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EXPERIMENTAL AND CFD ANALYSIS TO ASSESS THE PERFORMANCE AND OPTIMIZE A LOW NOX COMBUSTOR

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ABSTRACT

To enforce ACARE 2020 80% NOx emissions reduction goal, Safran Helicopter Engines is developing a low-NOx combustor technology based on lean burn combustion. Safran Helicopter Engines considers that only the creation of a low-temperature flame combustion regime can be compatible with ACARE goal which aims at reducing NOx emissions by 80% compared to conventional technology of 2000.
This activity is carried out in the FP7 European research program IMPACT (2011-2016). The main objectives of the project are:

- The assessment of low-NOx burners performance in representative operating conditions
- The improvement of numerical modeling tools to predict the pollutant emissions (especially NOx)

In this framework, Safran Helicopter Engines developed an annular, low-NOx combustion chamber at scale 1 representative of a real turboshaft combustor. The performances of this chamber and its injection system is characterized on a test bench at ONERA up to a pressure of 14 bar and a chamber air temperature inlet of 720 K. Combustion efficiency, pollutant emissions and gas temperature field at the exit of the combustion chamber is measured at a reference operating condition. The established database is used to compare the performance of this low NOx technology to conventional technology and demonstrates that the emissions reduction goals are achieved over a wide range of operating conditions. In addition, the thermal behavior of the combustion chamber liner is analyzed with 32 thermocouples distributed over the outer and inner liner: even at the most stringent thermal conditions, the liner temperature remains below the critical temperature affecting its lifetime.
This experimental database is also used to improve and validate the CFD tool used by Safran Helicopter Engines: in the range of investigated thermodynamic conditions, the CFD results for NOx emissions are in good agreement with measurements. Safran Helicopter Engines now possesses a predictive tool for NOx pollutant emissions in order to perform targeted optimization. Instantaneous results, such as flame topology unsteady behavior, and mean distributions of thermo-chemical quantities can be analyzed. Used on Low NOx combustor computations, these analyses show that the flow has a strong influence on mixture fraction distribution and NO creation process. Optimization of the combustion chamber design may be obtained by modifying the interaction between pilot and lean injection devices or their geometry.

Combining most advanced CFD simulation with experiments provides a clear understanding of the complex phenomena governing the impact of an improvement of the combustor design on NOx emissions. Increasing the maturity of the Low NOx chamber design and implementing it on a future engine development will imply decreasing the mass of the combustor and the fuel nozzles, the overall dimension as well as manufacturing and operating costs. These objectives require an optimization of the technology and an assessment of the minimum size of the combustion chamber without compromising performances and ignition.
Although this technology is not yet at a technology readiness level (TRL) or compatible with an immediate implementation in a new engine project, the IMPACT combustor constitutes a significant step in developing a low NOx combustion chamber, meeting emerging requirements for pollutant emissions. Achieved improvement in reducing the pollutant emissions will be used in future rotorcrafts applications.

1. INTRODUCTION

Reducing polluting emissions is a global society issue for which the air transport has to take its share. Compared to the technology of certified aircraft in 2000, ACARE recommends that aircraft emissions be reduced by 80% for NOx and 50% for CO2. These targets rolled out at the engine leads to a reduction of 60% for NOx and 20% for CO2. Achieving such ambitious goals requires an evolution of the engine technology in particular at the combustion chamber level.

Although so far there is no regulation for emissions of gaseous pollutants from helicopters, Safran Helicopter Engines is particularly sensitive to the achievement of the ACARE objective. Indeed, for more than 15 years, Safran Helicopter Engines combustion design office has been developing low NOx technology combustor. These activities are conducted partly on own funds and partly through research projects financed by European funds: including in particular the research programs LOPOCOTEP, NEWAC and IMPACT [2].

For this research and development activity, Safran Helicopter Engines goal is to meet the ACARE recommendations for the low NOx technology to already be validated at high TRL when regulations affect helicopters. This publication provides an overview of achieved results.

2. LOW NOX COMBUSTOR DESIGN

The most effective technique to reduce the production of NOx, at any point of the combustion chamber, is to keep the flame temperature below 1850 K. This technique, called lean combustion, is adopted by most aircraft engines manufacturers (GE, RR, Safran Aircraft Engines ...). It allows limiting the formation of "thermal NO", which is the major contributor to the total NOx formation in the gas turbine high power cycles. It is generally accepted in the literature that the amount of thermal NO produced increases exponentially with flame temperature.

ACARE target of 20% reduction in CO2 engine emissions leads manufacturers to increase the compression rate (OPR) and the turbine inlet temperature (TET) to increase the overall efficiency of the engine cycle. In consequence, the flame temperature increases and so does the risk of NOx production.

