TLC - Towards Lean Combustion

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Project summary

The mitigation of aviation emissions in terms of their environmental impact is a priority for both air quality (local impact) and the greenhouse effect (global impact).

For a fixed engine cycle, the margin of progress depends on the combustor technology. Lean combustion is the breakthrough, which should enable high-level reductions in NOx emissions both during the LTO cycle (air quality) and at cruise speeds (global impact). In addition, lean combustion also enhances particulate reduction. Injection systems form the most critical issue in achieving a satisfactory level of lean combustion and will be the technological focus for the project.

Within this framework, a wide range of experiments will be carried out on mono-sector or tubular combustors. This new program will be a crucial effort in achieving sufficient maturity for the single annular combustor application. The objectives will be an 80% reduction in NOx emissions in relation to the CAEP2 regulation limit during the LTO cycle, and low NOx emission indices at cruise speed (EINOx=5g/kg as target). Other gaseous emissions and soot performance characteristics will be also precisely evaluated.

In this prospect, the project will support the adaptation of most advanced, non-intrusive laser-based measurement techniques to combustors actual conditions and their application (in addition to intrusive techniques) to experiments of various concepts of injection systems. The injection systems tested will derive from the LOPOCOTEP program or other projects and from advanced CFD optimisation of new concepts. The entire range of operating conditions will be experimentally evaluated (LTO points, cruise speeds). Auto-ignition and flashback risk issue as well as lean extinction limit will be assessed. Advanced CFD simulation will also exploit the data from the fundamental experiments, thereby enabling calibration of the latest codes in emissions predictions.

The TLC consortium gathers 19 partners from 6 countries (France, Germany, Italy, Sweden, Spain and Poland). Main European actors in aero-engine combustor technology are involved (Snecma, Rolls-Royce Deutschland, MTU, Avio, Turboméca). The 2 main national research centers in aeronautics (DLR, ONERA) and best universities and laboratories in measurement and computation participate to TLC (Ulund, CORIA, ECN, ITS, EBI, Gen-U, Na-U, CERFACS, LITEC, DMA , IMP)

Public information can be reached on the WEB site : **www.TLC-project.eu**

Scientific and technological objectives

Taking advantage of all the knowledge gained in previous European or national projects, the **TLC** project allowed achieving maturity in the development and design of lean injection systems with fuel staging for single annular combustors.

Evaluation of various concepts, use of design optimisation procedures, large number of tests, development and application of advanced experimental diagnosis for realistic combustor conditions, strong support of numerical diagnosis with the latest European CFD tools, have contributed to this goal.

On the technological point of view, two essential features of **TLC** were that:

- the five manufacturers involved will be all exploring lean combustion applied to single annular combustor architecture,
- an ambitious reduction in NOx levels during LTO cycle is not the only target; we shall also consider NOx levels at cruise speeds, particulates reduction during LTO and at cruise speeds. Moreover, the trade-off with CO&UHC and operability will be addressed and the injection systems will have to perform satisfactory combustion at low regime.

The engine manufacturers may have different constraints when optimising an injection system. In particular, the ability to design LPP systems will be higher for small OPR (in particular for small engines such as TM engines) than for higher OPR, and the LP (Lean Premixed) solution may be easier to implement than the LPP (Lean Premixed Pre-vaporized) solution (serious instability problems have been encountered by RR in the LowNOx III program on LPP systems for OPR=40 engines). All the experiments have been carried out either on tubular combustors or on mono-sector combustors.

In relation to the general scope, detailed objectives were as follows:

- **To intensively explore various fuel staged LP or LPP injection systems** covering various engine compression rates (OPR $\in$ [15, 35]) and all operating regimes. Emission performance characteristics have been measured. Risk of auto-ignition, flash-back and stability has been also assessed.
- **To develop appropriate non-intrusive measurement techniques** to enhance knowledge and understanding of all the phenomena occurring in the combustor and the injection system. To acquire high diagnosis capability for:
  - NOx measurements: gas analysis
  - Particulates: SMPS on samples and LII
  - Combustion process (OH, kerosene, T, velocities, turbulence): LIF, CARS, PIV, LDA, PDPA. These techniques are based on laser use and are non intrusive measurements.
- **To calibrate CFD tools** (RANS or LES codes, combustion and emission formation models) for the purposes of combustion and emission prediction. To acquire or assess prediction capability. Choice has been made not to carry out numerical developments. Development activities are largely covered in recently completed or still on-going projects.
- **To develop systematic optimisation procedures**: definition of a lean injection system concept and associated design parameters, definition of design criteria and constraints, definition of design objectives, application of advanced optimisation algorithm.
- **To extrapolate real engine performance** for the future. To assess what is technologically feasible in the long term.

