS and SAS models were set up and run. Results have been compared against 2D maps of temperature, CO, UHC and NOx.

Main results achieved in task 3.4 include:

- Demonstration of accurate QCL-based fast emissions probe on full annular rig test of lean burn combustor;
- Achievement of significant speed up of the traversing, which can be relied on to reduce test time or increase the number of test points run;
- Comparison against conventional slower emissions measurement techniques demonstrated good accuracy of the newly developed measurement system;

- RANS and SAS runs were performed. Temperature and NOx maps are well predicted, CO map predicted qualitatively well. The comparison against measured UHCs confirmed that an improvement is required in the modelling approach.

In task 3.5 (Technology Assessment), technologies developed within WP3 were continuously assessed and risk assessment and mitigation was performed.

WP4 – Design Methodology Demonstration for Efficient Low NOx Combustion

In subtask 4.1.1, SNM and ONERA performed the emissions mapping of a lean burn injector using a 4-sector rig, as shown in Figure 22.
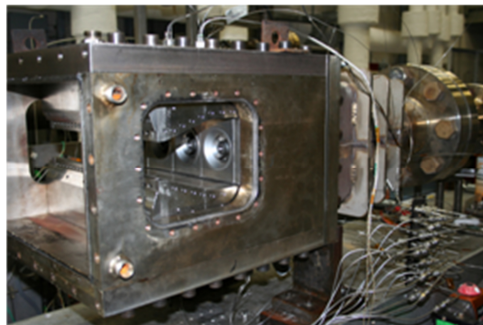
Figure 22: Lean burn multi-sector rig

At low inlet pressure and temperature, a pilot-only air-to-fuel ratio sweep was carried out. The corresponding CO and UHC emissions are summarised in Figure 23.
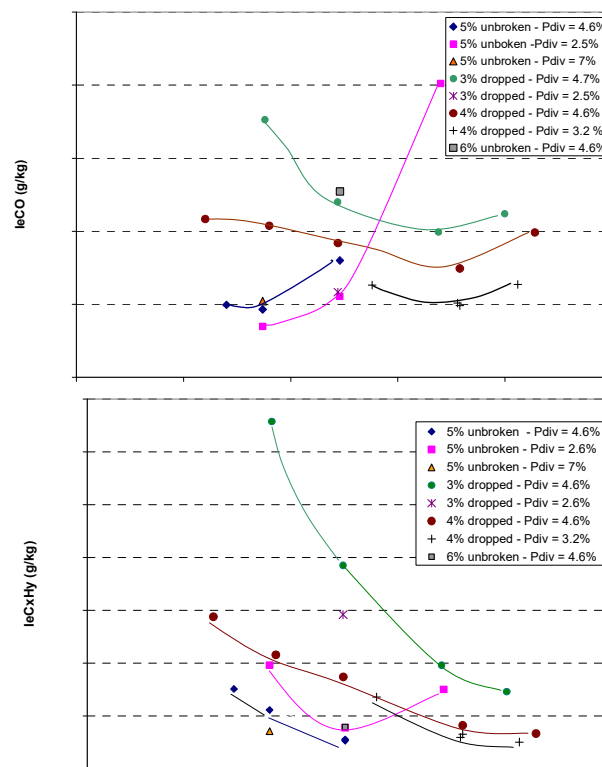
Figure 23: CO and UHC emissions plotted against pilot FAR

Different injector geometries were investigated as well as the impact that pressure drop has on the emission of pollutant species. Exit traversing provided an insight into the mechanisms for production of the pollutants. An example of the mapping of species at the exit of the combustor tested is shown in Figure 24 for a high power condition.
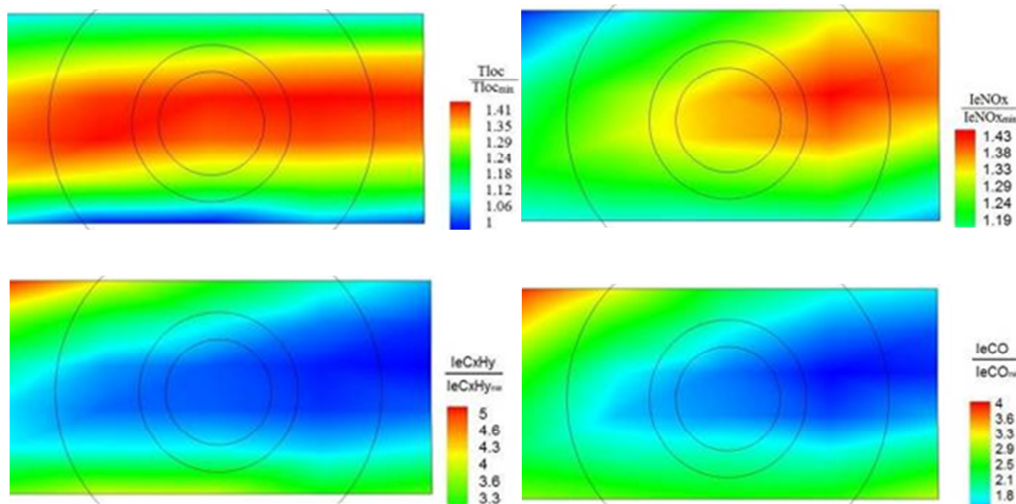
Figure 24: 2D maps of temperature, NOx, UHC and CO

The NOx pattern was confirmed to be broadly following the temperature pattern, while CO and UHC were found to be concentrated near the walls.

A summary of the dependence of pollutant species on fuel-to-air ratio and pilot-main split is shown in Figure 25 for high inlet pressure and temperature conditions.
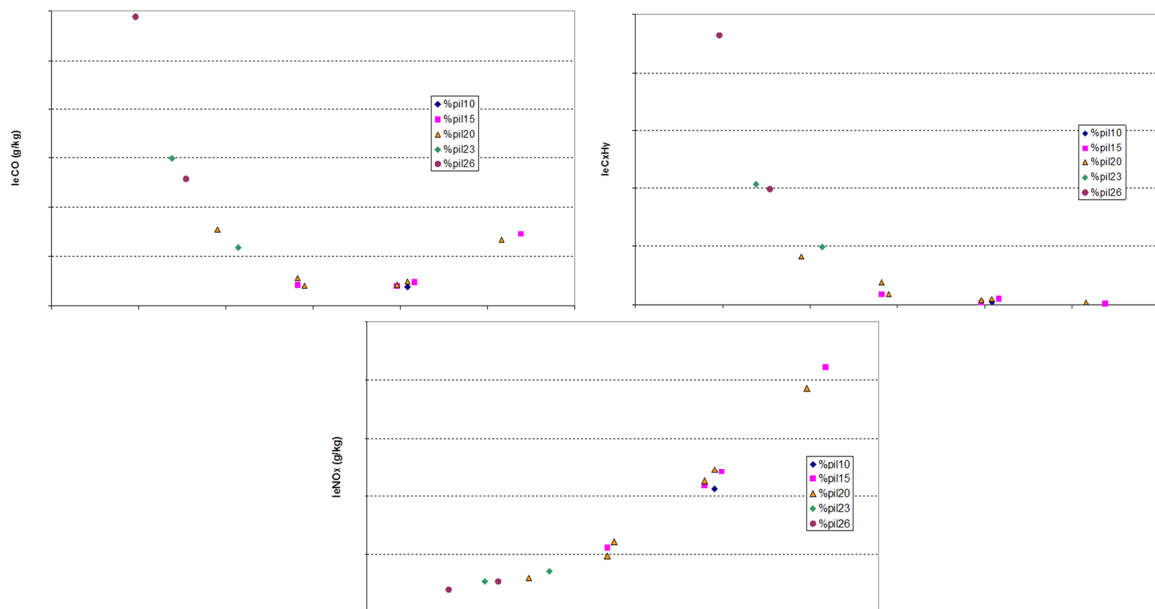
Figure 25: Emissions trends with fuel split and FAR

These results showed the expected trends with FAR but more importantly the negligible sensitivity to fuel split for the given injector design.