This is illustrated Fig. 1: for different engines of a given power, the red curve shows the evolution of the specific consumption according to the characteristics of their thermodynamic cycles. These thermodynamic cycles are characterized (x-axis) by the TET or by the air-fuel mixture ratio (FAR) or by the OPR. Fig. 1 shows that when the engine cycle gets more powerful (by increasing FAR or OPR) the specific consumption (Cs) and therefore the CO2 emissions are reduced.

For an engine certified in 2000, points 1 and 1' are respectively the emission levels of CO2 and NOx. At same combustor technology, increasing the OPR or the TET to decrease Cs, leads to operate in point 3' in terms of NOx emissions. Clearly, without changing the combustor technology, more powerful thermodynamic cycle would cause a major increase in NOx emissions. In order to achieve the ACARE target of NOx reduction it is necessary to operate in point 2' on the blue dashed curve, which is representative of lean combustion.

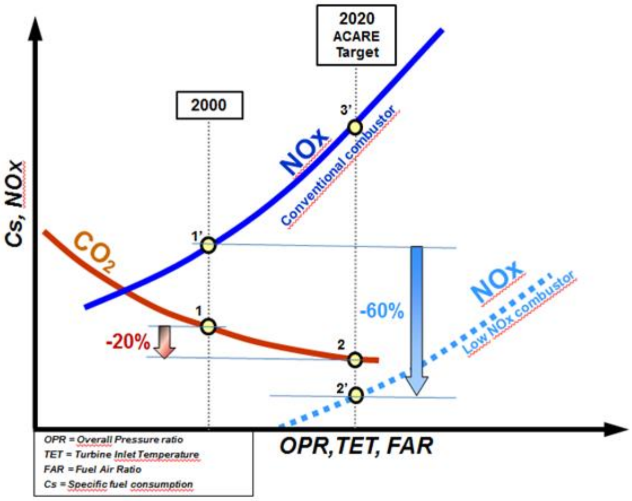

Fig. 1: Evolution of NOx and CO_2 emissions according to engine cycle

The development of a lean combustion helicopter engine faces various serious challenges:

1. Lean blow out limits must be improved by using a Pilot stage injection device. Pilot injectors create rich gas pockets inside the combustor primary zone where the flame can be sustained during fast power reduction;
2. Fuel and air mixture must be as lean and homogeneous as possible. Comparatively to conventional combustor, increasing the air mass flow dedicated to Lean Premixed injection systems (LP) is mandatory. In a traditional combustion chamber, roughly 15% of the air flow is dedicated to the injectors. For lean combustion chambers, it can reach up to 70%. The exact amount of air is determined according to the engine cycle and the power range where the emissions reduction should be optimized;
3. Increasing injectors' air mass flow implies dramatic reduction in available air dedicated to cool the combustor walls and to tune the radial temperature profile at the HP turbine inlet plane.

Moreover, helicopter engines are generally low power engines (lower than 3500 shp) and are therefore equipped with very compact combustor. Consequently, an ideal lean combustion chamber concept should:

1. limit the interactions between the wall cooling air flow and the lean flame (to avoid reducing combustion efficiency and thus increasing CO emissions). The risk of interaction is all the higher as the combustor size is limited;
2. limit the price increase due to the more complex technology which requires 2 injection systems, composed of Pilot injectors, Lean Premixed Injectors (LP) and their fuel regulation systems.

Safran Helicopter Engines prototyped a combustion chamber for real size application engines of 1500 shp. This power range corresponds to the ARDIDEN 1 Safran Helicopter Engines's engines family intended to equip the 5 to 7 tons class helicopters. However, this technology could be used in the full range of engine power - 450 up to 3500shp - of Safran Helicopter Engines.
For industrial confidentiality reasons, technological details are voluntarily omitted.

3. DEVELOPPEMENT PROCEDURE

Most of the efforts carried out focused on developing injection systems (LP and Pilot injectors) and the full annular combustor at scale 1. These components were evaluated in a combustion test rig.
Injectors and combustor have been developed using CFD RANS tools to predict aerodynamic behaviors inside injectors and the combustor: velocity and temperatures fields, gas temperature profile at the combustor exit, fuel and air mixing…
The injectors have been experimentally characterized in Safran Helicopter Engines' injection test rig under atmospheric conditions. ONERA and DLR laboratories carried out investigations at real operating conditions to emulate temperatures and pressures of air in main operating conditions.
The scale 1 full annular combustor was manufactured and a combustor test module was developed. This test module was installed in the ONERA test bench M1 in Palaiseau. Several tests campaigns have been carried out to measure the global performance of the combustor in real stationary operating conditions. The whole operating power conditions of the engine has been analyzed. During these tests campaigns, various injectors and various combustors, where the main differences relate to the wall cooling, have been tested.
To study start performances, a specific test module limited to a 3 LP injectors sector was developed. A test campaign yielded a first assessment of the light up envelop of this combustor. The climatic conditions investigated cover an altitude of 0 to 6000 meters and a minimum temperature of -40°C. However, it is noteworthy that this investigation is only a first approach to evaluate performance and should be complemented by other test campaigns. In this paper, these particular results are omitted for concision purposes. The focus is rather put on the primary objective of this technology: NOx emissions reduction.

