ENVIRONMENTAL CONSTRAINTS AND APPROPRIATE R&T STRATEGY FOR COMBUSTOR TECHNOLOGY

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Abstract

Aviation emissions have potentially an impact on both local air quality and the global green house effect. Although air-traffic is increasing, technology improvements should allow to mitigate these impacts in the future. The first part of this paper reminds the environmental constraints concerning gaseous and particulates emissions which the aviation industry will increasingly have to confront . The second part presents the main promising innovations relating to SNECMA Moteurs combustor technology.

1 Introduction

Air traffic is one of the anthropic sources that produces gaseous emissions and particulates. These pollutants contribute to air quality deterioration and climate change. Recent ICAO estimates [1] give a yearly average air-traffic growth of 4.1% in passenger per kilometre transported until 2020. This implies an increasing effort to integrate environmental constraints in the aircraft engine design and optimisation. The combustor technology is a key element of this strategy. The first part of this paper draws a status of the current situation and of main environmental issues linked to aviation. The second part describes the most promising solutions related to combustor technology. It ranges from conventional single annular combustor technology improvement to more innovative solutions based on lean combustion concepts.

2 Aviation emissions environmental constraints

2.1 Aero-engines emissions

Aero-engines emissions are the product of air-kerosene combustion. Carbon dioxide (CO2) and water (H2O) are the main gaseous emissions. Their production is directly proportional to aircraft fuel-burn. Nitrogen oxides (NOx), unburned hydro-carbons (UHC), carbon monoxide (CO) and sulphur dioxide (SO2) are species produced in smaller quantities. SO2 is linked to the fuel sulphur content. Exhaust gases also contain small quantities of carbonaceous particulates. These particulates may adsorb a part of above-mentioned sulphur and organic compounds.

The emission of a given species is defined by its emission index (EI). It is the average mass produced per fuel mass unit measured at the engine exit. It is linked both to combustor technology and to the engine cycle (in particular Overall Pressure Ratio, OPR, and Fuel Air Ratio, FAR). The engine production rate of the species is the fuel mass flow times the EI. The following table gives typical values of emissions indices (in g/kg) representative of current engines for different flight phases. Typical ranges of specific fuel consumption (sfc) are also provided.

	Idle	Take-Off	Cruise
sfc (kg/kN)	[0.010, 0.026]	[0.008, 0.013]	[0.015, 0,018]
CO2	3160	3160	3160
H2O	1230	1230	1230
SO2	1	1	1
NOx	[2.5, 6.2]	[13.2, 61]	[8, 18]
CO	[10.3 , 49.7]	[0.02, 4.48]	[1.0, 3.5]
UHC	[0.06, 10.35]	[0. , 0.2]	[0.2 , 1.3]

Table 1: aero-engines typical emission indexes

The following figure shows the amount of NOx produced in the vicinity of airports versus the maximum take-off thrust (F00).

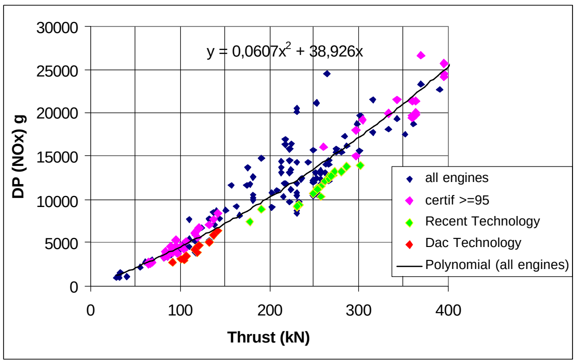

Fig. 1. NOx LTO mass against F00 (ICAO data bank)

This amount is calculated using the LTO cycle (Landing and Take-Off) which is recalled in section 2.3. Input data for the figure is provided from the ICAO engine exhaust emissions data bank. The fact that the NOx mass increases more than linearly with the thrust is the result of an increase of design OPR with engine maximum thrust. However it highlights the benefit of the continuous technological improvements of conventional SAC (Single Annular combustors) and of the introduction of the DAC (Double Annular Combustor) technology on the GE/ Snecma Moteurs CFM56-5B and –7B engines. The low emission level of some older engines is due to their moderate OPR which is lower than modern engines but this implies a higher fuel consumption.

Figure 2 shows the distribution of the amount of each emitted species over the 4 LTO cycle ratings. NOx is produced mainly during climb and take-off whereas CO and UHC are mainly produced at the lowest rating (idle during taxi phase).

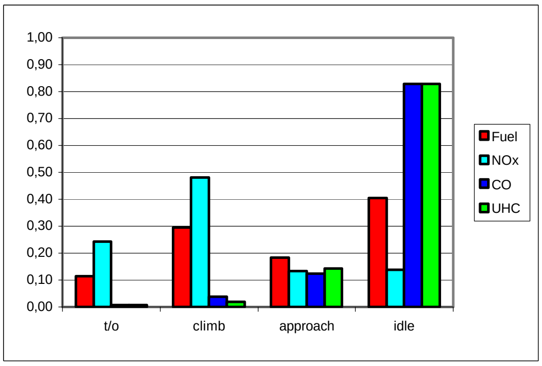

Fig. 2. Emissions for each LTO regime (%)

Particulates are generated mainly at high power. A typical size distribution is given on Fig. 3. It was obtained by SMPS (Scanning Mobility Particle Sizer) measurements on a SNECMA Moteurs combustor. Note that particulates may still evolve inside the turbine and in the exhaust plume, with agglomeration and/or condensation of volatile organic compounds.

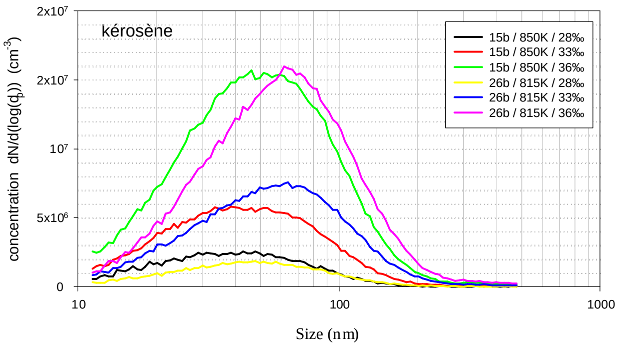

Fig. 3. Particulates size distribution on Snecma Moteurs prototype combustor

Essential is to state that for a given engine cycle, gaseous species production and particulates formation depend on the quality of the combustion and so on combustor technology.