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In subtask 4.1.2, TM and ONERA carried out a full annular rig testing of a combustor designed and manufactured as part of the IMPACT-AE programme. Figure 26 shows a summary of the CO and NOx emissions of the IMPACT-AE with respect to a datum, which has been obtained as part of the NEWAC programme.
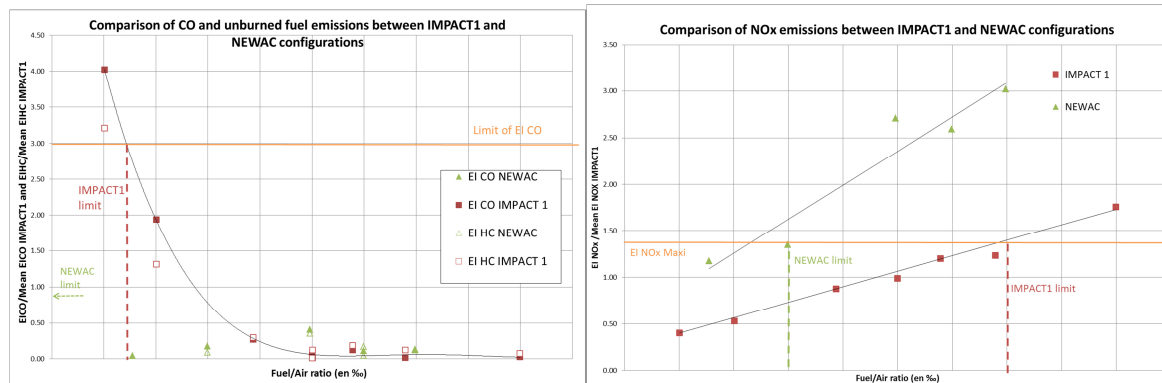

Figure 26: CO and NOx comparison between the IMPACT-AE and NEWAC combustors

The results show that a significant (up to 50%) drop in NOx is achieved if an increase in CO is accepted. Altogether, it can be concluded that for a wider range of fuel-to-air ratios an acceptable trade-off between CO and NOx was achieved. This result was mainly obtained by leaning up the fuel injector through an increase in its effective area. Two further observations that could be made by the end of the test campaign were the relatively low sensitivity of NOx to pilot-main fuel split as well as the challenge of changing the temperature traverse through use of dilution holes for the low emissions combustor design style considered.

In task 4.2 GE-AVIO and UNIFI have commissioned an intermediate pressure three sector rig, which was then used to test effusion cooling designs at a range of different pressure and temperature conditions. Figure 27 shows the rig developed within the IMPACT-AE programme.
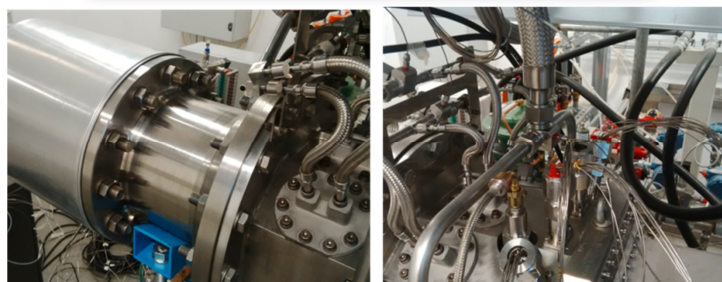
Figure 27: Intermediate pressure rig

Additive manufacturing techniques were used to make the effusion liners (Figure 28) as well as other parts of the rig.
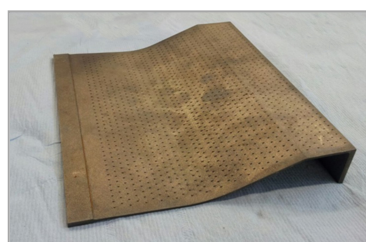
Figure 28: Effusion liner manufactured using additive techniques

During the commissioning of the rig, thermoacoustic instabilities were encountered, as shown in Figure 29 by the pressure spectrum. The resonance occurring at a frequency of about 350 Hz was removed by changing the downstream geometry.
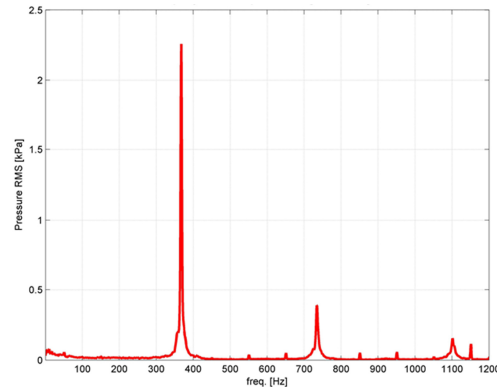
Figure 29: Pressure spectrum

The rig could then be used to measure metal temperature with thermocouples located along and across the liner for a range of operating conditions. A typical set of results is shown in Figure 30.
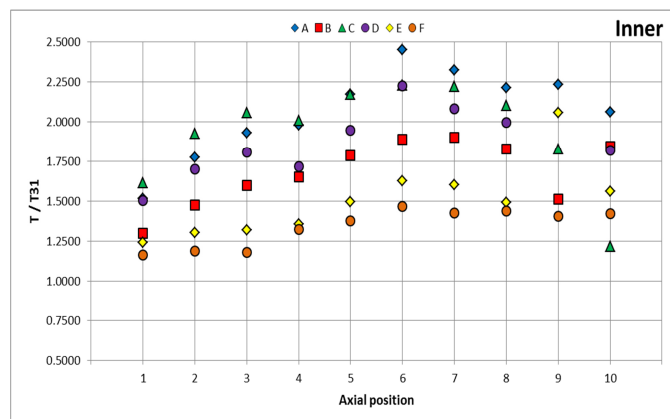
Figure 30: Non-dimensional metal temperature map

The sensor design requirements are bounded by both the need to map combustor inefficiency at a reasonable speed (and therefore cost) and the capability to interface to existing fully annular combustor rigs. In subtask 4.3.1, SNM and INSA-CORIA developed further a Trapped Vortex Combustor (TVC) design concept. The TVC concept, which was introduced a few years ago, was investigated here using a full annular low pressure rig. The TVC design presents interesting features, mainly its simplicity and capability to deliver a Lean Premixed Prevaporised (LPP) flame which is known to have the potential for low NOx. Application of advanced diagnostic techniques allowed gaining insight into the behaviour of this combustor. Figure 31 shows the layout of the annular facility used as part of the investigation.
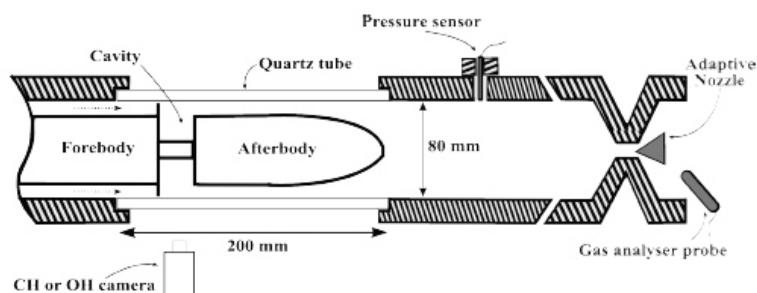
Figure 31: Layout of the full annular rig

Figure 32 shows details of the combustor geometry. Methane and air are premixed for both the main and cavity. The main flow goes through a number of radial flameholders before interacting with the cavity flow when operating in normal mode. The main and cavity stoichiometries could be changed as well as the mode of injection of the downstream cooling air and cavity depth.
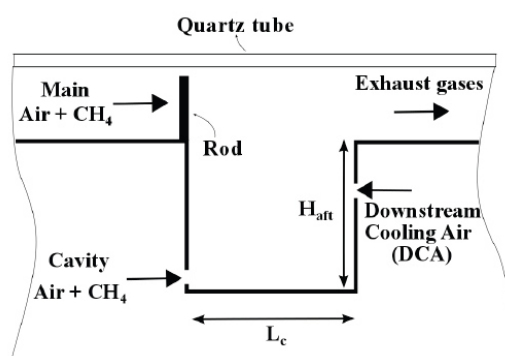
Figure 32: Details of the TVC geometry

To start with, an optimisation was carried out to identify the best trade-off among the various species. Reactive PIV, OH PLIF as well as LES were used to understand how the combustor works in detail. Figure 33 shows an example of comparisons done between measurements and predictions.
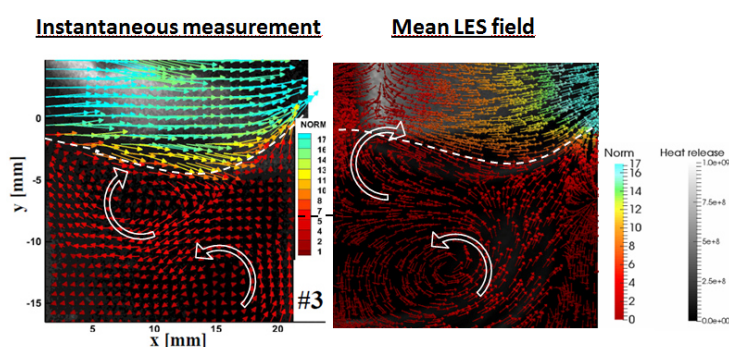
Figure 33: Velocity and heat release fields as measured and predicted

Throughout the development and test campaign, close attention was paid to the thermoacoustic instabilities, in terms of both sensitivity to operating parameters and fundamental mechanisms.

