Low Emissions Propulsion Engine Combustor Technology Evolution Past, Present and Future

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ABSTRACT

To date, most technology development for NOx reduction has focused on emissions at low altitude. However, the need for a technological breakthrough to significantly reduce cruise emissions is also evident. There is evidence that the effect of aircraft NOx emissions at cruise could be up to four times more important than that of aircraft CO_2. If this relationship is confirmed, cruise NOx will probably become a more urgent issue than low altitude NOx. The Twin-Annular Premixing Swirler (TAPS) combustor, a 4th generation low-emissions technology, offers significant NOx reduction over state-of-the-art Low Emissions Combustor (LEC) technology for both low- and cruise-altitude operation.

INTRODUCTION

Significant reduction has been achieved during the last 40 years in the pollutant emissions of commercial aircraft. Technology has been developed and implemented to reduce CO_2 (as a result of reduction in specific fuel burn), partially burned hydrocarbons (HC), CO, oxides of nitrogen (NOx), and particulates. The reduction in specific fuel burn is attributed to advances in airplane aerodynamics and propulsor, the latter in turn has been due to increases in propulsion and engine efficiencies. Advances in the fuel injection system technology coupled with continuous evolution in designs of the fuel/air mixing devices and flame stabilization and combustion have resulted in substantial reduction in HC emissions. Continuous increase in bypass ratio (and improved airframe and engine integration), coupled with improvements in component efficiencies, materials technology and reduction in parasitic losses (all contributing to improving propulsor efficiency) have resulted in increasing combustor operating pressure and fuel/air ratio (combustor exit temperature) levels by > 100% in the last 40 years. This along with environmental considerations, as explained in the next section, provided impetus for the development of NOx/CO emissions reduction technologies as summarized in this paper.

The evolutionary emissions technology improvements have resulted in providing affordable low emissions rich-dome Low Emissions Combustion (LEC) for both Single and Dual Annular Combustors (SAC & DAC), the latter primarily for reduced engine length and weight.

In order to implement lean-dome combustion technology, which has better long-term potential for reducing NOx and particulate emissions, it has been necessary to develop several enabling technologies including fuel staging and controls in addition to addressing key issues, such as tradeoffs between low-power efficiency, high-power NOx, operability, durability and cost. Critical feedback on all of these factors has been gained in the field through introduction of the lean-dome DAC into selected product engines such as the CFM56. This experience has enabled the development of an affordable second-generation lean dome combustion technology, the Twin Annular Premixing Swirler (TAPS) combustor described in this paper. TAPS technology is fully matured for next-generation product introduction. This paper also describes plans for further improving TAPS emissions technologies by another 50% to 75%.

Effects of NOx Emissions

As noted above, considerable progress has been made in reducing aircraft engine emissions. Over the past 40 years, the commercial aviation industry has been able to reduce fuel consumption by 70% while also limiting noise and reducing gaseous CO and HC emissions by approximately 50 and 90%, respectively. Much of this improvement is due to materials and cooling technologies that enable modern engines to operate at very high temperature and pressure. However, the high temperatures that provide such a wide range of environmental benefits also tend to increase NOx. The problem of increasing NOx emissions goes beyond aviation. For example, the EPA[1] indicates that since 1970, emissions of all principal air pollutants other than NOx decreased between 1970 and 1998, while NOx emissions increased by approximately 10%.

Local and Regional Effects

In the vicinity of airports, part of the NOx emitted by aircraft, ground service equipment and access road traffic is in the form of nitrogen dioxide (NO_2), which can contribute to respiratory problems. NOx emitted at low altitude is also a key contributor to the formation of ground-level ozone (smog), and can also contribute to particulate formation, reduced visibility, deterioration of water quality and acid rain.

The EPA[2] points out that while the contribution of aircraft to total NOx emissions is currently relatively small, the contribution is expected to increase. Figure 1 shows how the EPA estimates that the aircraft component of total regional emissions is expected to increase in 10 US metropolitan areas between 1990 and 2020. On the average, the proportion aircraft emissions is expected to increase from 1.06% to 3.63% of total regional NOx, but the contribution is expected to be as much as 8% in some individual regions.