However, fuel composition is another relevant parameter. In particular, higher H/C ratio is beneficial for NOx (as observed in [2]). Higher aromatic content increases the formation of particulates and fuel sulphur has an effect on their hydrophobic properties.

Fuel composition is a potential important levy which still needs to be quantified. Fig. 4

illustrates some current observations concerning the aromatic content.

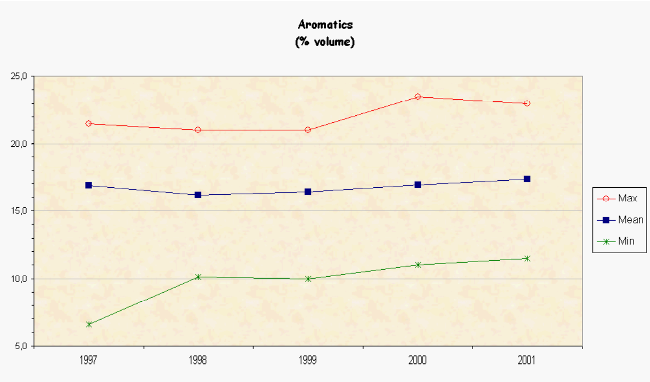

Fig. 4. Evolution of fuel aromatics content (SEA)

2.2 Environmental impacts

The two main environmental impacts of aviation emissions are on air quality (local impact) and on climate change due to the green-house effect (global impact).
Air quality is affected by pollutants emitted mainly in the atmosphere boundary layer even if some exchanges may occur with the free troposphere. These are principally CO, UHC, NOx and particulates. NOx and UHC have some direct effect on health but contribute also to the formation of ozone (O3). Aviation emissions during cruise, in the upper troposphere lower stratosphere contribute to green house effect. CO2, H20 (water vapour) are well known green-house gases. NOx has an indirect effect through ozone formation and methane destruction but the budget indicates a positive green house effect. Finally, investigations are carried out to assess contrails and aviation particulates induced cirrus..

Either locally or globally, aviation is one among many anthropic sources. Some research and investigation is still necessary to better assess the impact of aviation for both effects.

The contribution of aviation to climate change has already generated considerable studies in particular in Europe. The completed *Trade-off* project has suggested some up-dated results from the IPCC 99 [3] conclusions. Fig. 5 (from [4]) recalls a current status. We highlight here two statements from [4] based on the AAC conference (Aviation Atmosphere and Climate) which took place in 2003 [10]: a) the global warming potential is inadequate (e.g. for NOx) and radiative forcing concept is preferred to quantify green-house effect. b) Aviation particulates induced cirrus are believed to be potentially one of the major aviation contributor to green-house effect but significant uncertainties remain as illustrated in Fig. 5.

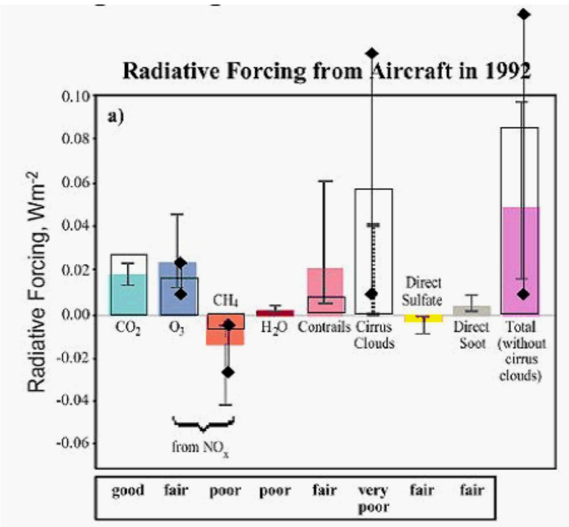

Fig. 5. RF from air traffic in 1992 from IPCC (1999; colored columns and bars with vertical end-lines) and revised estimates (white columns and bars with end-diamonds) based on recent research results (TRADEOFF and AAC conf.)

This clearly requires further investigation. The recently initiated European project *Quantify*, will pursue some studies dedicated to aviation and in addition will try to quantify the relative part of each means of transport on global climate change. But some gaps are not covered. In particular, the effort to predict particulates evolution in the aircraft/engine plume in no-contrails ambient conditions may be an important progress to clarify the cirrus cloud conjecture.

Air quality impact assessment requires both precise inventory, and dispersion modelling (including chemistry) at local and regional scales. Today, the relative weight of aviation is principally measured in term of total mass of pollutant emitted (inventory) which is done with satisfactory accuracy for gaseous emissions. Dispersion modelling application is much more complicated in particular for ozone formation prediction: it is necessary to include all the NOx and UHC sources, not only from aviation, at the regional scale and to have even speciation of UHC. Other open issue is the particulates. The appropriate characterisation of particulates for the effect on health is not yet defined and the associated measurement methodology is to be proposed.

Fig. 6 gives a breakdown of all CO2 transport sources and illustrates the relatively limited contribution of aviation. Table 2 gathers estimations from IPCC 99 [3] based on some air-traffic growth scenario.

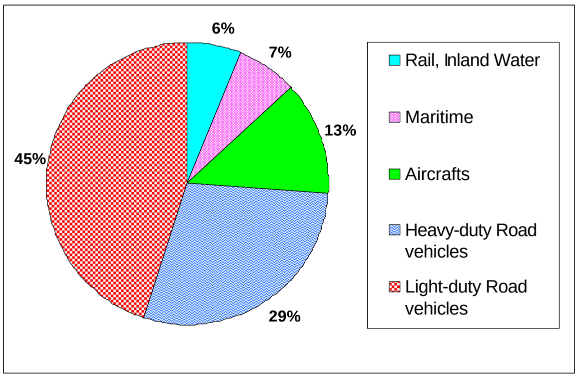

Fig. 6. CO2 from different transport sources

	1992	2050 (*)
aviation CO2 total mass (GtC/an)	0,14	0,4
% CO2 anthropic	2	3
% CO2 all transports	13	?
aviation Radiative Forcing (**) (W/m2)	0,05	0,19
% RF anthropic	3,5	5,0

Table 2: IPCC 99 estimations for aviation ; (*): Fa1 scenario ; (**) all emissions excluding particulates

To conclude this brief overview on environmental impacts and the specificities of aviation, we believe that in addition to CO2 and NOx reduction priorities , concerns linked to the impact of particles on the climate change and health may become more critical in the near future. The development of lean combustion concepts that allow a simultaneous reduction of NOx and smoke emissions has been favoured by SNECMA Moteurs.