The effects of aerodynamics on the system stability were in the end summarised, as shown in Figure 34, through a momentum ratio parameter.
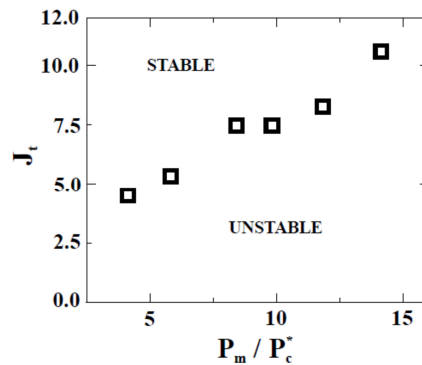
Figure 34: Stability map expressed as a function of momentum ratio and power

The effects of stoichiometry on the system stability were summarised through the ratio of pilot and main equivalence ratios, as shown in Figure 35.
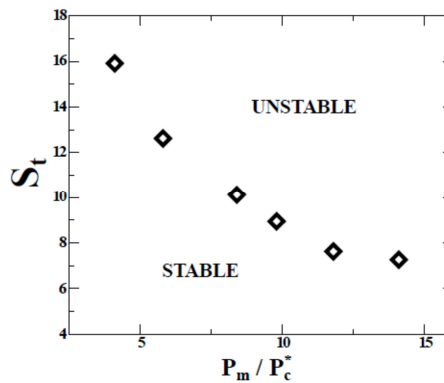
Figure 35: Stability map expressed as a function of stoichiometric ratio and power

In subtask 4.3.2., RRD tested a DLD manufactured combustor, which has been designed using the design processes and tools developed within WP1. The full annular combustor has been divided into 4 quadrants, which all had a different mixer configuration. One quadrant represented the reference combustor, in one quadrant the ports have been inclined, in one quadrant the mixing ports have been moved forward, and in the 4th quadrant both the ports have been inclined and moved forward.

The measured and predicted NOx emissions (by CFD in the design phase) are presented in Figure 36.
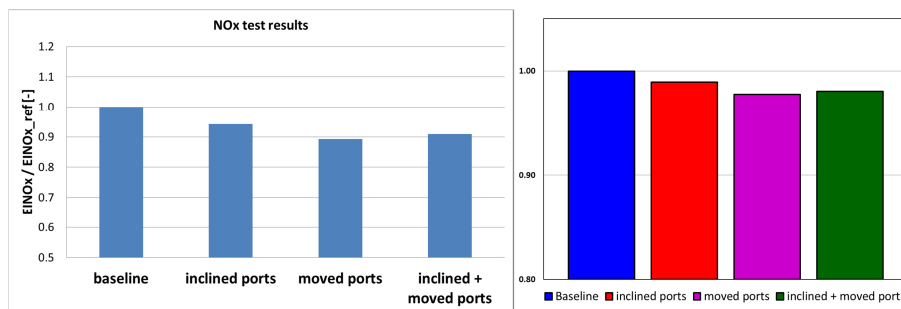
Figure 36: Measured and predicted NOx emissions for 4 different mixer configurations

The measurement results shows that an inclination of the intermediate ports leads to a NOx reduction by 5% compared to the baseline configuration. The movement of the ports upstream leads to an even more improved NOx performance. EINOx decreases by about 11% compared to the baseline configuration. The combination of port inclination and upstream movement leads to a NOx improvement of 9% relative to the baseline design. Based on the test results the movement of the ports upstream have the most significant effect on NOx formation for the investigated combustor design. The CFD predictions shows a very good agreement compared to the measurement results. The ranking of the different designs has been predicted correctly. The most significant effect on NOx emissions has been found for the moved ports, followed by the inclined ports. The combination of both variants leads to an improvement compared to the baseline but less high compared to the moved ports. The absolute reduction in NOx emission however has been under-predicted by CFD by a factor of 2 to 3. However, it has to be kept in mind that the measurement uncertainly due to uncertainties in AFR is a few percent. While the difference in emissions between the different configurations is up to 10 percent, the relative uncertainty is quite high.

Additionally, the temperature traverse at combustor exit has been measured. The differences in the temperature profiles of the combustor configurations are small, this has also been predicted correctly by CFD.

In subtask 4.3.3, LU and RRUK developed and tested different cooled cooling air design concepts and assessed their impact on the aerodynamics of a lean burn combustor. Figure 37 shows the cooled cooling air concept, whereby air is bled out of the main gas path somewhere in the high pressure section of the combustion system, passed through a heat exchanger whose low pressure side is fed with bypass air and eventually returned to the engine core to cool turbine components.
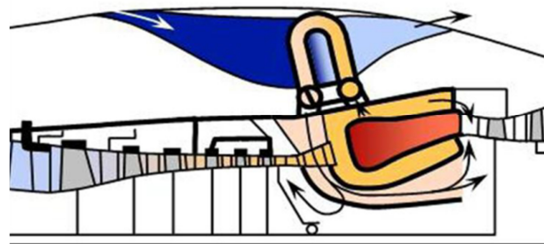
Figure 37: Cooled cooling air concept

A full annular isothermal facility, whose schematics is shown in Figure 38, was used to assess the impact of various cooled cooling air design on the external aerodynamics of a lean burn system.
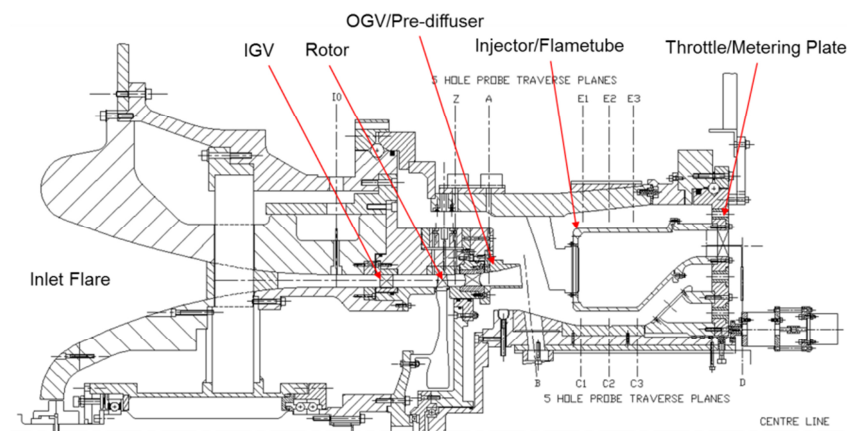
Figure 38: Schematics of the test rig

Different designs were tested: a clean datum, a strutted prediffuser system with no air bleeds, CCA baseline with air bled from the dump and eventually an alternate CCA design with air bled from the outer prediffuser wall. These 4 configurations are shown in Figure 39.