Work performed and results

The Work Package 1 treats the validation and the adaptation of non intrusive measurement techniques to the conditions foreseen for the tests, in particular for HP tests (up to 30 bar). Thanks to TLC project, the following achievements have been made :

A combustion chamber with optical access was built, assembled and tested up to 22 bar in combustion. This manufacturing has been used during the project to apply innovative measurement techniques on an industrial injection system

Concerning the 2 phase flow, LDA (gas velocity measurement) and PDA (drop size and drop velocity measurement) techniques were performed under high pressure conditions,

Flame characterisation techniques was validated in high pressure conditions :

- The feasibility of LIF measurements on kerosene in harsh conditions (high temperature – high pressure) was demonstrated and Simultaneous LIF of OH and kerosene were performed up to 22 bars.
- The coherent anti-Stokes Raman Scattering technique (CARS) has been developed for probing CO_2 in high-pressure high-temperature flowfields. An innovative method based on the dependency of pure CO_2 CARS spectra (figure 1) offers the opportunity to measure simultaneously temperature and CO_2 concentration in reactive flowfields. This method has been successfully applied to characterise an industrial burner up to 20 bars.
- A method of combining PLIF of OH with absorption measurements to obtain planar, single-pulse temperature measurements in lean, high temperature mixtures near equilibrium was discovered. The procedure to correct the obtained images to arrive at a temperature value was established. Experimental validation was obtained with temperature measurements in a controlled high pressure environment using CARS.
- Measurements of soot sizes and soot particle radiative properties have been obtained at atmospheric and pressure conditions,
- calibration of LII was performed in a burner under high pressure conditions
- Time-resolved tracking and 3D imaging of turbulent phenomena were achieved in LIF, filtered Rayleigh and Raman scattering.

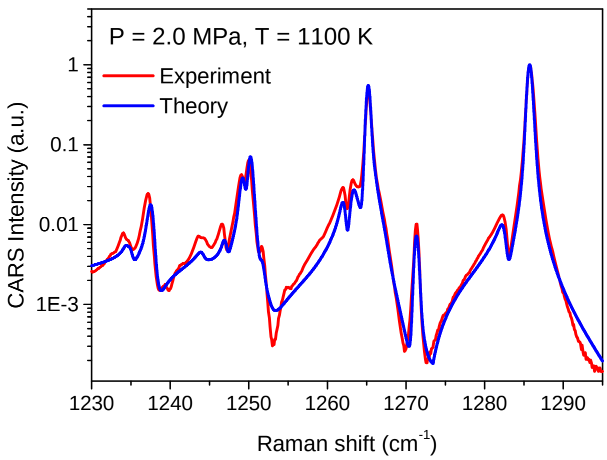

Figure 1 : Comparison of experimental and theoretical CO_2 CARS spectra at T=1100 K and P=2.0 MPa.

The objective of the ***Work Package 2*** is to perform an experimental investigation of various lean combustion injection systems (Lean Premixed Pre-vaporised –LPP-, Lean Premixed –LP-, Lean Direct Injection -LDI-, Multipoint Staged Fuel Injector, lifted flames, etc). They are either existing injection systems from previous programs (e.g. LOPOCOTEP) or new configurations designed, optimised and manufactured through the WP3.
Highly instrumented experimental campaigns have been carried out under realistic conditions (pressure up to 22 bar and high temperature). Advanced experimental diagnosis developed in the WP1 were applied and complemented by more conventional measurements like gas analysis for instance.
The whole set of measurements permit to have a complete evaluation and understanding of the system performances: Spray characterisation, pre-mixing, pre-vaporisation, combustion process and efficiency, NOx emissions, particulates, radiation, lean extinction limit.

The main achievements concerning the isothermal characterisations are:

- The study the aerodynamic of centripetal swirlers. The discharge coefficient has been evaluated, the mean exit flow angle has been calculated on the base of velocity measurements and LDV traverses have been performed at the mixing tube outlet in order to characterize the exit flow pattern.
- The characterisation of the Snecma multipoint injection system : Full characterisation of two-phase flow at atmosphere & ambient temperature LDA & PDA. Characterisation at IDLE operating point (4 bar, 500 K). PDA characterisation at equivalent 100% OACI operating point (13 bar, 500 K).
- A complete characterization of jet in a crossflow test device led to the formulation of empirical correlations of jet trajectory, opening angle. A jet model was elaborated and validated against experimental results showing a remarkable good agreement. The model was then implemented in a 3D CFD code. Performances of multipoint injection in a premix duct were studied exploiting a purposely built test facility.
- The aerodynamic characterisation of an LPP injector has been conducted. A complete set of data about the air flow field within and downstream the injector has been acquired, in order to point out a fuel injection modality optimisation. Several fuel injection modalities have been tested and analysed. A multipoint injection has been individuated in order to achieve a better evaporation and distribution of the fuel droplets within the combustion chamber.
- Drop size measurements (Mie scattering with a Malvern instrument) downstream from a LP injection system according to air pressure up to 20 bar. 2 test campaigns (basic then improved set-up) with several test conditions (air pressure, temperature & flow rates, kerosene flow rates). Always too much window pollution for Malvern measurements. Unfortunately, results was not valid.
- Spray characteristics of a jet plain in a cross flow have been measured thank to shadowgraphs and PDA measurements. A correlation have been derived to get the SMD depending on operating condition and hole diameter.
- Aerodynamic studies of interaction between swirl flow and cooling flows. Thermal investigations of the influence of swirl flows on the cooling effectiveness of cooling flows.

The second part of the work package concerns the combustion tests:

- Multipoint injection system have been characterised thank to OH LIF and kerosene LIF and LII (soot) up to 20 bars. CARS measurements give flame temperature level in realistic conditions. The gas analysis demonstrates a high reduction of N0x emission with a status around CAEP6 – 65%.
- Based on an experimental parametric studies in partially prevaporized lean spray flames, design criteria for low NO LDI combustion systems were developed. Emission testing (NOx, UHC, CO)

of an according to the generated design criteria modified (performed by RRD) RRD LDI burner has been carried out.

- Experiments on both attached and lifted flames have been performed. Determination of isothermal flow field and measurement of emissions under high pressure conditions have been done. Due to high thermal load during pressure conditions (up to 18bars), a new optically accessible experimental setup was designed. Exhaust and optical measurements at elevated pressure were performed.
- After a first test campaign at DLR on 3 existing LPP injection systems, Turbomeca designed and manufactured 2 new injection systems on the base of the first campaign results. Theses optimized injection systems have been characterised by laser techniques and gas analysing.

Based on the experimental characterisations and on extrapolations to full annular combustor, all the industrial configurations reached an important NOx emission reduction. However, further improvements are needed to improve the operability of these technologies. The following table sums up the status of the injection technologies investigated in TLC :

	Application targeted	NOx emissions	TRL demonstrated in TLC	Further improvements needed
SN : multipoint	Single Annular Combustor for medium engine	37.2% CAEP2 limit (1 engine)	TRL 3-4 : single sector in realistic conditions Up to 20 bars	Idle condition, Altitude relight, Internal cokefaction
RRD : LDI	Single annular combustor for small/ medium size engines	Technology capable for NOx < 40% CAEP2	TRL 3-4: single/ multi sector testing (TRL5-6: supports injector-combustor optimisation)	Pilot only performance, lean burn combustor integration, thermoacoustics
TM : LPP smal engines	Single Annular Combustor for small engine (helicopter…)	Estimation : ≈50% reduction compare to currrent engine	TRL 3-4 : single sector in realistic conditions Up to 10 bars	• Demonstration on annular combustor (Newac project) • Optimisation NOx/CO • Internal cokefaction
AVIO : LPP aero engine	Single annular/reverse combustor for small engine	50% reduction respect CAEP2	TRL 3 : single sector up to 20 bars	Idle condition, Altitude relight

The high quality measurements produced in this work package constitute a large support of experimental data to understand the lean combustion phenomena and to calibrate CFD codes.

The key objective of the ***Work Package 3*** “Lean injection systems – design and optimization” is to apply optimization methods for low emission injection systems in order to improve the performance of the current combustion technologies. The main focus of the optimization is to reduce NOx emissions while keeping all other emissions at a low level. Furthermore, no deterioration for other performance aspects e.g. operability, lean blow out behaviour, combustion efficiency etc. has to be shown.
An important part of the tasks within WP 3 is to demonstrate the applicability and effectiveness of optimisation methods applied for lean injection systems. Based on the results of the injector combustor optimization design criteria will be derived for lean injection systems using either combined experimental/ numerical investigation or empirical/ systematic approaches.

Five different fuel injector/ combustor applications have been investigated within WP 3 by means of CFD and partially by the use of optimisation techniques:

- multi-point injection (task 3.1), Snecma/ Onera-Defa
- lean premixed and prevaporized (LPP) injectors (task 3.2 and task 3.4), Avio/ Genova University
- lean direct injection (task 3.3), RRD
- Trapped Vortex Combustor (task 3.5), Avio/ IMP/ DMA
- lifted flames (task 3.6), MTU/ EBI

An overview of the different low emission combustion concepts is shown in Figure 2.