2.3 Regulation

International regulation is one means to guaranty that the most recent technologies put into service meet a level of requirements compatible with emission control policy. The International Civil Aviation Organisation (ICAO) defines it and makes it evolve. The current standard is based on concern for air quality and addresses NOx, CO, UHC and soot emissions. The standard definition is based on the ICAO Landing & Take-Off cycle (LTO). Actual aircraft operations in the airports vicinity up to 3000 feet (atmosphere boundary layer estimated limit), are ideally broken down in 4 phases with the corresponding engine ratings (referring to maximum take-off thrust F00) and times in mode: take-off (100%), climb (85%), approach (30%) and idle or taxiing (7%). Emissions certification tests data provide the fuel flow and the gaseous emission indices at the exit of the engine for these 4 points. The total mass DP of each gaseous pollutant emitted on the LTO cycle is then derived. The resulting certification parameter DP/F00 should be below a given limit depending on the engine OPR. The dependency of this limit to the OPR has been introduced to take into account a necessary trade-off between fuel consumption improvements and NOx emission control.

The standard has evolved regularly following propositions from the ICAO Committee on Aviation Environmental Protection (CAEP). “CAEP2” standard applied to engines newly certified since 1996, “CAEP4” to engine newly certified since 2004. Recently, “CAEP6” has proposed a more stringent NOx standard for engines, which will be certified in 2008 and after. The proposed reduction is 12% from CAEP4.

Fig. 7 presents the evolution of the NOx regulatory limit and the position of engines (in production and under development) in terms of DP(NOx)/F00. Important observations may be drawn:

- A clear increase of stringency since 1986 whereas the CO, HC and smoke limits have remained unchanged .

- the trend that DP/F00 increases with OPR is illustrated by the general distribution of points.
- Many current modern engines do not pass the future CAEP6 limit. This is an incentive for aero-engine manufacturers to develop and introduce new combustor technology.

Currently, optimised conventional combustor technology has been developed and already implemented on some certified engines. It is the case for the GE LEC, the RR Phase 5 and the P&W Talon II technologies. The Snecma Moteurs SM146 engine, which will be certified in 2006, relies on similar improvements. Intensive use of 3D modelling during combustor design phase has enabled airflow distribution and dilution hole pattern optimisation. The first tests of the combustor in the K11 CEPr test bench confirmed the ability to meet CAEP6 NOx limit with a good margin and ahead of time. The un-equalled margin of CFM56 DAC (double annular combustor) engines is also to be noted. A technology, based on fuel staged lean combustion like DAC combustors but in a single annular architecture (TAPS combustor) has been experimented by GE on CFM56 and represents a promising medium/ long term solution for high OPR engines.
The European project CLEAN (described in §3 and involving Snecma, MTU, Avio) also has long term more ambitious objectives.

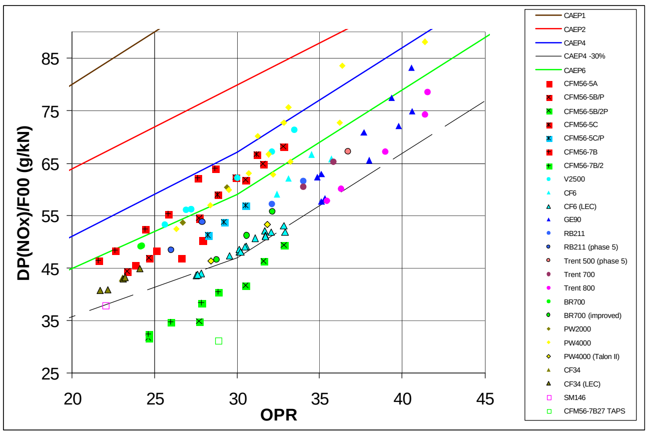

Fig. 7. In production certified engines

On-going evaluation is carried out at ICAO to consider better cruise emissions and their impact on the green-house effect.

The SAE ARP-1179 filtration method is used for measuring exhaust smoke. But weakness of the smoke number (SN) as a measure of particulates emissions, is recognised and future work will investigate a more appropriate characterisation with the help of the SAE E31 committee.

2.4 Environmental impact minimization strategy

In order to anticipate further regulation evolutions and to fulfil public expectation in term of environmental performance, SNECMA Moteurs aims at integrating environmental constraints in their design process without jeopardizing operability performance.
Above all, it is essential to note that significant progress will be achieved not only by working on engine technology (cycle, components efficiency, combustor technology) but also on the aircraft performance, on the operational practices and air-traffic management. The long term ambitious goals of ACARE [5] strongly rely on such an integrated approach.