(a) Datum Clean Diffuser – No CCA   (b) Datum Strutted Diffuser – No CCA

(c) Baseline CCA System   (d) Alternate CCA System
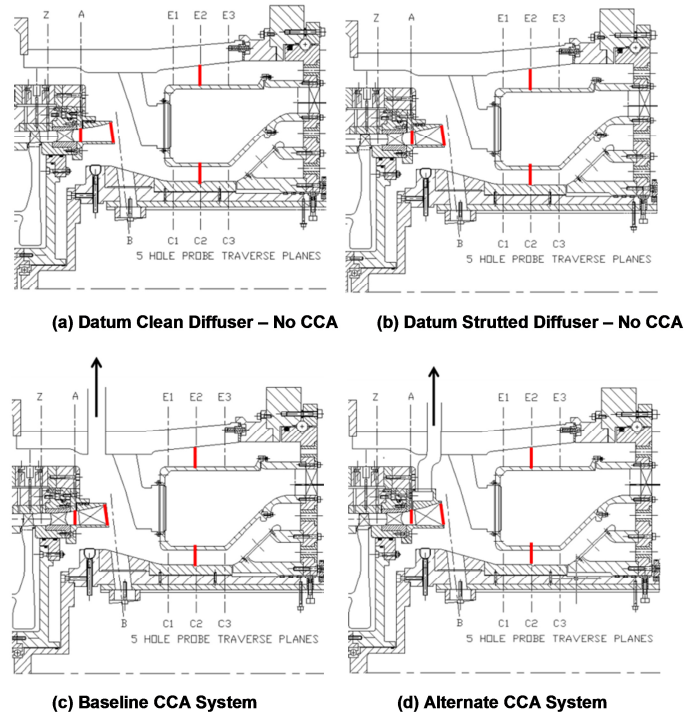
Figure 39: Configurations tested

Struts were introduced as a means of returning the bleed air back to the engine core. Presence of the struts increased the prediffuser loss and more importantly led to an increase in dump loss, while the bleeding of air from the dump did not impact the external aerodynamics. Introduction of the alternate or hybrid diffuser design allowed restoring the area ratio to a value close to that of the clean diffuser configuration. Through extraction of the air from the outer wall of the prediffuser the losses incurred as a result of introduction of struts could be recovered.

Another part of the investigation focused on the ducting system directing the flow to the heat exchanger and back to the engine core. A preliminary ducting design was chosen as starting point and an experimental and numerical investigation carried out with the aim of assessing pressure losses. Figure 40 shows a schematic of the simple flow rig used for the verification of ducting performance.
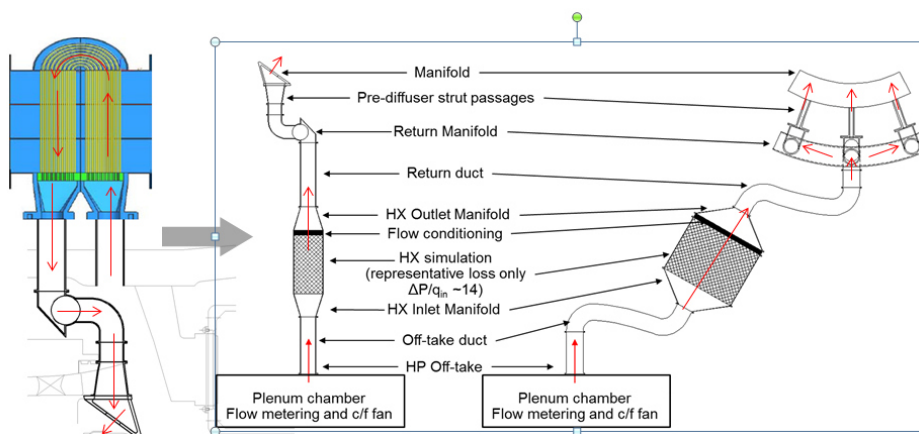
Figure 40: Flow rig schematic

The testing confirmed the system loss to be low enough to justify application of a cooled cooling air concept. The ducting part of the CCA system was confirmed to be responsible for a small proportion of the overall loss. Various manifold configurations were assessed mainly in terms of their ability to feed the heat exchanger with a uniform velocity profile (see Figure 41). A horizontal manifold design turned out to offer the best compromise between the aerodynamic feed to the heat exchanger and the compactness of the solution.
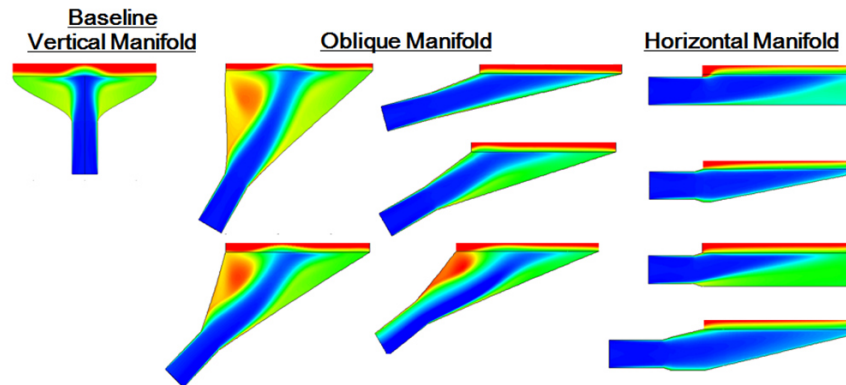
Figure 41: CFD-predicted velocity profiles feeding the heat exchanger for different designs

WP5 – Project Management

WP5 was dedicated to the overall strategic as well as financial and contractual management of the project. At the beginning of IMPACT-AE, a dedicated project office was set up to establish the management infrastructure consisting of the general assembly, project management committees, management procedures, a quality plan and a risk register, project management tools (financial and person month monitoring), and a secure collaborative internal website.

The Coordinator, supported by the project office, organised, chaired and followed-up a total of ten project meetings (a Kick-off meeting and nine Internal Technical Review Meetings). In addition, a total of 47 technical/progress monitoring meetings took place at WP level (in person or via conference calls) in the course of the project. Project quality control was ensured through continuous monitoring of the project progress against contractual commitments (deliverables and milestones). In addition, the project office maintained and updated the contractual documents, provided financial control for the project, and supported all financial reporting aspects and the distribution of EC payments. The project office acted as central contact point for all project partners.

All contractual periodic reports were submitted to the European Commission on time on a regular basis (at M18, M36, M48 and M55), including the scientific/technical reporting and financial statements. Rules and regulations as stipulated in the Grant Agreement and Consortium Agreement were implemented throughout the project.

Figure 42: IMPACT-AE Internal Technical Review Meetings in Derby (UK) and Cameri (IT)

WP6 – Dissemination, Collaboration, and IPR Management

Activities in WP9 focused on the organisation of workshops, the development of a dissemination strategy for the project, the management of external communication and of exploitation and IPR plans and activities.

Two IMPACT-AE workshops were organised to disseminate knowledge generated in the project. The first workshop was held on 11 December 2014 in Florence and the second took place on 25 May 2016 in Dahlewitz (Blankenfelde-Mahlow) near Berlin.

In these events, the IMPACT-AE consortium presented in several key notes the project results in five sessions, reflecting the main research and engineering topics of the project:

- Session 1: Design System Development for clean Combustors

- Session 2: Emission Modelling of Aero Gas Turbines

- Session 3: Modelling of Wall Cooling

- Session 4: Detailed Flame Diagnostics

- Session 5: Technology Demonstration

Coordinators of the DREAMCODE and NEWSMILE Clean Sky projects also contributed to the second IMPACT-AE workshop by presenting progress and results achieved in these projects.

The first workshop in Florence was attended by 40 persons and 27 persons participated in the final IMPACT-AE workshop.

Figure 43: IMPACT-AE Workshops

Project partners presented IMPACT-AE in various conferences and workshops, including for example at the European Conference for Aeronautics and Space Sciences (EUCASS), Aerodays2015, ASME Turbo Expo, European Combustion Meeting (ECM), European Rotorcraft Forum (ERF), American Institute of Aeronautics and Astronautics Science and Technology Forum and Exposition (AIAA SciTech), the KIAI & TECC-AE Public Workshop, and CFTL (Congrès Francophone de Techniques Laser).

A dissemination plan as well as an exploitation database have been prepared to provide an overview of the information and results arising from the project ("Foreground"). Specifically, these documents provide an overview by work package of how the knowledge and technology developed within the project is exploited. It also described how technology and models developed by academic partners are used and exploited by the industrial partners.

In addition, dissemination of project results was achieved via different communication tools such as the project website (www.impact-ae.eu), university lectures and scientific publications (17 papers already published in peer-reviewed journals/as conference contributions and 8 additional publications planned to be published in 2016/2017; see Section 2.1.1 below).