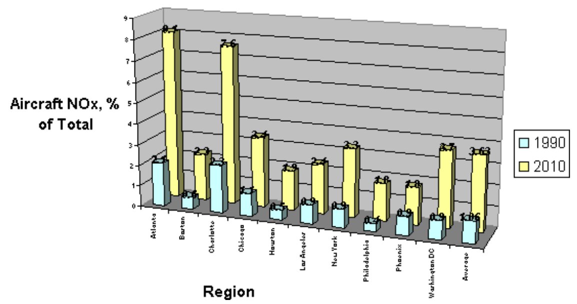


Figure 1: Aircraft contribution to total regional emissions in the U.S.A.

Total worldwide aircraft NOx emissions are also expected to grow significantly. For example, as indicated in Figure 2, the Forecasting and Economic Analysis Support Group[3] (FESG) of the International Civil Aviation Organization (ICAO) predicts that worldwide aircraft NOx emissions will increase by a factor of 2.6 between 2002 and 2020. The ICAO Committee on Aviation Environmental Protection (CAEP) recently recommended a 12 % increase in the stringency of international NOx standards, based on the best current performance of conventional aircraft engine combustion systems, but even with this new standard, NOx emissions in the year 2020 are only expected to be reduced by 3.2 to 4.3 % (22,276 to 29,965 tonnes).

The UK Department for Transport[4] points out that the environment could limit growth of the civil aviation industry, saying, "We have to recognize that simply building more and more capacity to meet potential demand would have major, and unacceptable, environmental impacts, and would not be a sustainable approach". It is clear that a leap in technology is needed to control aircraft engine NOx emissions at low altitude.

Global Effects

NOx emitted at typical commercial aircraft cruise altitudes contributes to ozone formation at high altitude, which can in turn affect climate. The Intergovernmental Panel on Climate Change (IPCC) estimated that in 1992, aviation was responsible for about 3.5% the total anthropogenic (human induced) climate effects[5]. More recently, a Special Report of the UK Royal Commission on Environmental Pollution[6] concludes: "the IPCC reference value for the climate impact of aviation is more likely to be an under-estimate rather than over-estimate. We conclude that, unless there is some reduction in the growth in the sector, or technology improves considerably more than assumed by the IPCC, by 2050 aviation will be contributing at least 6% of the total radiative forcing consistent with the necessary stabilisation of climate. A safer working hypothesis is that it will be in the range of 6% - 10%".

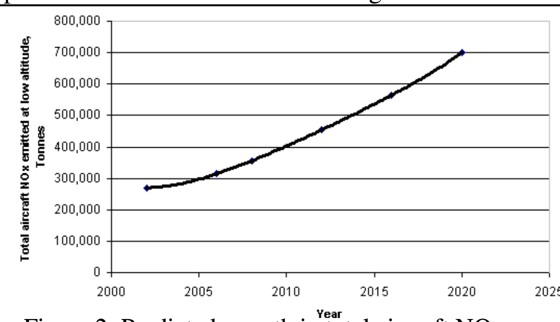
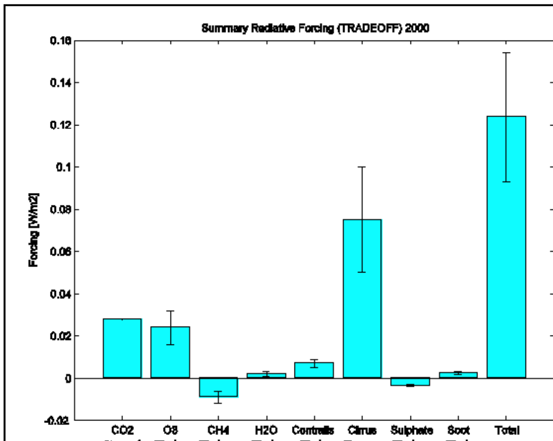


Figure 2: Predicted growth in total aircraft NOx emissions.

Figure 3 (from Reference 7) shows the relative "forcing" (approximate global effect on climate) due to different aviation emissions, and also indicates the level of scientific understanding (good, fair or poor).



Good Fair Fair Fair Fair Poor Fair Fair

Figure 3: Relative "forcing" due to different aviation emissions.

The effect of aviation CO_2 is well understood and its magnitude is roughly equal to an equal amount of CO_2 emitted at ground level. Ozone (O_3) due to NOx appears to be of the same order of magnitude as CO_2, but the ozone will occur primarily near flight corridors, and will therefore have a stronger effect in the northern hemisphere than in the southern hemisphere. In fact the U.K. Department of Transport asserts[8,9] that, "despite the similar RFs [forcing] of aviation O_3 and CO_2, the temperature response is rather different because of the different equilibrium surface temperature response of aviation O_3 to CO_2. Of the total temperature response from CO_2 and O_3, approximately 82% of the temperature response arises from O_3".