When reducing the total NOx produced in the vicinity of the airport ($DP(NOx)_{LTO}$), or total NOx produced over an entire mission ($DP(NOx)_{cruise}$), formulae expressing the mass of pollutant in terms of the engine performance and the aircraft performance is a useful guide in the optimisation process. It shows where to focus efforts. For this, we use the Breguet approximation (similar approach in [6] and complete analysis in [7]) and other simplifying assumptions (constant cruise altitude, constant cruise velocity, cruise fuel burn close to mission fuel burn). We have chosen a given mission defined by the payload to be transported (PW), the range (R), and the cruise velocity (V_c). Engine performance is described by cruise specific fuel consumption (sfc_{cruise}), cruise average NOx emission index ($\overline{EINOx}$) and the certification parameter DP/F00 (where DP=

NOx mass over LTO cycle). Aircraft performance is described by Cd/Cl (= drag coefficient of the plane / lift coefficient) and the structural factor α (=aircraft structure weight / maximum take-off weight MTOW). Gravity is noted g and λ is a coefficient of proportionality. Then we obtain :

$$DP(NOx)_{LTO} = \lambda \times \frac{DP}{F00} \times MTOW$$

$$DP(NOx)_{cruise} = \overline{EINOx} \times MTOW \times [1 - \exp(-\frac{R}{\chi})]$$

$$MTOW = PW / [\exp(-\frac{R}{\chi}) - \alpha]$$

$$\chi = \frac{Cl}{Cd} \times \frac{V_c}{sfc_{cruise} \times g}$$

Although these quantities are estimates, they show very well qualitatively, at least at the engine level, what may be beneficial in reducing NOx at LTO or during cruise for the same mission performed. It justifies in particular the indirect positive effect of lowering sfc (if not balanced by too high an increase of combustor emission index).
The minimisation of environmental impact at the engine level depends on the cycle choice and on the combustor technology. Any progress on the performance of other components (compressor and turbine efficiencies, weight) will have however, positive consequence on pollutant emissions reduction.

In the general optimisation of the engine design, environmental considerations are included as constraints. Trade-offs may naturally appear and cannot be ignored. The most frequently addressed are : (fuel consumption/ NOx) equivalent to (CO2/NOx), (NOx/CO&UHC) and finally (Noise/NOx). It must be underlined that:

- CO2/NOx and Noise/ NOx trade-offs are mainly linked to cycle choices
- NOx/CO&UC trade-off is mainly linked to combustor choices combined with cycle ones
- Clear definition of environmental priorities are necessary to solve some of the trade-offs.

A rational approach for the (fuel consumption/green-house effect) trade-off management is proposed in [8]: First the design minimizing a cruise sfc is chosen as reference. Then the idea is to minimise the green-house effect when authorizing a small increase of sfc (δsfc). This is done by optimising **all** the engine design parameters. The output of the analysis is a simple curve δgreen-house effect = f(δsfc).
The results obtained in [9] should be considered cautiously because the engine modelling includes simplifications and because of the use of global warming potential to evaluate the green-house effect. However the approach is valuable in general and could be applied to other trade-offs (e.g. NOx(LTO)/fuel consumption).

SNECMA Moteurs has the objective to include more and more environmental constraints in the engine cycle optimisation process. In parallel, improvements of the combustor technology offer the possibility to progress further and to solve some of the conflicts that may appear between environmental objectives.

SNECMA Moteurs has chosen the lean combustion technology pathway, as this is the most promising solution to reduce simultaneously both NOx and particulates over LTO cycle and in cruise condition. The challenge of lean combustion is to cope with low regimes requirements: combustion efficiency, lean blow-out limits and relight capabilities.

This is illustrated by Figure 8 that compares NOx and CO emission indices over the whole engine thrust range for a conventional combustor (with OPR around 30) and an ideal Lean Premixed Prevaporized concept (LPP) with the same engine cycle base. The LPP advantage is obvious for take-off and climb. At low rating, stability becomes more critical and

CO or UHC emissions increase significantly. Besides combustor architecture solutions, fuel staging should contribute to mitigate this difficulty.

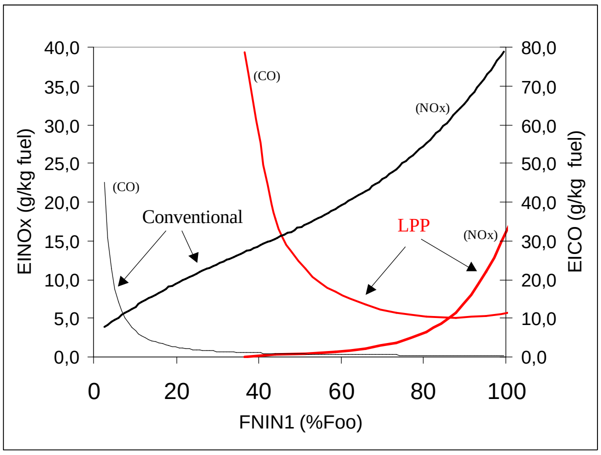

Fig. 8. Lean combustion expectation

3 Low emission combustor technology R&T

It is now well recognized that the classical current in-service combustors, or their optimisations, will not have the capability to satisfy the challenging environmental concerns described previously. A technological mutation / revolution resulting in an important and continuous efforts in research and technology (R&T) focused on the combustor architecture and the fuel injection system has been undertaken by all the aircraft engine manufacturers.

Contrary to the development of the previous generation where numerous experimental tests at different scales were conducted and where the experience was synthesised into inviolable design practices, the next generation of combustors and injection systems will integrate more directly fundamental knowledge at the early stages of the design. Secondly, to reduce the number of tests, intensive use of appropriate numerical methods will be devoted to the evaluation and the optimisation of these new concepts. Use of 3D tools will contribute to make design practices more flexible too.

The following paragraph refers to aspects of conventional SAC technology and then describes and illustrates the leading principles of the R&T strategy followed by SNECMA Moteurs in the development of new low emission combustors.

3.1 Classical design process for classical combustors

Most current in-service combustors are Single Annular Combustors (SAC) equipped with conventional injections systems (with airblast or aeromechanical fuel nozzle), feeding a primary zone axially limited by a first row of dilution holes. The combustion is initiated in the primary zone and completed downstream in the dilution zone. The air going through the second row of dilution holes quenches the chemical reactions. combustion efficiency and NOx emission are highly linked to airflow distribution and secondary dilution holes location and pattern. All the engine manufacturers have designed them using quite similar procedures. This procedure starts after the thermodynamic cycle is specified, and deals with three main issues: operational (airworthiness), environmental, economical (Fig 9).