In parallel of experimental work, NOx production models improvement activities were carried out. A new model was implemented in the CFD Large-Eddy Simulation (LES) code used by the combustion department at Safran Helicopter Engines. The results of test campaigns conducted with the annular combustion chamber were used to validate the NOx model. It was demonstrated that the validation level of the LES tool is high enough to be used in the framework of optimizing the Low NOx technology.

As explained above, developing lean-combustion technology includes various activities. This paper highlights the experimental results obtained with the full annular chamber and the CFD tool maturity level for pollutant emissions predictions compared to the measurements.

4. PRESENTATION OF THE FULL ANNULAR COMBUSTOR TEST MODULE

Figure 2 gives some views of the test module installed in the ONERA test rig. The blue arrows represent the flow of fresh air at the test module entrance and the red arrows, the flow of exhaust gas downstream of the combustion chamber. A hot valve located downstream of the outlet of the combustor is used to set and regulate the air test pressure.
The test module is designed to supply air to the full annular combustor identically to the real air supply in the full engine. In particular, air velocities in the airflow around the combustor are perfectly reproduced. This ensures that the air distribution into the combustor on the combustion test bed is the same as on engine.
The ONERA test rig allows to perfectly reproduce the thermodynamic conditions at the combustor entrance in terms of pressure, temperature and air mass flow. During testing, the maximum conditions investigated reached 14 bar and 750 K.

The fuel system of the test rig was designed to provide any desired fuel flow split between the various injectors (pilot stage, lean stage).
The bench parts in contact with exhaust gases are cooled by circulating water. Far downstream of the last measurement plane, the burnt gases are cooled by injection of a water flow directly into the vein.

All the parameters necessary to adjust and control the operating conditions are measured (air mass flow, air temperature and pressure at the test module entrance, fuel mass flow and fuel pressure for each injection stage…) prior and during the test.

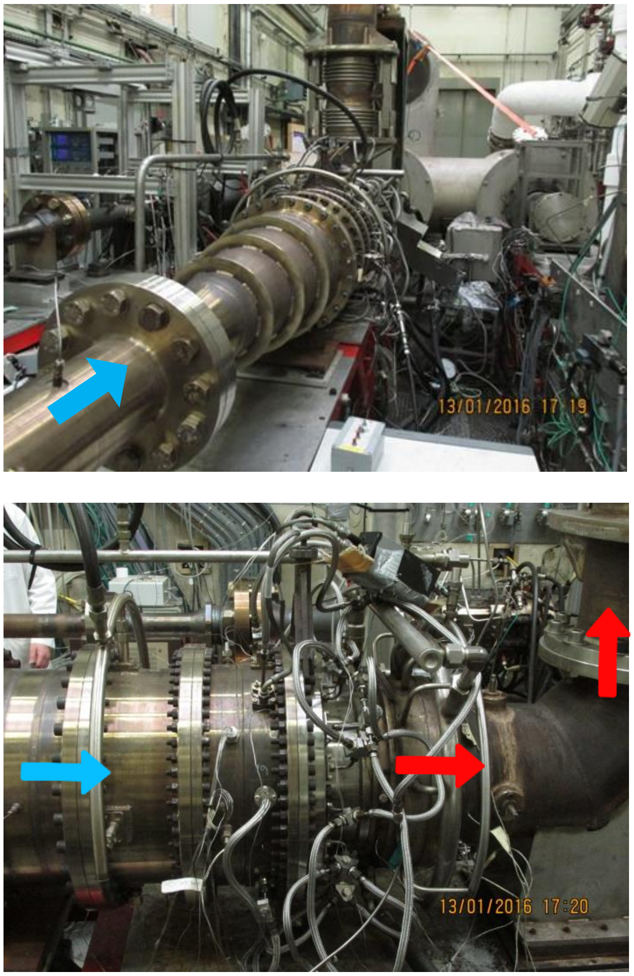

Figure 2: Views of the IMPACT2 FANN combustor test module installed in M1 ONERA test rig.