1.4 Potential impact, main dissemination activities and exploitation of results

1.4.1 Socio-economic impact

IMPACT-AE had an overall positive impact on employment and workforce distribution in the participating organisations (industry, universities, SMEs).

Over the 4.5 years of the project, more than 173 people have contributed at some point in the project. They provided their expertise to the different work packages when required. Altogether many people have been involved in numerical studies, manufacturing, instrumentation and assembly of test rigs. About a third of the people who worked on the project were experienced researchers (see Section 3 below). Two additional researchers were recruited specifically for IMPACT-AE.

Six women have contributed to IMPACT-AE, i.e. three experienced researchers, one PhD student, and two other staff members. Several project partners carried out specific gender equality actions, such as designing and implementing an equal opportunity policy, setting targets to achieve a gender balance in the workforce and organising activities to improve the work-life balance. For example, the project partners Snecma and Turbomeca contribute to the partnerships "Elles bougent" and "Women's forum" which promote gender balance in the workforce.

IMPACT-AE researchers were involved in outreach and education activities with university students through training activities (bachelor/master theses and lectures which used results of research conducted in the project).

IMPACT-AE did not directly work with or target policy makers. However, results originating from the project could be used by policy makers in the relevant fields, especially in the areas of research and innovation and transport.

Several articles were published in peer-reviewed journals; other publications were prepared for conference contributions (see Section 2.1.1 for more details). Additional dissemination activities are described in Section 1.4.3 and listed in Section 0.

1.4.2 Wider societal implications of the project

The expected annual growth rates of air traffic with about 3% for the next two decades are only sustainable if the environmental footprint of engines for aviation is minimised. Besides the progressing stringency of legislative requirements for noise and NOx emissions, customer requirements and thus the market competition are increasingly focussing on the environmental friendliness of aero-engines.

In this context, IMPACT-AE directly supports the target reduction of NOx by 80% set by the Advisory Council for Aeronautics Research and Innovation in Europe (ACARE) for 2020. The environmental benefits of low emissions lean burn technology in reducing NOx emissions can only be effective when these are deployed to a large range of new aero-engine applications. While integrating and developing low emission combustion design rules, IMPACT-AE has delivered novel combustor design methodologies for advanced engine architectures and thermodynamic cycles. It supports European engine manufacturers to pick up and keep pace with the US competitors, who are already able to exploit their new low emission combustion technology to various engine applications with short turn-around times. Specifically, within IMPACT-AE combustor improvements with regard to NOx emissions have been demonstrated, improvements up to 50% have been achieved. Furthermore, methodologies for combustor wall cooling have been developed, enabling more advanced cooling schemes. This can be used to reduce the cooling air, which subsequently can be used for improved mixing, thereby reducing NOx. Optical techniques have been performed to obtain a better understanding of the combustion processes in aero gas turbines and provide data to validate design methods for low emissions combustors. Consequently, they support the introduction of low NOx combustors in the next generation of engines.

1.4.3 Main dissemination activities

IMPACT-AE results were published in peer reviewed journals and presented at national and international conferences (see Section 2 of this report). Dissemination highlights include the two public workshops in 2014 and 2016 (held in Florence, Italy and Dahlewitz, Germany, respectively) as well the presentations of the IMPACT-AE project in several conferences and workshops.

Examples of events at which the project was presented include the European Conference for Aeronautics and Space Sciences (EUCASS), Aerodays2015, ASME Turbo Expo, European Combustion Meeting (ECM), European Rotorcraft Forum (ERF), American Institute of Aeronautics and Astronautics Science and Technology Forum and Exposition (AIAA SciTech), the KIAI & TECC-AE Public Workshop, and CFTL (Congrès Francophone de Techniques Laser).

Project results have been the topic of a total of 17 publications (including articles in peer reviewed journals and conference papers) prepared by the project partners (in addition, 8 publications are currently under review/planned to be published in 2016/2017. The academic partners Loughborough University and the University of Florence also used the research carried out in the project as materials for lectures e.g. on gas turbine design, propulsion design for the environment, and combustion in aeronautic gas turbine engines.

The project also had a dedicated website (www.impact-ae.eu) on which the project was presented and news about events (such as workshops) and publications were provided. The IMPACT-AE project was also presented on several partners websites.

1.4.4 Exploitation of results

A draft dissemination plan was issued at the beginning of 2014 which was updated at the end of the project (May 2016). An exploitation database was also produced.

The dissemination plan and the exploitation database describe the exploitation of the work performed with the IMPACT-AE project. Specifically, these documents explain how new or further developed tools and methodologies are exploited by industrial partners. They provide an overview by work package of how the knowledge and technology developed within the project is exploited. It also specifies how technology and models developed by academic partners are used and exploited by the industrial partners.

Developed tools and methods have been introduced into the design processes of low emissions combustors of industrial partners. Measurement data has been used to understand and improve the performance of fuel injectors, combustors and combustor wall cooling. Furthermore, test facilities have been built, and used to verify the performance of new developed technologies. Subsequently, these facilities will be used in further research projects and support engine design projects.

Last but not least, high TRL level of newly developed combustor concepts have been reached, and it has been demonstrated that the technology has been matured.

The following paragraphs provide an overview of the exploitation of the results in the four technical work packages.

WP1 - Smart Design systems for Clean Combustion

In WP1, methodologies and methods have been developed, which will be introduced into the design process of combustors. Two categories of design method can be distinguished: (1) the Knowledge Based Tools to be used within the design process and (2) the further developed CFD methods to improve the predicting capability of emissions and wall temperatures.

WP2 - Modelling and Design of Advanced Combustor Wall Cooling Concepts

Within WP2 design methods have been developed to improve wall cooling concepts of combustor. The exploitation in this work package consists of the improvement and development of tools to design

and layout the combustor wall cooling. Secondly rapid prototype techniques have been assessed to manufacture wall cooling parts.

WP3 - Technology Validation by Detailed Flame Diagnostics

Within WP3 new diagnostics methods have been developed, and consequently applied to validate improved or new combustion concepts. The objective of this work package was to get detailed measurements of velocities and emissions.

WP4 - Technology Validation by Detailed Flame Diagnostics Design Methodology Demonstration for Efficient Low NOx Combustion

Within WP4 the performance of low emission design concepts developed either within IMPACT-AE or in earlier EU projects have been demonstrated.

The experimental results from task 4.1.1 (TM) and the numerical simulations have been compared to the results obtained with the injector that has been designed in task 3.2.

Within sub-task 4.1.2, ONERA performed extensive high-pressure testing of an annular combustor developed by TM, with the aim to optimise combustor performances (improved operability and reduced pollutant emissions).

The fuel laws defined in task 4.1.2 to optimize the balance between pollutants emissions and lean blow out limits via various fuel split laws have been made available to all partners in the IMPACT-AE deliverables.

In tasks 4.2.1 and 4.2.2 the VALIDATOR test rig has been designed, manufactured and installed in the reactive test facility of the THT Lab of UNIFL. The main outcome of the experimental campaign is represented by a large database of wall temperature useful to validate numerical methodology in a Quick Design and Rapid Validation (QDRV) approach.

The comparison between LES and experiments on TVC (task 4.3.1) validates the numerical methodology and allows further numerical studies one the impact of geometric features on the TVC performances (flame structure, stability).

The full annular test as planned in task 4.3.2 (RRD) has been on the full annular facility of Rolls-Royce UK and demonstrated that the improved combustor performs as expected on the full scale engine configuration and brings the improved combustor standard to a higher TRL level. Next, the developed technology can be introduced into new aero-engine combustors.