In simple terms, the effect of aircraft NOx emissions at cruise could be up to four times more important than that of aircraft CO_2. As scientific understanding improves, if this conclusion is verified, cruise NOx will be recognized as a more urgent issue than low altitude NOx. To date, most technology development for NOx reduction has focused on emissions at low altitude. However, the need for a technological breakthrough to significantly reduce cruise emissions is also evident.

TECHNOLOGY EVOLUTION

Rich Dome Combustion

The "Experimental Clean Combustor" and "Pollution Reduction Technology" programs sponsored by NASA in the middle 1970's[10-13] paved the way for improving fuel injection devices which along with combustion/dilution airflow optimization led to the state-of-the-art Low-Emissions Combustor (LEC) technology development during the last 25 years. Consequently, the low-altitude NOx emissions (at 30 overall pressure ratio) have come down from 100 to ~45 grams of NO_2 per kiloNewton of takeoff thrust over the ICAO specified Landing-Takeoff cycle, a 55% reduction. As shown in Figure 4, several propulsion engine combustors fall within a narrow technology band of LEC including CF6-80C2, CF6-80E, GE90-94B, GE90115B, Trent 800 and PW4000 TALONII.

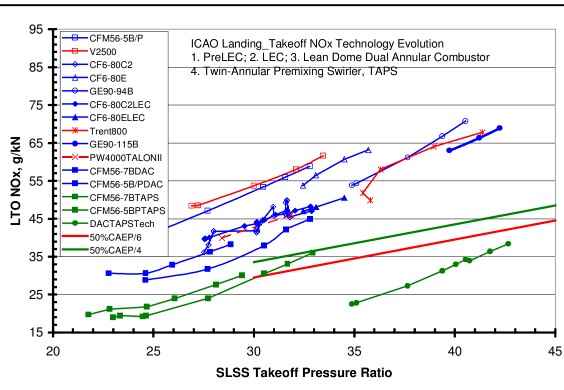


Figure 4: Propulsion engine combustors low-altitude NOx reduction technology evolution as represented by ICAO specified Landing-Takeoff cycle.

The ICAO LTO cycle for subsonic aircraft consists of operation for 0.7 minute at takeoff (100% rated thrust), 2.2 minute for climb to 3000' altitude (85% rated thrust), 4 minutes during approach (at 30% rated thrust) and 26 minutes for taxi-out/in at 7% rated thrust. The ICAO Committee on Aviation Environmental Protection (CAEP) introduced standards for gaseous and smoke emissions in 1982. For example for NOx CAEP/1 is:

LTO NOx = 40 + 2*OPR

Which has since steadily become more stringent, the most recent being CAEP/6 proposed this year for OPR= 30-82.5 and rated takeoff thrust > 89kN:

LTO NOx = -1.0 + 2*OPR; an overall reduction of 41% at 30 OPR from the CAEP/1 standard. In other words, the NOx stringency is being introduced consistent with the best available NOx technology.

LTO NOx value clearly represents a composite of emissions indices and the corresponding engine fuel flows in each of the four power points. In other words, emissions indices reflect on the status of the combustion emissions technology whereas LTO a combination of fuel burn and the emissions indices. For example, a comparison between the engine sea level static take-off SFC for some of the engines of Figure 4 is presented in Figure 5; falling in the range of 7.73 to 10.7 g/s-kN or ±16% of the average value.

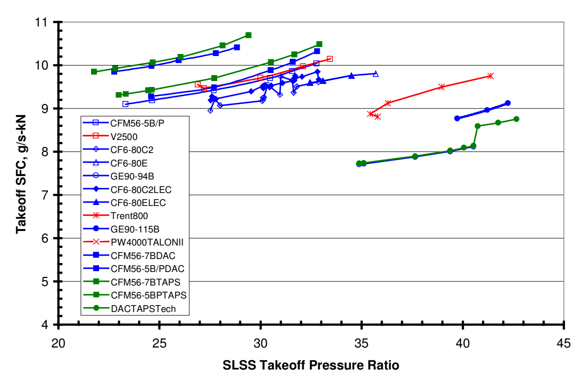


Figure 5: Sea-level static takeoff specific fuel consumption, SFC, g/s-kN) of some of the modern propulsion engines.

Figure 6 shows EINOx versus power setting, expressed in terms of combustor inlet temperature (T_3) normalized by square root of combustor inlet pressure (P_3) to compare emissions technology levels of several combustors. The following summary observations are relevant to Figures 4 and 6.