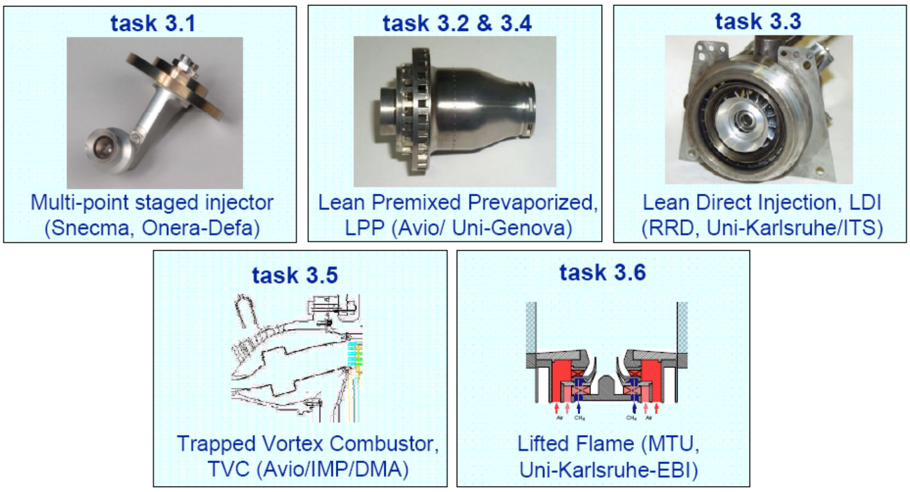

Figure 2 : Fuel injector/ combustion designs investigated within work package 3 of the TLC project

New lean combustion designs have been derived based on a significant number of “isolated” CFD simulations or even via numerical optimizations. Overall, all efforts have lead to a noticeable improvement of the new fuel technologies compared to the baseline designs.

Across all design variants investigated within WP 3 the applied CFD models seem to be feasible to predict a NOx reduction potential of the baseline designs and this was demonstrated via combustor rig testing. However, CO emissions/ combustion efficiency still needs to be addressed in further design iterations, especially during low and part power operation of the (staged) lean injectors.

The scope of the ***Work Package 4*** was the calibration of CFD tools (RANS or LES codes, combustion and emission formation models) for the purposes of combustion and emission prediction and to acquire or assess prediction capabilities.
Choice was made not to carry out numerical developments. Development activities are largely covered in recently completed or still on-going projects, like TIMECOP.
Numerical simulations on injection systems and tubular combustors were performed in parallel. The range of calculations was RANS, URANS and LES, gaseous or two-phase flow, reactive or nonreactive.
In this frame, developments realized in recently completed European Programs like CFD4C (physical modeling) and MOLECULES (unsteady calculations) were exploited as much as possible.

First, the various numerical predictions partially calibrated on the experimental results permitted to get a deeper understanding of the behaviour of the various injection systems tested and of the main physical phenomena occurring.

Secondly, the comparison of the numerical calculations with experiments offered an indispensable assessment of the current numerical capability to predict combustion, pre-mixing and pre-vaporization, pollutant and some operability features.
Numerical simulations exploited the numerous experimental results of WP2. Comparisons with experiments made it possible to assess the ability of the codes to correctly predict the system's performance characteristics under all operating conditions. RANS were used to help design optimization. Unsteady CFD (URANS, LES) were also carried out for better analysis.

From the results and discussions, the following general conclusions can be made:

- The calculation mesh must be chosen very carefully because different meshes can give results drastically different. Unstructured meshes composed by tetrahedral cells give problems at wall and difficulties in the convergence. Hybrid meshes, composed by both tetrahedral and hexahedral (near the walls) work better.
- Non-reacting gaseous turbulent flows are correctly predicted by most models, either RANS (for the average flow) or LES. RANS results are sensitive to the turbulence model and extensive parametric studies have been made. LES results compare very well with experimental data on both mean and fluctuating flows.
- Comparisons for the liquid phase show that RANS results give correct trends and flow structure. However only LES results agree well with the measurements on velocity profiles (mean and fluctuating).
- The Eulerian and Lagrangian approaches for the liquid phase give the same results and none of the two methods can be said superior.
- Reacting cases (RANS only) give access to the flame structure with again a correct trend. However quantitative comparison with experimental data show that the simulations fail to predict emissions (CO and NOx).