The combustion performance is measured at the exit plane of the combustor by a rotating probe which ensures analysis of the entire 360 degrees of the annular outlet section. This probe, which is located inside the exhaust gas flow, is cooled by circulating water. It is composed of 3 rakes: 2 are equipped with thermocouples to measure the gas temperature and the last rake is dedicated to gas sampling. The gas samples are analyzed to determine their composition and to the combustion efficiency and emissions. Figure 3 gives a view of the rotating probe before the combustor test module is installed in the rig. Each rake is composed of 4 individual measurements: 2 times 4 thermocouples and 4 sampling tubes. Measured species are: CO2, CO, NO, NOx and unburnt fuel.

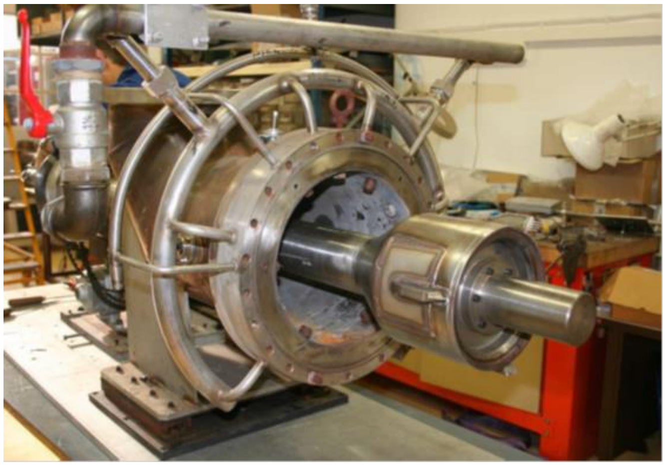

Figure 3: Annular rotating probe (cooled by circulating water).

During each test campaigns, the combustion chamber is instrumented with thermocouples and pressure taps to determine the wall temperatures and pressure drops in crossing the chamber wall. The typical instrumentation for each test campaign was composed of 30 thermocouples and 15 pressure probes.
Several other parameters are continuously checked during tests, to ensure security in acceptable ranges of pressures, temperatures and mass flows of the cooling water, gas temperatures in the exhaust pipe, casing temperatures…

5. EXPERIMENTAL RESULTS

These test results are summarized to provide a global comparison of performance between low NOx combustor technology and conventional combustor technology.
Since the Low NOx configuration was tested in partial bed combustion rig, variation of thermodynamic parameters at the entrance of the combustion chamber was possible in a wider range than the ones of the engine cycle. In particular, it was possible to vary these

parameters (P3, T3, FAR, W3) independently of engine cycle in order to build a database yielding correlations to estimate NOx and CO emissions for every operating point. Figures 4 to 6 give NOx emissions with respect to, respectively, FAR, air pressure P3, and air temperature T3 at the combustor inlet.

For each figure we present the results obtained with 2 low NOx combustors (Impact 1 and Impact 2).

The Impact 2 combustor is the most advanced variant. Compared to Impact 1, it features an increase of LP injector air mass flow rates. Because of this change, NOx emissions of Impact 2 (red diamonds) are below those of Impact 1 (blue squares), and all the more so at high FAR.

On Figure 4, the abscissa represents the evolution of FAR divided by the value of FAR at the operating point at which the low NOx technology has been designed (this FAR value is noted “FAR ref.” in figures 5 and 6). At this operating condition, the air mass flow dedicated of the LP injectors of the Impact 2 combustor was designed to reach 60% of NOx reduction.

To ease comparison of Low NOx and conventional technologies, each figure shows the evolution of the ratio between the emissions produced by the two technologies.

Emissions values for conventional technology are estimated from correlations available at Safran Helicopter Engines. These correlations are obtained directly from emissions measurements at the engine exit. They are representative of the behavior of the conventional technology on an engine operating line.

Some operating points, realized on combustion bench during the test campaigns Impact 1 and 2, are outside of engine operation line and thus, are estimated with a lower accuracy. These points correspond to high engine power conditions but carried out with artificially low FAR.

All the operating points presented in this paper are far from idle condition. That is why only the LP injectors are fueled. The operating conditions in which the pilot injectors are fed are not discussed here.

Figures 4 to 6 clearly show that the Low NOx technology developed by Safran Helicopter Engines reduces significantly NOx emissions. The NOx emissions ratio varies from 0.15 to 0.6. In the case of the Impact 2 configuration, the maximum value is does not exceed 0.5.

Up to a 1.15 FAR, a 60% reduction of NOx emissions is already reached. This is in accordance with the ACARE objectives.