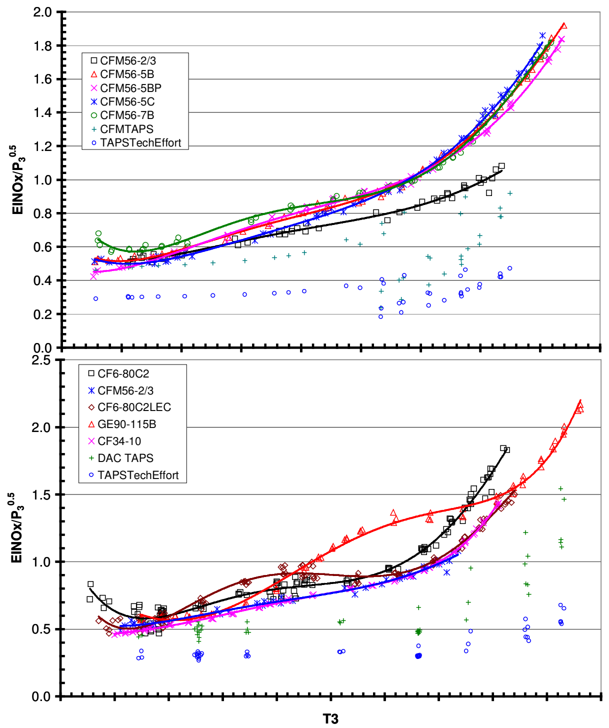


Figure 6: EINOx/√P3 plotted as a function of combustor inlet temperature, T3 for several engine combustors. All data except for DAC TAPS and TAPSTechEffort are from engine emissions testing.

Emissions certification of the CFM56-2/3, CF6-80C2 and CF6-80C2LEC took place in 1983, 1985 and 1995, respectively. EINOx/$\sqrt{P_3}$ levels of the CFM56-5B, 5C, 7B and CF6-80C2 versus T_3 are comparable; whereas those of the CFM56-2/3, CF6-80C2 LEC, GE90-115B and CF34 fall among the lowest levels except in the intermediate power settings for some of these engine models. Typical high-power EINOx/√P3 reduction e.g. at 1500 R from preLEC to LEC technology development of last ~20 years has been ~20%. Since engine operating pressure ratios have steadily gone up during the last 20 years to reduce fuel consumption; nominal takeoff pressure ratio of engine certified in the 1980's being 30 compared to 42 for the GE90-115B. Consequently, low-altitude NOx emissions (as represented by LTO NOx) have gone up from 45 g/kN to 69 g/kN even with LEC technology; ~50% increase in NOx with the resulting gain in the takeoff SFC of ~8%. The propulsion engine industry has been working very hard during the last 20 years to develop and certify affordable LEC technology without adversely impacting other combustor design requirements; and it appears that we are essentially close to LEC emissions entitlement considering tradeoffs between high-power NOx/smoke, low-power HC/CO, combustor exit temperature quality control, operability, durability and cost of ownership.

Figure 7 shows LTO HC and CO emissions of some of the combustors compared to the standards corresponding to what is required to pass three-engine emissions certification. In regard to partially burned hydrocarbons these engines fall into basically three categories, namely low, medium and high HC emissions, all below the standards falling approximately in the ranges [0.5-5.0], [5.0-10.0] and [10.0-16.5]. LTO CO values fall basically into two camps, low [15-50] and high [30-109]. Generally for a given emissions technology, operability and durability requirements, there is inverse relationship between NOx and CO emissions and to a lesser extent with HC emissions.

What is more challenging is keeping the increase in cruise NOx emissions manageable. The nominal cruise NOx emissions index of ~10 with the engines entering service in the 1980's is closer to 15-20 range for the recently introduced engines with altitude pressure ratios exceeding 40; resulting in 50-100% increase in cruise NOx with LEC technology.

In summary, with LEC technology we have made approximately 40-50% reduction in LTO NOx (at an engine pressure ratio of 30), ~50% reduction in CO and ~90% reduction in HC; while cruise NOx has increased 50-100%. We have reached close to entitlement with LEC technology, so significant further reductions will require introduction a new generation of emissions technology in future engines.