1.5 IMPACT-AE consortium

The IMPACT-AE consortium is composed of the following partner organisations:

(1)   ROLLS-ROYCE DEUTSCHLAND LTD & CO KG (RRD)

(2)   SNECMA SA (SNM)

(3)   ROLLS-ROYCE PLC (RRUK)

(4)   TURBOMECA SA (TM)

(5)   MTU AERO ENGINES AG (MTU)

(6)   OFFICE NATIONAL D'ETUDES ET DE RECHERCHES AEROSPATIALES (ONERA)

(7)   DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV (DLR)

(8)   UNIVERSITE DE PAU ET DES PAYS DE L'ADOUR (UPPA)

(9)   KARLSRUHER INSTITUT FUER TECHNOLOGIE (KIT-U)

(10)   UNIVERSITAET DER BUNDESWEHR MUENCHEN (UBWM)

(11)   IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY AND MEDICINE (IC)

(12)   THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITYOF CAMBRIDGE(UCAM)

(13)   LOUGHBOROUGH UNIVERSITY (LU)

(14)   UNIVERSITA DEGLI STUDI DI FIRENZE (UNIFI)

(15)   CAMBRIDGE FLOW SOLUTIONS LTD (CFS)

(16)   INSTITUT NATIONAL DES SCIENCES APPLIQUEES DE ROUEN (INSA-CORIA)

(17)   ARTTIC (ART)

(18)   GE AVIO SRL (GE AVIO)

Contact details:

Ruud Eggels, Rolls-Royce Deutschland Ltd & Co KG
Eschenweg 11, Dahlewitz, 15827 Blankenfelde-Mahlow, Germany
Phone: +49 (0) 33708 6 1145
e-mail: mailto:Ruud.Eggels@rolls-royce.com

Project website address: http://www.impact-ae.eu/

2.   Use and dissemination of foreground

2.1 Section A (public)

2.1.1 List of all scientific publications (A1)

No.	Title	Main author(s)	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Rele-vant pages	Permanent Identifiers	Is/Will open access provided to this publication?
1	Investigation of combustion dynamics in a cavity-based combustor with high-speed laser diagnostics	P. Xavier, A. Vandel, G. Godard, B. Renou (INSA), F. Grisch, G. Cabot, A.M. Boukhalfa, M. Cazalens	Experiments in Fluids	Vol. 57/Issue 4	Springer Verlag	Germany	April 2016	57:50	Doi: 10.1007/s00 348-016-2135-7	
2	Modelling nitrogen oxide emissions in turbulent flames with air dilution: Application to LES of a non-premixed jet-flame.	F. Pecquery, V. Moureau (INSA), G. Lartigue, L. Vervisch, A. Roux.	Combustion and Flame	Vol. 161/Issue 2	Elsevier Inc.	United States	01/02/2014	496-509	10.1016/j.co mbustflame. 2013.09.018	
3	Chaos in an imperfectly premixed model combustor	L. Kabiraj, A. Saurabh, N. Karimi, A. Sailor, E. Mastorakos, Ann P. Dowling and C. Paschereit (UCAM)	Chaos in Thermo-acoustics	Vol. 25/Issue 2	American Institute of Physics Inc.	United States	01/02/2015		10.1063/1.4 906943	

No.	Title	Main author(s)	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Rele-vant pages	Permanent Identifiers	Is/Will open access provided to this publication?
4	Impact of a Cooled Cooling Air Installation on the External Aerodynamics of a Gas Turbine Combustion System	A. D. Walker , L. Guo	Volume 4B: Combustion, Fuels and Emissions		ASME Turbo Expo 2015	Montreal, Canada	2015		10.1115/GT2015-43186	Yes
5	Intelligente Entwurfsmethoden für Magerbrennkammern für Flugzeugtriebwerke (IMPACT-AE)	C. Clemen (RRD), M. Rullaud (SNM), A. Peschiulli (GE AVIO), M. Orain (ONERA), M. Zedda (RRUK)			Deutscher Luft- und Raumfahrt-kongress 2012		2012		DocumentID: 281170 http://www.dglr.de/publikationen/2012/281170.pdf	Yes
6	Towards Low-NOx Operation in a Complex Burner. Optimization of an annular Trapped Vortex Combustor	P. Xavier, B. Renou, G. Cabot, M. A. Boukhalfa (INSA-CORIA), M. Cazalens, (SNM)	Volume 1A: Combustion, Fuels and Emissions		ASME Turbo Expo 2013		2013		10.1115/GT2013-94704	
7	Demonstration of an alternative combustion concept	P. Xavier, A. Vandel, B. Renou, G. Cabot, M.A. Boukhalfa (INSA CORIA)			EUCASS 2013		2013			

No.	Title	Main author(s)	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Rele-vant pages	Permanent Identifiers	Is/Will open access provided to this publication?
8	Analysis of the flame structure in a TVC using low and high-speed OH-PLIF	P. Xavier, B. Renou, G. Cabot, M. A. Boukhalfa (INSA CORIA) and M. Cazalen (SNM)	Volume 4A: Combustion, Fuels and Emissions		ASME Turbo Expo 2014		2014		10.1115/GT 2014-25207	
9	Detection of carbon monoxide in aircraft combustors using Planar Laser-Induced Fluorescence	O. Carrivain, M.Orain (ONERA)			14ème Congrès Francophone de Techniques Laser (CFTL-2014)					
10	Development of an advanced automated knowledge based combustor preliminary design process for low Nox combustion systems optimisation	M. Gessel, M. Pfitzner (UBWM), R. Eggels (RRD)	Volume 4A: Combustion, Fuels and Emissions		ASME Turbo Expo 2015		2015		10.1115/GT 2015-42328	
11	Evaluation of the Turbulence Radiation Interaction and the Validity of the Optically Thin Fluid Approximation in a High Turbulent Premixed Methane Flame	F. Eiberger, N. Zarzalis, P. Habisreuther (KIT-U), F. Turrini (GE AVIO)	Volume 5C: Heat Transfer		ASME Turbo Expo 2015		2015		10.1115/GT 2015-42478	

No.	Title	Main author(s)	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Rele-vant pages	Permanent Identifiers	Is/Will open access provided to this publication?
12	Detection of carbon monoxide in aircraft combustors using Planar Laser-Induced Fluorescence	O. Carrivain, M.Orain (ONERA)			European Combustion Meeting (ECM)		2013			
13	The challenge of pollutant emission predictions in realistic burners	V. Moureau. & G. Lartigue (INSA CORIA)			15th International Conference on Numerical Combustion - ICNC 2015		2015			
14	Proper Orthogonal Decomposition Analysis of a Turbulent Swirling Self-Excited Premixed Flame	Anna-Maria Kypraiou , Ann Dowling , Epaminondas Mastorakos , Nader Karimi	53rd AIAA Aerospace Sciences Meeting		American Institute of Aeronautics and Astronautics	Reston, Virginia	2015		10.2514/6.2015-0425	
15	Multi-threaded radiation calculation	F. Eiberger, J. Keller, M. Volz, P. Habisreuther, N. Zarzalis (KIT-U), F. Turrini (GE AVIO)			9th OpenFOAM Workshop		2014			
16	Experimental and numerical investigation into the propagation of entropy waves in a small-scale rig	A.Giusti, N.A. Worth, E. Mastorakos and A.P. Dowling (UCAM)	54th AIAA Aerospace Sciences Meeting		American Institute of Aeronautics and Astronautics	Reston, Virginia	2016		http://dx.doi.org/10.2514/6.2016-1942	

No.	Title	Main author(s)	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Rele-vant pages	Permanent Identifiers	Is/Will open access provided to this publication?
17	A 3D Coupled Approach for the Thermal Design of Aero-Engine Combustor Liners	L. Mazzei, A. Andreini, B. Facchini (UNIF) and L. Bellocci (GE AVIO)	Proceedings of ASME Turbo Expo	GT2016-56605	ASME/IGTI	Seoul, South Korea	2016	9		No
18	Development of a model for unsteady conjugate heat transfer simulations	DLR	Progress in Computational Fluid Dynamics, An international Journal				2016 (under review)			
19	Impact of a cooled cooling air installation on the external aerodynamics of a gas turbine combustion system	A.D. Walker, B. Koli, L. Guo, P. Beecroft (LU), M. Zedda (RRUK)	ASME Journal of Engineering for Gas Turbines and Power				2016 (under peer review)		Paper No. GTP-16-1199	
20	To be defined – paper on investigation of gas turbine operation by means of gas sampling analysis and optical diagnostics	ONERA	Journal of Propulsion and Power				Planned for 2016			
21	Implementation of an advanced automated knowledge based combustor preliminary design process, suitable for low Nox combustion systems optimization (draft title)	M. Gessel, M. Pfitzner (UBWM) and Ruud Eggels (RRD)	Journal of Turbomachinery				Planned for 2016/2017			

No.	Title	Main author(s)	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Rele-vant pages	Permanent Identifiers	Is/Will open access provided to this publication?
22	Development of a hybrid CFD-Reactor network model for aero-engine emissions prediction (draft title)	A. Innocenti, D. Bertini, A. Andreini, B. Facchini (UNIFI), F. Turrini (GE AVIO)	International journal TBD							
23	To be defined – article on Further application/validation of the Therm3D methodology for the estimation of metal temperature	L. Mazzei, A. Andreini, B. Facchini (UNIFI), F. Turrini (GE AVIO)	International journal TBD							
24	Experimental and CFD analysis to assess the performance and optimize a low NOx combustor	H. Verdier, G. Cottin (TM), J. Lamouroux (SNM), C. Guin (ONERA)	European Rotorcraft Forum 2016 (5-8 September 2016)		European Rotorcraft Forum 2016					
25	Improvement of the multi-staged fuel injector performances by optimization of the pilot/main interaction zone (LEMCOTEC and IMPACT programmes)	Guin, C., M. Orain (ONERA)	2nd Greener Aviation conference (13-13 October 2016)		2nd Greener Aviation conference					

2.1.2 List of all dissemination activities

Below are presented other dissemination activities carried out.