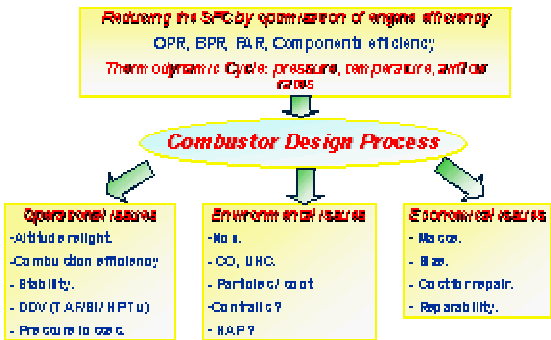

Fig. 9. Principal issues linked to combustor design

A very important airworthiness issue consists in meeting the wind milling restart domain specifications. It defines the primary zone volume and airflow distribution. Next, the combustor volume and length are chosen to comply with efficiency requirements. Cooling and dilution systems are fitted to ensure the durability requirements for turbine and combustor. Few degrees of freedoms are left to comply with the environmental requirements.

Let us focus on the problem of windmilling altitude relight. For a given altitude the windmilling restart domain lies between two Mach numbers (Fig. 10) $M_a^{\min}(Z)$ and $M_a^{\max}(Z)$. Passing through the compressor, those limits are transformed into limits for air mass flow rate, pressure and temperature at the combustor inlet corresponding to two completely different fundamental problems.

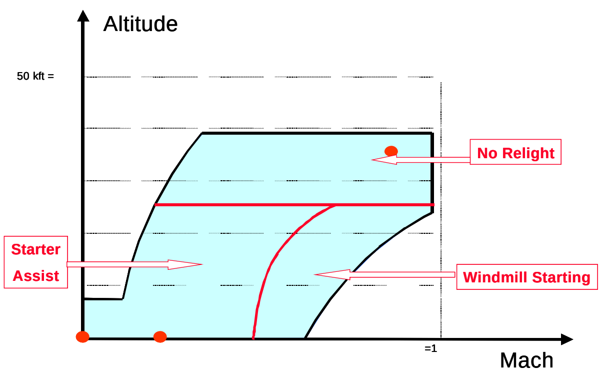

Fig. 10 Example of altitude restart domain

- case 1: $M_a^{\min}(Z)$

Since air mass flow rate is very low, the value of pressure drops through the primary holes and through the liner are very slight. As a consequence, atomisation performance of the injection system is generally deteriorated even for pressure atomizing systems, and mixing is of poor quality due to the lack of turbulence production. Combustion performance is then very poor. So, increasing the primary zone volume leads to a higher residence time and consequently to a better flame stability.

- case 2: $M_a^{\max}(Z)$

Air mass flow rate is very high, there is no problem related to the quality of atomisation. Turbulence levels are so high that the stretch imposed to the flame by turbulence can lead to partial or complete blow out. In contrast with the previous case, the mean residence time is now very low. But as for case 1, increasing the primary zone volume is the solution for improving flame stability.

Once the flame has been ignited and stabilised inside the combustor it is necessary to ensure a sufficiently high combustion efficiency for the engine to accelerate (combustion efficiency must be high enough for the turbine to overcome inertia of the rotating parts of the engine and aerodynamic loads on compressor blades). Increasing the combustor length results in combustion efficiency improvement. Global combustor volume also sets the mixing performance that is important to meet the required exit temperature profiles in order to ensure an acceptable turbine durability.

Design practices available for this task, synthesize past experience gained through previous developments and through continuous acquisition of knowledge. Those rules give -as a function of the percentage of air flowing through the injection system- the volume that is needed for the primary zone to succeed in ignition and stabilisation of the flame for all restarting requirements in engine windmilling conditions. The volume and the length of the combustor are laid out to meet combustion efficiency requirements. The design criteria are based on aerodynamic loading considerations.

Within the classical design procedure, some major geometrical features of the combustor are selected to satisfy operability specifications (start and relight altitude capabilities), but remain irrelevant for pollutant emissions, mainly NOx and Soot emitted at take-off, climb and cruise. **The primary zone volume and combustor volume are set at the beginning of the design, thus leaving little room to include**

these parameters in the NOx emissions reduction strategy.

Based on design criteria coming from analysis of quite similar combustors, the application of classical design rules can only lead the designer to classical combustor, that is not necessarily optimised for the reduction of NOx and soot. Emissions requirements may lead the designer to break established rules in some situations, which is the key to success in innovation.

Under the thermo chemical conditions of aeronautical combustors at climb or take-off it is well established that the prevailing NOx formation mechanism is a thermal one, which is piloted by local temperature and the residence time of the mixture inside zones where temperature is high (>1850K). Moreover NOx is not an equilibrium product for combustion inside classical aeronautical combustors. All the in-service engines use liquid injection into the combustor which leads to the occurrence of stochiometric combustion mainly because the processes of injection, atomisation, evaporation, mixing and combustion all occur together and there is no means to control the way the combustion will work and proceed. Unfortunately the kerosene stochiometric flame temperature is around 2500K. So there is a constant possibility of getting very high NOx emissions mainly from the thermal mechanism.

The stochiometric reaction zones are formed for all the ratings of the engine but it is clear that the volume occupied by those zones inside the combustor is much higher in the case of high ratings of the engine corresponding to take-off, climb and cruise than in the case of low ratings corresponding to idle. Moreover in the latter cases the environment of the flame is mainly composed by fresh air, and the opportunity exists for the burned stochiometric fluid element to be mixed and quickly cooled.

For high ratings of the engine, if one wants to quench NO reaction rate quickly within hot burned mixture there are two options. The first one is based on the dilution holes localization optimization to improve mixing, while the other one consists in reducing the global residence time inside the combustor. Both options are applied as a medicine after the combustion has proceeded; As the NOx formation rate is very sensitive to temperature, they do not usually have the required potential to yield sufficient NOx reduction margins with respect to future regulations.

Indeed an efficient strategy for thermal NOx emissions reduction should be based on the control of the flame temperature by avoiding / reducing the formation and the combustion of the stochiometric mixture, which can be combined or not with one or both previous means. Note that now the remedy is intended to be applied before the combustion has occurred. Control of the flame temperature is obtained by the control of the equivalence ratio before the combustion of the mixture of fresh gases.

The solution of rich combustion makes stability problems easier to solve but leads to the formation of more soot. Therefore the SNECMA Moteurs development strategy is only oriented towards lean combustion.