As explain above, operating conditions at low FAR (Fuel Air Ratio dimensionless lower than 0.9 in fig 4) are not on the engine operating line. Therefore, the corresponding NOx reductions (70% to 85%) are only representative of the efficiency of the technology developed by Safran Helicopter Engines but will not be achievable on engine.

As shown in figures 5 and 6, an increase of the pressure or temperature of the air at the combustor entrance induces an increase of NOx emissions. This result is consistent with the scientific literature.

Figure 7 provides a comparison of CO emissions between Low NOx technology and the conventional one. In the range of FAR dimensionless from high values to 0.9 the behaviors of the 2 technologies are equivalent. Below 0.9, there is an increase of CO emissions. Yet, as explained for figure 4, these FAR values are not representative of the operating engine line: they are collected to obtain correlations between emissions and operating conditions.

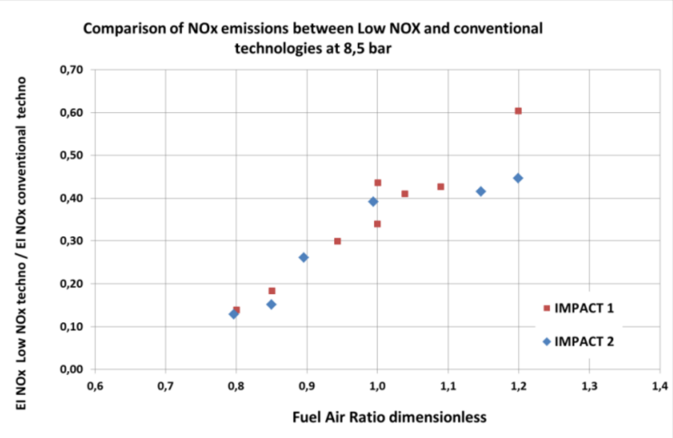

Figure 4: Variation of NOx emissions according to FAR

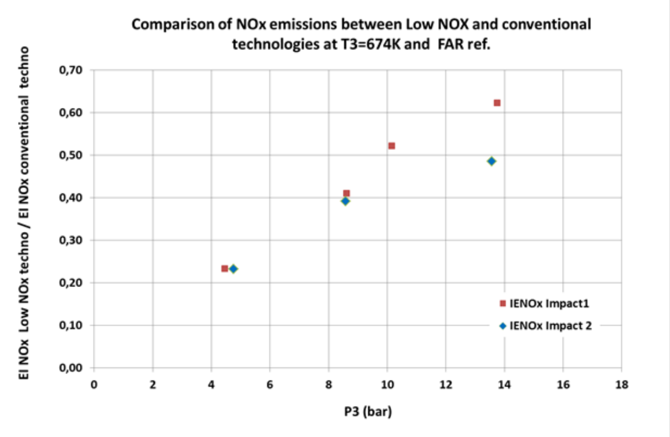

Figure 5: Variation of NOx emissions according to P3

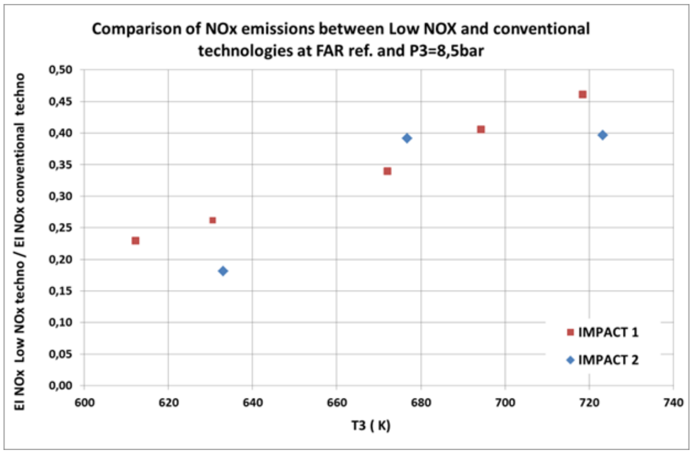

Figure 6: Variation of NOx emissions according to T3

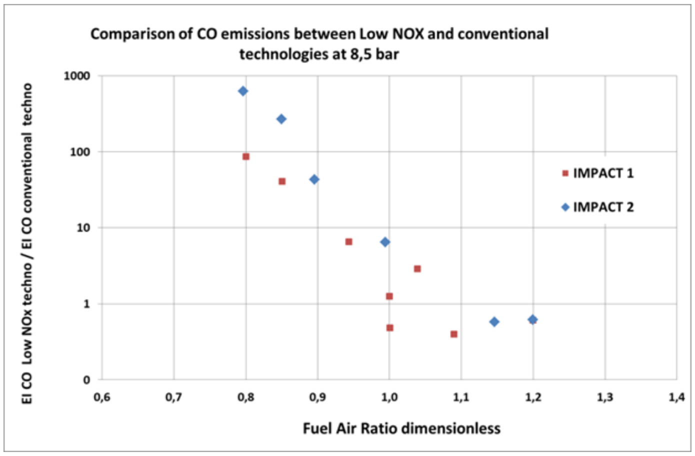

Figure 7: Variation of CO emissions according to FAR

Beyond emissions, all other combustion performances are measured: lean blow out limits, wall temperatures and gas temperature distributions at the combustor exit. Two major points are noteworthy:

- despite the reduction in the amount of air that can be devoted to walls cooling of the lean combustor, temperatures are maintained below the design criteria of Safran Helicopter Engine for both Impact 1 and Impact 2 combustors. At the end of the two campaigns, the combustors are in a very good state;
- despite the drastic increase in primary zone airflow for the lean combustion technology, the lean blow out limit is perfectly controlled by the effectiveness of the pilot stage.

Finally, during all test campaigns conducted with this technology, no combustion instability was triggered. This was ensured by using dedicated unsteady pressure sensors.

Globally, all targets are met for this new technology (reduction of polluting emissions, combustion stability, thermal behavior of walls...). However, investigations should be completed to demonstrate that ignition performance and components lifetime are also entirely satisfactory.

6. CFD MODELISATION OF THE LOW NOX COMBUSTOR