Numerical simulation appears to be more and more performant, in particular the LES approach which is truly predictive. Efforts on the development of such tools and their application to industrial configurations must be continued, in particular : the description of the flame chemistry needs to be improved to allow a correct prediction of emissions important missing features are the description of the atomization of the liquid, which has a great impact on the flame structure heat transfer must be better described, including conduction in the solid walls and radiation.

Publications

Date	Authors	title
mai-07	Christian H. Beck, Rainer Koch, Hans-Joerg Bauer	INVESTIGATION OF THE EFFECT OF INCOMPLETE DROPLET PREVAPORISATION ON NOX EMISSIONS IN LDI COMBUSTION SYSTEMS
mai-07	Paris A. Fokaides , Plamen Kasabov, Nikolaos Zarzalis	EXPERIMENTAL INVESTIGATION OF THE STABILITY MECHANISM AND EMISSIONS OF A LIFTED SWIRL NON-PREMIXED FLAME
October-07	Paris A. Fokaides , Plamen Kasabov, Nikolaos Zarzalis	EXPERIMENTAL INVESTIGATION OF THE STABILITY MECHANISM AND EMISSIONS OF A LIFTED SWIRL NON-PREMIXED FLAME
janvier-08	Elizaveta Ivanova, Berthold Noll, Massimiliano Di Domenico, Manfred Aigner	Improvement and Assessment of RANS Scalar Transport Models for Jets in Crossflow
juin-08	Edward Canepa, Pasquale Di Martino, Davide Lengani, Marina Ubaldi, Pietro Zunino	RADIAL SWIRLERS AND MIXING TUBE ASSEMBLY AERODYNAMICS AND PERFORMANCE PARAMETERS EVALUATION PART 2 LDV MEASUREMENTS AT THE MIXING TUBE OUTLET
juin-08	Edward Canepa, Pasquale Di Martino, Davide Lengani, Marina Ubaldi, Pietro Zunino	RADIAL SWIRLERS AND MIXING TUBE ASSEMBLY AERODYNAMICS AND PERFORMANCE PARAMETERS EVALUATION PART 1 HOT-WIRE MEASUREMENTS IN THE SWIRLER EXIT PLANE
July 2008	Grisch F., Orain M., Rossow B., Jourdanneau E., Guin C.	Simultaneous equivalence ratio and flame structure measurements in multipoint injector using PLIF
septembre-08	Stefan Freitag, Christoph Hassa	SPRAY CHARACTERISTICS OF A KEROSENE JET IN CROSS FLOW OF AIR AT ELEVATED PRESSURE
septembre-08	Bellofiore A., Di Martino P., Lanzuolo G., Ragucci R.	IMPROVED MODELING OF LIQUID JETS IN CROSSFLOW
septembre-08	A. Bellofiore, A. Cavaliere, R. Ragucci	PIV Characterization of sprays generated by crossflow injection in high-density airflow
mars-09	M. LARAIA, M. MANNA, S. COLANTUONI and P. DI MARTINO	A multi-objective design optimization strategy as applied to pre-mixed pre-vaporized injection systems for low emission combustors
juin-09	R. Ragucci, A. Bellofiore, A. Picarelli, A. Cavaliere	Statistical Analysis Procedures for Morphological Investigation of Jet in Crossflow Images
juin-09	Matthias Kern, Paris Foaides, Peter Habisreuther, Nikolaos Zarzalis	APPLICABILITY OF A FLAMELET AND A PRESUMED JPDF 2-DOMAIN-1-STEP-KINETIC TURBULENT REACTION MODEL FOR THE SIMULATION OF A LIFTED SWIRL FLAME
juin-09	Plamen Kasabov, Nikolaos Zarzalis	PRESSURE DEPENDENCE OF THE STABILITY LIMITS AND THE NOX EXHAUST GAS CONCENTRATIONS IN CASE OF SWIRL-STABILIZED, DIFFUSION FLAMES BURNING IN A LIFT-OFF REGIME
juin-09	Ivanova, E., Noll, B., Di Domenico, M., Aigner,	Unsteady Simulations of Flow Field and Scalar Mixing in Transverse Jets
July 2009	Orain M., Grisch F., Jourdanneau E., Rossow B., C. Guin, B. Tretout	Investigation of performances of innovative aeronautic injection systems using advanced laser diagnostics
juin-10	S Ochoa, A Sanchez, N Fueyo	Subgrid Linear Eddy Mixing and Combustion Modelling of a Turbulent Nonpremixed Piloted Jet Flame
juin-10	S Ochoa, N Fueyo	Structure of turbulent nonpremixed piloted flames obtained by a subgrid linear eddy model