Associated with the optimization of the appropriate flow distribution through the combustor, the main levies available to the designer for diminishing and/or suppressing the stochiometric zones inside the combustor and going towards lean combustion are:

- the optimization of the atomization process to reduce evaporation time prior to mixing.

- the increase of the mixing rate of fuel vapours with air by optimizing the aerodynamic field in the primary zone.

- The optimization of the axial position of the dilution holes in order to enhance mixing rate after combustion so as to diminish the lifetime of hot fluid elements.

- The reduction of global residence time inside the combustor.

- The increase of the percentage of air passing through the injection system which contributes directly to the improvement of atomization, evaporation and mixing.

- The increase of pressure losses through the liner to enhance flow dynamic and turbulence production, contributes to improving the mixing. Nevertheless, this strategy needs to minimize the pressure losses of the upstream diffuser, to recover the global thermodynamic performance of the engine, and consequently the level of specific fuel consumption.

- The separation of the combustion process from the other processes, since the major problem comes from the simultaneous operation of mixing and combustion giving rise to uncontrollable non-premixed combustion.

These strategies can be used alone, in a combined manner or all together, depending on the objectives for NOx reduction.

It has sometimes been argued that other mechanisms could prevail over the thermal one. Prompt NO could be the dominant mechanism in a rich premixed combustion and for certain conditions of diffusion flame. Prompt NO formation rate increases with the local equivalence ratio up to 1.4 and with pressure, but only slightly with temperature.

Usually the increase of the reaction rate for the reaction O+N2=NO+N by O radicals overshoot concentrations inside the reaction zone structure for non-premixed combustion, could not be responsible for the major part of prompt NO formation. The main reason is that the temperature levels associated with radical overshoot concentrations are too low for this reaction to be enhanced significantly [9].

The main reaction for the formation of prompt NO is: CH+N2=HCN+N, while the reaction C+N2=CN+N could be a minor contributor at very high temperature [9].

Soot particles are mainly composed of carbon which are formed in fuel rich combustion or by reactions without O2 inside hot temperature zones. As for NOx, soot is not an equilibrium product, then in the exhaust gases the soot concentration results from the difference between two large numbers corresponding to the production of soot in the primary zone and the oxidation of soot downstream from the flow inside the combustor.

Favorable conditions for soot formation are within a larger range of equivalence ratio than for NOx. This domain extends from 0.3 to 4 which corresponds to the higher flammability limit for kerosene. For classical combustors which are stabilised by recirculating partially burned hot gases towards the injection system there are always opportunities for soot particles to be produced in very large quantities. Globally the increase of air affected to combustion tends to reduce soot emissions. So it is important to keep in mind that contrary to other principles, all the previous strategies to reduce NOx by lean combustion, work together with soot emission reduction.

As illustrated previously, solutions which can be considered at one end of the flight envelope are often conflicting with those required at the other. Then the classical process for designing a combustor consists in finding the best compromise between all the conflicting issues to be addressed.

Trends in the future will still probably be to increase the engine OPR, in order to decrease specific fuel consumption. **The combustor inlet air temperature rise will reduce the cooling capacities so that more air will be needed to cool the hottest parts like blades, and in turn the available air for controlling combustion and emissions will be reduced. Therefore, continuously improving the efficiency of cooling techniques as well as using new materials has been drivers for SNECMA**

Moteurs R&T strategy. Operational requirements must be met over a wide range of temperature and pressure. Altitude ignition must be ensured after unscheduled extinction while inlet air is very cold (typically 220K) and pressure very low (typically 0,3bar) for altitudes near 9km. Combustion must be stabilized over a wide range of inlet air velocity and equivalence ratio so as to avoid blow off during engine deceleration.

3.2 Possible strategies to address the trade-off between NOx reduction and operability

As previously demonstrated it appears that all strategies to reduce NOx and soot are at the opposite of what is needed to enlarge the altitude relight domain. So R&T strategies based on lean combustion are all looking to the means to create new degrees of freedom of the system compared with the classical optimization of classical systems.

There are three ways :

- Staged combustion aimed at setting at least two combustion zones inside the combustor, one is optimized for low ratings required performance: stability and altitude relight domain, the other one is optimized for high rating required performance: emissions, temperature profiles…

- Variable geometry concept aimed at varying the combustor airflow distribution with respect to the engine rating.

- Active stability for injection systems aimed at accelerating the chemical reaction for recovering the part of lost stability margins caused by the increase of the air flow rate through the injection system.

In addition to optimization of classical combustors, SNECMA Moteurs is currently investigating all these possibilities taking advantage of the experience gained during the last three decades. Examples of each ones are given hereafter.

3.3 Classical optimization of classical systems

The objective of the DEM21 program was to develop a civil High Pressure core for application to engine of the 90-100 kN thrust class. The corresponding know-how is used for the design of the SM146 engine.

The SM146 engine, developed in cooperation with NPO Saturn, is the turbo-fan which has been selected by Sukoi to power the RRJ airplane.

The DEM21 combustor (see Fig. 11) is a single annular combustor characterized by:

- 18 double circuit fuel nozzles systems associated with an air system mainly composed of two radial swirlers.

- Effusion cooling combined with a thermal barrier coating

- An airflow rate distribution leading to a global equivalence ratio for which the primary zone becomes globally stochiometric at take-off rating.

Some relevant objectives are :

- 25 kfts for the maximum altitude restart domain limited by $M_a^{min} = 0{,}57$ and $M_a^{max} = 0{,}76$
- With reference to CAEP4, -34% reduction for NOx.

The combustor has been tested at ambient pressure (K9 test rig of CEPr), at high pressure conditions up to 30 bar (K11 test rig of CEPr) and at sub atmospheric pressure up to 45Kpa (A06 test rig of CEPr). Finally the combustor has demonstrated good operability during the DEM21 HP core tests.

Fig. 11 DEM21 combustor and the inner liner

3.4 Staged Combustion

The staged combustion function can be achieved through two different means, double annular combustors (DAC) and multi-point injection systems.

In the case of DAC, two domes are put together to constitute the combustor. Usually there is the idle dome which is designed to improve low rating performance (combustion stability, relight capability, CO and HC emissions) and the take-off dome which is designed for high rating performance (NOx emissions, temperature map..) Two physical principles are used during the design process of the take-off dome to reduce NOx emission: reduction of residence time inside the combustor and adaptation of the air flow split to make the combustion leaner.