To optimize a combustion chamber in order to reduce its pollutants emissions, CFD is less expensive and faster to implement than an experimental campaign like the one presented in the previous paragraphs. During the IMPACT-AE project, the work carried out by F. Pecquery et al. [1] regarding NO production modeling has been extended to kerosene chemistry. This model has been implemented in two LES industrial codes, AVBP and YALES2. The comparison between the numerical simulations and the experiments in terms of NOx emissions is given in this section. Numerical simulations for several operating conditions are carried out for the IMPACT1 Low NOx chamber and two conventional combustors and show a good agreement with the experiments. The last part of this section presents an analysis of the NOx formation in the IMPACT1 combustor and how it can be used to optimize the configuration of the injection system or the interaction between the pilot and the LP stages.

7. NUMERICAL SIMULATIONS AND EXPERIMENTS NOX EMISSIONS COMPARISON.

The IMPACT1 combustion chamber, tested during the test campaign presented in the previous sections has been simulated for 4 operating conditions.

To validate the modelling approach, the gas temperature distribution at the exit of the chamber is first compared with experimental data. Time and azimuthal averages of normalized temperature, for the four heights of the sampling tubes of the rotating probe, are compared between simulation and experimental data. These values are plotted Fig. 8 and show a good agreement that validates the integral behavior of the computations (overall thermal behavior).

Discrepancies arise for profiles of maximum of adimensioned temperature (OTDF), but remains close, or inside, the confidence margin of experimental data.

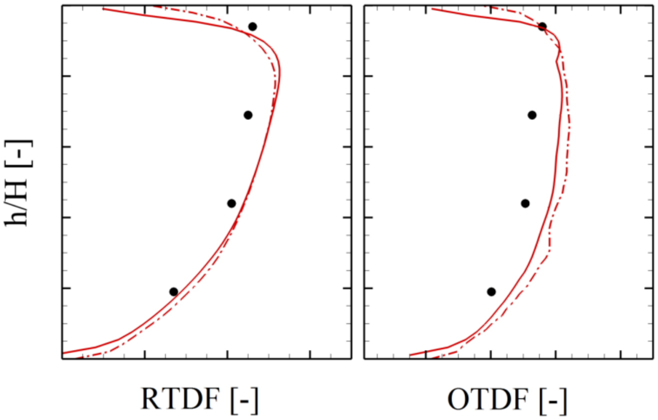

Figure 8: Comparison of azimuthal average (left) and maximum (right) of adimensioned temperature as function of the height. Symbols: experimental data points; continuous lines: simulations.

At this point, even if the results do not perfectly fit the experimental values, the thermo-chemistry and mixing modelling of the combustion chamber are considered validated, particularly for integrated values, which are of interest for pollutant emissions.

Figure 9 shows the comparison between the numerical and the experimental results in terms of NOx emissions. The 45° solid line is representative of a perfect agreement between numerical and experimental results. The two doted lines represent a deviation of 5%. The red diamonds correspond to 4 operating conditions with the low NOx chamber which allow an evaluation of the NOx model against variations of inlet temperature, pressure and FAR. The reference condition has a very good agreement with the experimental results, the effects of inlet temperature, pressure and FAR variations are well predicted since deviation does not exceed 10% with regards to the experiments.