Activity no.	Type	Description	Date	Location	Impact observed	Partners involved
1	Workshop	1st IMPACT-AE Workshop The aim of the workshop was to exchange information on project developments.	11/12/2014	Florence, Italy	Exchange of development and knowhow	Presentations by RRD, SNM, UBWM, GE AVIO, IC, INSA-CORIA, DLR, UNIFI, KIT, ONERA
2	Workshop	Final IMPACT-AE workshop Provided overview of the results achieved within the IMPACT-AE project and of CFD developments which have overlap with other EC projects (Clean Sky projects DREAMCODE and NEWSMILE)	25/5/2016	Dahlewitz (Berlin)	Exchange of development and knowhow (including with Clean Sky projects)	Presentations by RRD, UNIFI, IC, RRUK, UPPA, UCAM
3	Technical conference	Deutscher Luft- und Raumfahrt-kongress 2012 Presentation of conference paper "Intelligente Entwurfsmethoden für Magerbrennkammern für Flugzeugtriebwerke (IMPACT-AE)"	10-12/9/2012	Berlin, Germany		RRD
4	Technical conference	ASME Turbo Expo 2013 Presentation of conference paper "Towards Low-NOx Operation in a Complex Burner. Optimization of an annular Trapped Vortex Combustor"	3-7/06/2013	San Antonio, Texas, USA		INSA CORIA
5	Technical conference	EUCASS 2013 Presentation of conference paper "Demonstration of an alternative combustion concept"	10/07/2013	Munich, Germany		INSA CORIA
6	Technical conference	ASME Turbo Expo 2014 Presentation of conference paper "Analysis of the flame structure in a TVC using low and high-speed OH-PLIF"	16-20/06/2014	Düsseldorf, Germany		INSA CORIA
7	International symposium	International symposium on application of laser techniques to fluid mechanics (Scientific colloquia)	07-10/07/2014	Lisbon, Portugal		INSA CORIA

Activity no.	Type	Description	Date	Location	Impact observed	Partners involved
8	Congress	14ème Congrès Francophone de Techniques Laser (CFTL-2014) Presentation of conference paper "Detection of carbon monoxide in aircraft combustors using Planar Laser-Induced Fluorescence"	15-19/11/2014	Marseille, France		ONERA
9	Technical conference	AIAA SciTech 2015 Presentation of conference paper "Proper Orthogonal Decomposition Analysis of a Turbulent Swirling Self-Excited Premixed Flame"	5-9/01/2015	Kissimmee, Florida, USA		UCAM
10	Technical conference	European Combustion Meeting (ECM) Presentation of conference paper "Detection of carbon monoxide in aircraft combustors using Planar Laser-Induced Fluorescence"	25/06/2013	Lund, Sweden		ONERA
11	Technical conference	International Conference on Numerical Combustion Presentation of conference paper "The challenge of pollutant emission predictions in realistic burners"	19-22/4/2015	Avignon, France		INSA CORIA
12	Technical conference	ASME Turbo Expo 2015 Presentation of conference papers: "Development of an advanced automated knowledge based combustor preliminary design process for low NOx combustion systems optimisation" (UBWM) "Impact of a cooled cooling air installation on the external aerodynamics of a gas turbine combustion system" (LU) "Evaluation of the turbulence radiation interaction and the permissibility of the optically thin fluid approximation for a high turbulent methane flame" (KIT-U, GE AVIO) "Determination of criteria for flame stability in an annular Trapped vortex combustor" (ONERA)	15-19/6/2015	Montreal, Canada		UBWM, LU, KIT-U, GE AVIO, ONERA
13	Technical conference	Aerodays 2015 Presentation of the IMPACT-AE project by Ruud Eggels, Rolls-Royce Deutschland.	20/10/2015	London		RRD

Activity no.	Type	Description	Date	Location	Impact observed	Partners involved
14	Technical conference	AIAA SciTech 2016 Presentation of conference paper "Experimental and numerical investigation into the propagation of entropy waves in a small-scale rig" (A. Giusti) Presentation of the recent findings and analysis on the response of self-excited flame (A.-M. Kypraiou)	4-8/01/2016	San Diego, California (USA)	Type of audience: People working in both Universities and industries, aerospace sector. Size of audience: 300	UCAM
15	Technical conference	ASME/IGTI Turbo Expo 2016 Presentation of conference paper about the innovative thermal design methodology developed within the project (Therm3D)	13-17/6/2016	Seoul, South Korea		UNIFI, GE AVIO
16	Technical conference	Thermoacoustic day at the University of Cambridge M. Kypraiou and A. Giusti	2014, 2015	University of Cambridge, UK		UCAM
17	Annual Reviews	Annual Reviews of Rolls-Royce/Loughborough University Technology Centre (UTC) in Combustion System Aerothermal Processes		Loughborough University, UK		LU
18	Planned technical conference	European Rotorcraft Forum 2016 Presentation of conference paper "Experimental and CFD analysis to assess the performance and optimize a low NOx combustor"	6-8/9/2016	Lille, France		ONERA
19	Planned technical conference	2nd Greener Aviation conference organised by 3AF Valorisation of the experimental work performed in the WP3 of the IMPACT-AE programme (conference paper on "Improvement of the multi-staged fuel injector performances by optimization of the pilot/main interaction zone")	11-13/10/2016	Brussels, Belgium		ONERA
20	Workshop participation	IMPACT-AE Coordinator presented the project at the KIAI-TECC workshop held at UNIFI	17/18 September 2012	University of Florence, Italy		RRD
21	Workshop participation	Presentation of paper "Multi-threaded radiation calculation" at the 9th OpenFOAM Workshop	23-26 June 2014	Zagreb, Croatia		KIT-U, GE AVIO

Activity no.	Type	Description	Date	Location	Impact observed	Partners involved
22	Lectures by Dr AD Walker at Loughborough University	Disseminate current activities to students at Loughborough University. Students include undergraduate students on the Meng Aeronautical Engineering course and PhD candidates in the Centre Doctoral Training (CDT) in Gas Turbine Aerodynamics. Material discussion on cooled cooling air systems has been developed to be included in lectures for various taught modules at Loughborough University (e.g. Gas Turbine Design, Propulsion Design for the Environment).	Ongoing	Loughborough University	Ensure course content is research lead and students are taught material relevant to their career aspirations	LU
23	Lectures by Prof. B.Facchini and Dr A. Andreini at UNIFI	Disseminate current activities to students at UNIFI. Students include Master students for Mechanical and Energetic Engineering courses and PhD candidates of Department School. Improvement of material discussion for combustor design methodology and cooling process at UNIFI specific courses (e.g. Gas Turbine, Combustion in aeronautic gas turbine engines)	Ongoing	UNIFI	Improve Master and PhD courses quality and ensure better opportunity for future career of the students	UNIFI
24	Website	IMPACT-AE public website	Since 2012	http://www.impact-ae.eu/		RRD, ART

2.2 Section B (confidential or public)

2.2.1 Part B1 – List of applications for patents, trademarks, registered designs, utility models, etc.

List of applications for patents, trademarks, registered designs, etc.			
Type of IPR	Application reference(s)	Subject or title of application	Applicant(s) (as on the application)
n/a			