A double-annular combustor architecture is already in service on the commercial engines CFM56-5B and CFM56-7B (developed and produced by GE and SNECMA Moteurs) with unequalled NOx reduction emissions performance. The experience gained by SNECMA Moteurs on DAC combustors has been achieved through civil commercial engine demonstrators developments, but also through military exploratory developments supported by the French Agency of Defence (DGA).

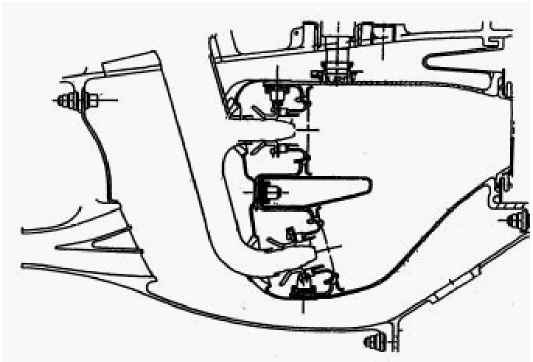

Fig. 12. SNECMA Moteurs DAC combustor demonstrator (civil project PAT - 1997)

As mentioned earlier it is also possible to optimize the air flow distribution in view of increasing substantially the proportion of airflow rate allocated to the combustor dome. The maximum Nox emission reduction is achieved when the fuel is prevaporized and premixed before combustion, and when the maximum airflow rate has been allocated to combustion. Those principles have been developed through the CLEAN project.

In the case of multi-point injection systems there is only one dome and one injection system. There are at least two independent fuel feeding systems, each of them associated to its own air flow rate. It should not be confused with the classical injector also having two internal circuits but only one injection point corresponding to the tip of the injector. Then it is not possible to create in the combustor more than one combustion zone, neither to vary the air flow rate allocated to combustion between high and low rating. For doing that, it is necessary for the injection points to be separated in space and for the air flow rate distribution to be adapted and optimized for each of them.

Examples of multi-points injection systems and DAC combustors are given below.

The CLEAN project

SNECMA Moteurs is a major contributor of the European Project CLEAN (*Component vaLidator for Environnementally friendly Aero-eNgine*), which involves 6 partners. CLEAN ambition is a reduction of 15 to 20 % for CO_2, and of 80 % for NOx compared to CAEP2, for new products entering into service in 2015.

The CLEAN program was built around a high pressure core (under SNECMA Moteurs responsibility) and includes a high speed low pressure turbine and a heat exchanger designed and manufactured by MTU Aero Engines.

SNECMA Moteurs is particularly implicated on two modules : the combustor and the compressor fitted with a stall active control system. To achieve the ambitious NOx target, SNECMA Moteurs, in cooperation with Avio, has explored a new concept of double-annular, axially staged combustor (Fig. 13).

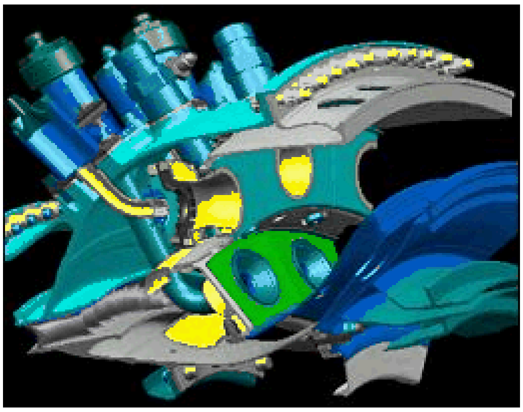

Fig. 13 CLEAN combustor

The great novelty of the Clean combustor is its lean premixed pre-vaporised (LPP) combustion take-off dome. The main challenge of this concept, under research since the 70's, is the risks management of auto-ignition of the fuel or flash-back of the flame in the injection systems.

SNECMA Moteurs has undertaken the development of this new type of injection system under European funding since the 80's and has identified innovative solutions to manage these risks.

More fundamental R&T European projects like LowNOx III (4^{th} FP, coordinated by SNECMA Moteurs) have permitted experience to be gained on LPP technology.

The multi-point injection systems

Through on-going European projects like LOPOCOTEP (5^{th} FP, Low Pollutant Combustor Technology Project) and TLC (6^{th} FP, Towards Lean Combustion) or national projects like ETNA (French Agency of Defence), SNECMA Moteurs is investigating multi-point injection for the single annular combustor. This new concept should be an answer for long term environmentally friendly engines.

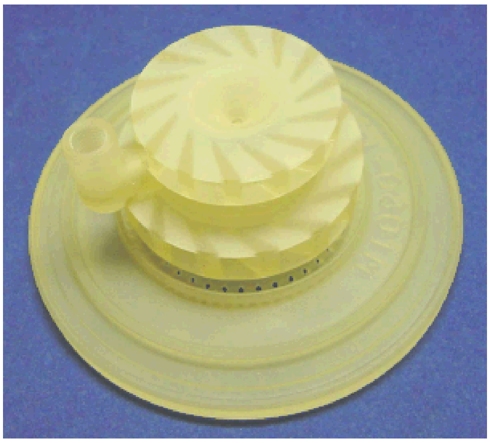

Fig. 14. An example of multi-point injection system

Principles for this kind of injection systems are given on Fig. 15. We can see that two different combustion zones are generated, one for low rating and the other one for high rating. Each of them corresponds to different characteristics for airflow rate and mixing and so exhibits different characteristics for NOx emissions. Premixing levels of fuel vapours with air can be adjusted by acting on the length of the injection system or on the localisation of the take off fuel injection holes.