Safran Helicopter Engines also disposes of databases in terms of NOx emissions to evaluate the NOx model against technological variations: several operating conditions for two conventional combustors of 2000 are simulated and represented on Fig. 9 by the black triangles and circles.

The results are also found coherent with experimental data, and mostly inside experimental error margins. Only one point presents a large deviation, this could be attributed to single phase as well as adiabaticity assumptions.

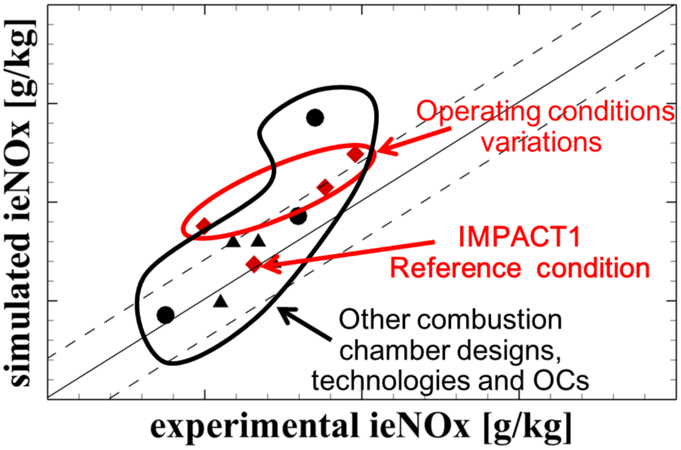

Figure 9: Comparison between numerical and experimental results of NOx emissions

NOX FORMATION ANALYSIS FOR THE LOW NOX CHAMBER

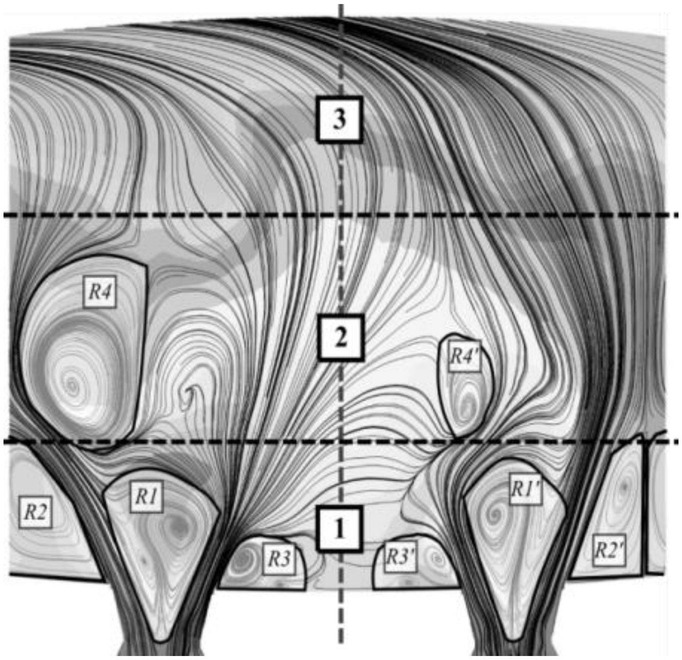

Figure 10: Streamlines restricted to a radial cut centered on LP injectors centers. The cut is divided into three parts referred to in the text. Main recirculation zones are highlighted by a gray mask and numbered R1 to R4 for the left zone (injector+pilot 1) and R1' to R4' for the right zone (injector+pilot 2).

The combustion chamber can be schematically divided into three sections regarding a macro description of the aerodynamics. In part 1 of figure 10, the flow field resembles to classical swirled flows, with inner recirculation zones (R1 and R1') coupled with two outer recirculation zones (R2, R3 and R2' and R3'). It must be noted that, even if behaviors of the flows exiting the LPs are quite similar, the recirculation zones R2 and R2' differ in surface extension, recirculation R2 being much broader. Moreover, zones R2 and R3 (respectively R2' and R3' for the second LP injector) are different in shapes and sizes. Knowing that temperature and mixture richness are greater near zones R3 and R3', the pilot injectors feed could be optimized in order to homogenize the temperature and mixture fraction distributions in part 1 of the combustion chamber. In part 2, the asymmetry of the flow field becomes even more evident, showing an extended recirculation zone R4 for injector 1 contrary to the zone R4'. This implies that residence times could be higher in R4 zone, favoring NOx creation in burnt gases. Last, part 3 of the combustion chamber presents the same features on both sides, with a gyratory flow which follows the swirl motion of the LPs and of the dilution devices. This description of the mean flow evolution along the combustion chamber drives the possibility of optimization of the injection methodology: as the two LP injectors behave differently, NOx creation process can be analyzed for each part, and geometrical changes can be prescribed to diminish its production.