2.2.2 Part B2 – Exploitable foreground

Type of Exploitation Foreground	Description of exploitation foreground	Confi-dential (Yes/No)	Foreseen embargo date dd/mm/yyyy	Exploitation products or measures	Sector(s) of application	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
General advancement of knowledge	Advanced automated knowledge based combustor preliminary design process, suitable for low NOx combustion systems optimisation. KBE design tools will be used in the design process of RRD and RRUK.	Yes	-	KBE combustor design tool	RRD design process	Provided to RRD, non-commercial	-	UBWM/RRD/RRUK
General advancement of knowledge	Exploitation of the developed three sector rig VALIDATOR. Test rig will be used in future research programs related to aeroengine combustors.	Yes		VALIDATOR test rig	Aeroengine combustors			UNIFI/GE AVIO
General advancement of knowledge	Exploitation of the QDRV methodology The methodologies developed (Therm3D and REACT) will be used in the design process by GE AVIO	Yes	-	Combustor design tools	Aeroengine	Provided to GE Avio, non-commercial	-	UNIFI/GE AVIO
General advancement of knowledge	Exploitation of test facilities. Test rig developed in IMPACT-AE will be used in future research related to cooled cooling air systems.	Yes		Improved designs and increased TRL	Aeroengine combustors			LU/RRUK

Type of Exploitation Foreground	Description of exploitation foreground	Confi-dential (Yes/No)	Foreseen embargo date dd/mm/yyyy	Exploitation products or measures	Sector(s) of application	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
General advancement of knowledge	Test data on LDI injector performance using optical methods. Improved understanding of design parameters affecting injector performance.	Yes		Directions for further injector design improvements	RRD combustor/injector design	Provided to RRD; non-commercial		DLR-AT/RRD
General advancement of knowledge	Models for the entropy diffusion and dispersion. The models developed in this project will be used in the LOTAN code.	Yes		Models for the entropy diffusion and dispersion	RRUK design process			UCAM/RRUK/RRD
General advancement of knowledge	Experimental database for the characterization of non-linear interactions in self-excited flames. The developed database will be used for the validation and assessment of advanced numerical tools.	No		Experimental database	Research on numerical models			UCAM
General advancement of knowledge	Exploitation of laser diagnostics. Laser diagnostics developed in IMPACT_AE will be used in future research related to aircraft combustors.	Yes		Improved knowledge on the interaction between combustor aerodynamics, fuel placement and pollutant formation	Aeroengine combustors			ONERA

3. Report on societal implications

A. General Information	
*(completed automatically when **Grant Agreement number** is entered)*	
Grant Agreement Number:	265586
Title of Project:	Intelligent Design Methodologies for Low Pollutant Combustors for Aero-Engines
Name and Title of Coordinator:	Ruud Eggels, Rolls-Royce Deutschland Ltd & Co KG

B. Ethics	
1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports?	*No*
2. Please indicate whether your project involved any of the following issues (tick box):	
RESEARCH ON HUMANS	
• Did the project involve children?	No
• Did the project involve patients?	No
• Did the project involve persons not able to give consent?	No
• Did the project involve adult healthy volunteers?	No
• Did the project involve Human genetic material?	No
• Did the project involve Human biological samples?	No
• Did the project involve Human data collection?	No
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	No
• Did the project involve Human Foetal Tissue / Cells?	No
• Did the project involve Human Embryonic Stem Cells (hESCs)?	No
• Did the project on human Embryonic Stem Cells involve cells in culture?	No
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	No
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	No
• Did the project involve tracking the location or observation of people?	No
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	No
• Were those animals transgenic small laboratory animals?	No
• Were those animals transgenic farm animals?	No

• Were those animals cloned farm animals?	No
• Were those animals non-human primates?	No
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	No
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	No
DUAL USE	
• Research having direct military use	No
• Research having the potential for terrorist abuse	No

C. Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator		2
Work package leaders		4
Experienced researchers (i.e. PhD holders)	3	54
PhD Students	1	8
Other	2	100

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	2
Of which, indicate the number of men:	2

D. Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project?	☒ ☐	Yes No

6. Which of the following actions did you carry out and how effective were they?

		Not at all effective				Very effective
☒	Design and implement an equal opportunity policy	☐	☐	☒	☐	☐
☒	Set targets to achieve a gender balance in the workforce	☐	☒	☐	☐	☐
☐	Organise conferences and workshops on gender	☐	☐	☐	☐	☐
☒	Actions to improve work-life balance	☐	☐	☐	☒	☐
☒	Other: Snecma and Turbomeca contribute to the partnerships "Elles bougent" and "Women's forum" to promote gender balance in the workforce. Loughborough University conformed to its policy on Gender Equality.					

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

☐	Yes- please specify
☒	No

E. Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

☒ Yes- please specify: Bachelor/Master theses

☐ No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

☒ Yes- please specify.
Some published results obtained in the project are reported in the lecture notes used for Mater Thesis course.

☐ No

F. Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

Main discipline: Other engineering sciences
Associated discipline: Mathematics and computer sciences
Associated discipline: Physical sciences

G. Engaging with Civil society and policy makers

11a. Did your project engage with societal actors beyond the research community?
(if 'No', go to Question 14)

☒ Yes ☐ No

11b. If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

☒ No

☐ Yes- in determining what research should be performed

☐ Yes - in implementing the research

☐ Yes, in communicating /disseminating / using the results of the project

11c. In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?

☐ Yes ☒ No

12. Did you engage with government / public bodies or policy makers (including international organisations)

☒ No

☐ Yes- in framing the research agenda

☐ Yes - in implementing the research agenda

☐ Yes, in communicating /disseminating / using the results of the project

13a. Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

☐ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)

☒ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)

☐ No

13b If Yes, in which fields?

Agriculture	☐	Energy	☐	Human rights	☐

Audiovisual and Media	☐	Enlargement	☐	Information Society	☐
Budget	☐	Enterprise	☐	Institutional affairs	☐
Competition	☐	Environment	☐	Internal Market	☐
Consumers	☐	External Relations	☐	Justice, freedom and security	☐
Culture	☐	External Trade	☐	Public Health	☐
Customs	☐	Fisheries and Maritime Affairs	☐	Regional Policy	☐
Development Economic and Monetary Affairs	☐	Food Safety	☐	Research and Innovation	☒
Education, Training, Youth	☐	Foreign and Security Policy	☐	Space	☐
Employment and Social Affairs	☐	Fraud	☐	Taxation	☐
		Humanitarian aid	☐	Transport	☒

13c. If Yes, at which level?

- ☐ Local / regional levels
- ☐ National level
- ☒ European level
- ☐ International level

H. Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	17
To how many of these is open access provided?	1
How many of these are published in open access journals?	1
How many of these are published in open repositories?	1
To how many of these is open access not provided?	4
Please check all applicable reasons for not providing open access:	
☒ publisher's licensing agreement would not permit publishing in a repository ☐ no suitable repository available ☒ no suitable open access journal available ☐ no funds available to publish in an open access journal ☐ lack of time and resources ☐ lack of information on open access ☐ other:	
15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*	0

16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	0
	Registered design	0
	Other	

17. How many spin-off companies were created / are planned as a direct result of the project?	0
Indicate the approximate number of additional jobs in these companies:	

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

☐	Increase in employment, or	☐	In small & medium-sized enterprises
☐	Safeguard employment, or	☐	In large companies
☐	Decrease in employment,	☐	None of the above / not relevant to the project
☒	Difficult to estimate / not possible to quantify		

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (FTE = one person working fulltime for a year) jobs:

Indicate figure:

Difficult to estimate / not possible to quantify

☒

I. Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

☐ Yes   ☒ No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

☐ Yes   ☒ No

22. Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

☐	Press Release	☐	Coverage in specialist press
☐	Media briefing	☐	Coverage in general (non-specialist) press
☐	TV coverage / report	☐	Coverage in national press
☐	Radio coverage / report	☐	Coverage in international press
☐	Brochures / posters / flyers	☒	Website for the general public / internet
☐	DVD / Film / Multimedia	☐	Event targeting general public (festival, conference, exhibition, science café)

23. In which languages are the information products for the general public produced?

☐	Language of the coordinator	☒	English
☐	Other language(s)		