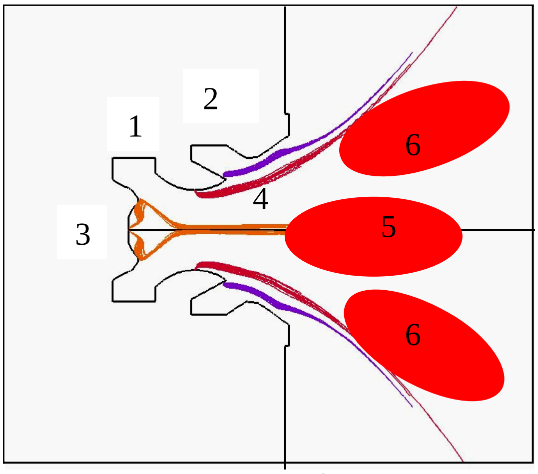

Fig. 15. Basic principles for multipoint injection systems. 1: primary swirler, 2 secondary swirler, 3 fuel injection for low rating, 4 fuel injection for high rating. 5: combustion zone for low rating, 6: combustion zone for high rating

First tests have revealed a very good atomization, even for low pressure losses.

3.5 The variable geometry concept

A SNECMA Moteurs variable geometry concept has been integrated on a single annular combustor. It was characterized by an injection system capable of two states allowing changes for the air distribution between the combustor dome, dilution system and cooling system.

Fig. 16. The SNECMA Moteurs variable geometry injection system multi-sector combustor

A diaphragm for varying air distribution was adapted to the external radial swirler; it modulates the permeability of this swirler between two states. It was made by a circular ring which can rotate to partly block the inlet area of the external swirler.

For the “all open” state, near 60% of the air flow rate is allocated to the dome of the combustor to minimize NOx and soot emissions and to homogenize the exit temperature map.
For the “closed” state, near 35 % of the air flow rate is affected to the dome of the combustor to ensure idle stability and altitude relight capability.

Wall cooling was performed by double wall impingement upstream of dilution holes and effusion with thermal barrier coating downstream from the dilution holes.

A combustor sector of six injection systems has been manufactured and fully characterized at ambient conditions, high pressure conditions (CEPR K11 test rig) and at simulated altitude conditions (CEPR A06 test rig).

K11 rig tests were realized with a combustor inlet pressure varying on the range [10bar, 40bar], combustor inlet temperature up to 900K and FAR on the range [$27(^{0}/_{00})$, $33\ (^{0}/_{00})$].

A slight reduction of combustion efficiency was observed from $30\ ^{0}/_{00}$ FAR to $35^{0}/_{00}$ which is linked to frozen chemical reactions at the wall in the effusion cooled part. This problem was solved by improving the cooling of this part.

In the near future the development of new materials will constitute a means for reducing the air mass flow rate allocated to the cooling system in view of improving emissions performance and wall durability. A new thermal barrier coating or CMC are the most serious candidates.

As expected, the GV concept demonstrated a very appealing potential for soot and NOx emissions reduction, which can be evaluated at 45% with respect to CAEP2.

Altitude relight capabilities have been assessed only for “closed state”. It has been demonstrated that they are equivalent to the ones of the classical combustors.

Although very interesting capabilities for Nox reduction and exit temperature distribution have been demonstrated by the variable geometry concept while maintaining altitude relight requirements, a major drawback lies within the complexity of the mechanical system needed to pilot the opening and the closing of the combustor dome.

One way of improvement consists in using a fluidic system to realize the variation of air distribution with respect to the engine rating.

3.6 Active injection systems.

The principle of active injection systems lies in the integration within the injection system of a specific cold plasma generator. The repetitively nanodischarge pulses which are generated inside the combustor produce active radicals species and can contribute to breaking up the large and complex kerosene fuel molecules. Those two effects combine themselves and lead to a reduction of the chemical characteristic time scale and to an enhancement of the reaction rate. Two kinds of application can then be considered.

Since the flame is made more resistant to extinction, lean blow out equivalence ratio can be diminished for given aerodynamic conditions. This effect can be especially used for extending the operability domain of LPP injection systems in such a way that it could be fitted on a SAC architecture.

Plasmas can also be used for combustion ratings where there is no problem related to flame-out. The main effect is to improve combustion efficiency without having to increase the residence time inside the combustor. Then it can be applied to classical injection systems in view of reducing volume of primary and dilution zones when mixing is faster than the chemical reaction rate. Note that global reduction of combustor volume leads directly to NOx emissions reduction. Since operational performance at low rating is ensured by the effect of plasma, it appears now that volume of primary zones could be fixed only from considerations linked to high rating performance.

Those technologies are assessed and developed by Snecma Moteurs in cooperation with ONERA (Office National d'Etudes et de Recherches Aérospatiales) and CNRS (Centre National de Recherche Scientifique), with funding from the French Agency of Defence (DGA).

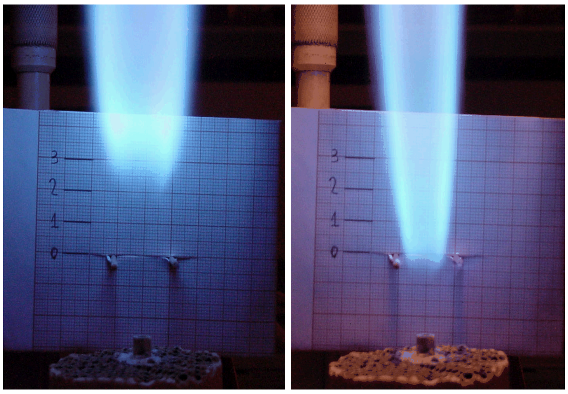

Fig. 17. Illustration of the plasma effect on a flame stabilization problem. Left: no plasma is applied and the flame is near the lean blow out limit. Right: only plasma is applied and the flame become perfectly stable. (Thanks to CNRS / CORIA for the picture)

4 General conclusion.

The reduction of pollutant emissions is a very efficient driver for combustor and injection systems Research and Technology strategy.

To meet current and future environmental concerns, and in order to develop "Environmentally" Friendly aircraft engines, SNECMA Moteurs has developed a large panel of new combustor technologies oriented towards lean combustion. In this prospect, environmental constraints are more and more integrated to the design process, in addition to airworthiness requirements. The potential technologies are the fruit of an experience of nearly three decades, supported by the experimental results from CEPr, ONERA and CNRS test rigs, that have contributed to the validation of physical modeling and the calibration of the CFD design tools used by SNECMA Moteurs. National and European research programmes have also supported this continuous effort.

Aknowlegdements

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