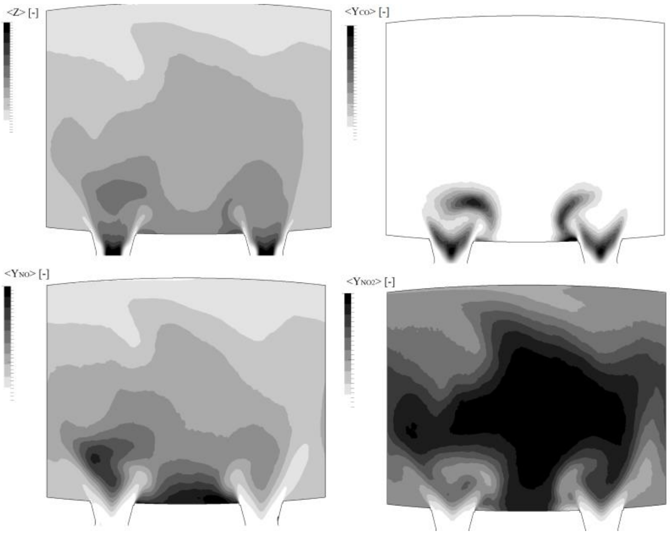

Figure 11: Mean distribution of mixture fraction, CO, NO and NO_2 along a radial cut centered on LP injectors center.

We focus now on the pollutants formation patterns. An analysis is first carried out to evaluate the amount of NO produced in the efficient carbon chemistry region. This analysis shows that 5.5% of the NO is produced in the flame development region. While it is difficult to discriminate the '*prompt*' contribution from the '*thermal*' one of NO formation without evaluating directly the contributions coming from the different chemistry steps, this ratio demonstrates the necessity to have a proper NOx modeling strategy inside the burnt gases. It is expected that at different operating conditions, this ratio will change.

Figure 11 presents mean NO distribution along a cut of the combustion chamber. The mixture fraction is also depicted to evaluate qualitatively the degree of correlation between the scalars. Formation of CO is located in rich regions, and well delimited to a region close to the exit of the LP injectors. CO and NO profiles follow the dissymmetry of mixture fraction, which is due to the different interactions of pilot injection with the swirl motion of LPs flow. Again, the left sector seems to favor pollutants creation. Regarding NO2 distribution, figure 11 shows that this species acts in contraposition to CO. As a remainder, it is noted that NO2 is not solved using a transport equation, but directly tabulated.

Safran Helicopter Engines now possesses a predictive tool for NOx pollutant emissions in order to perform targeted optimization.
Detailed analysis of the simulations predictions pave the way to understanding NOx formation process associated with technological choices, and optimization of the combustion chambers. Further work will include modeling of two phase flows as well as fluid-solid heat transfers to characterize NOx formation on critical operating conditions.

8. CONCLUSION

While no regulation for emissions of gaseous pollutants now exist for helicopters, Safran Helicopter Engines remains particularly sensitive to the achievement of the ACARE objective of CO2 and NOx emissions reduction and has been developing low NOx technology combustors for 15 years.

It was demonstrated that, with this technology, the NOx emissions of an engine designed in 2000 are reduced by 60% in accordance with the recommendation of ACARE. This experimental demonstration was carried out with a full annular combustor at scale 1 in representative operating conditions up to about 14 bars for the air pressure at the combustor inlet.

All the measured performances of this technology are satisfactory. Yet, to level up the technology to TRL 5, it is of paramount importance to carry out a dedicated test campaign to determine the light up performance in cold and high altitude conditions.

The data base obtained with this lean combustor have been used to complete the validation of NOx production models implemented in the LES numerical simulation code used by the combustion design office of Safran Helicopter Engines. With the accuracy achieved by this tool, it is now possible to optimize this technology to reduce its size and its cost.

The development of a NOx reduction technology based on lean combustion allows Safran Helicopter Engines to prepare for future regulations on NOx emissions and contribute to achieving the ACARE objectives.

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2. This deliverable is part of the IMPACT-AE project which is a European initiative financed under the FP7 and addresses innovative design methodologies for the development of low pollutant combustors in aero-engines. IMPACT-AE project aims to validate these design methodologies and providing optimised design solutions for future combustor designs. IMPACT-AE is a 4.5-year project started in November 2011 and gathering all the required expertise from several countries with both academic and industrial partners

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