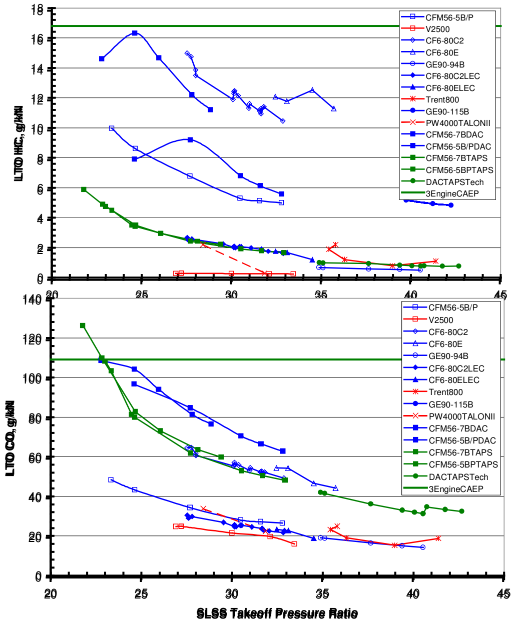


Figure 7: LTO HC and CO emissions of selected combustors.

Lean Dome Dual Annular Combustion

Several 3rd generation low-emissions combustion concepts have been pursued including Dual Annular (DAC)[10] and axially-staged combustion[10-13]. Due to many reasons including business decisions, only DAC, Figure 8 has been introduced into service; three different engine models, CF56-5B, CF56-5BP and CFM56-7B have been emissions certified in 1994, 1996 and 1997, respectively. Generally speaking, the original intent of DAC was to get 50% NOx reduction over state-of-the-art combustors introduced in the early 1970's, i.e., a generation before the PreLEC combustors. In today's vernacular, it could be reinterpreted as achieving 50-60% reduction from CAEP/1 standard, i.e. LTO NOx of 40-50 at 30 OPR. Specifically, DAC at 30.5 OPR achieved LTO NOx of 37.9 compared to 53.4 achieved by PreLEC-based CFM56-5BP SAC, see Figure 4; 30% reduction. DAC also achieved ~50% reduction in cruise NOx. However, DAC introduced many design challenges including low-power emissions, Figure 7, cost of ownership, combustor exit profile and its impact on fuel burn. These and the challenge to design lean-dome DAC for nominal 40-OPR engines provided impetus for stepping up to developing next-generation low-emissions technology TAPS with more emphasis on premixing than afforded in the swirl cup mixers of preLEC, LEC and DAC combustors as explained in the next section.

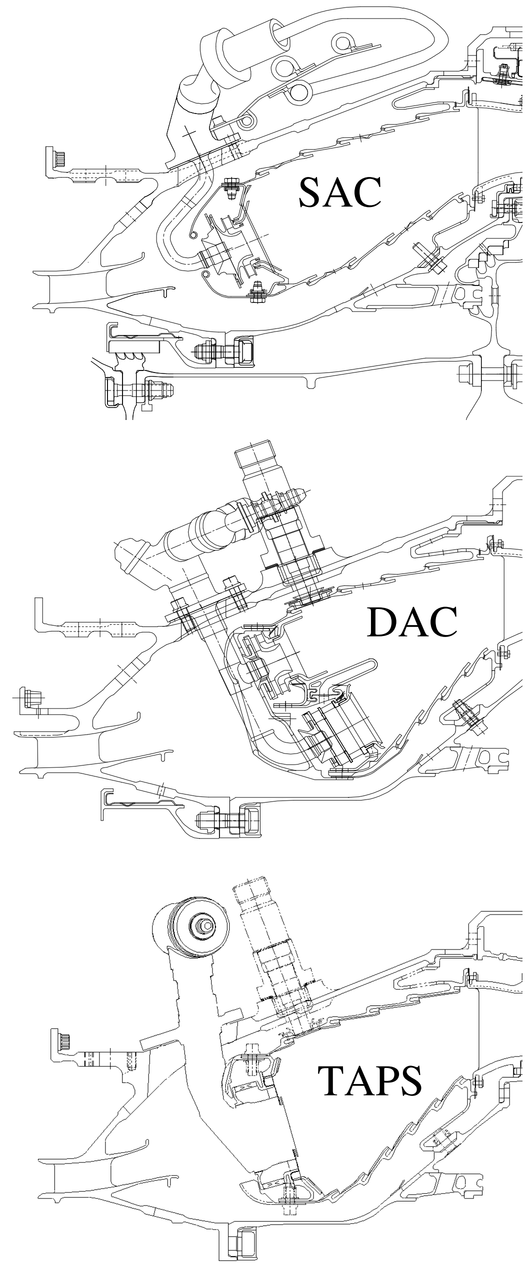
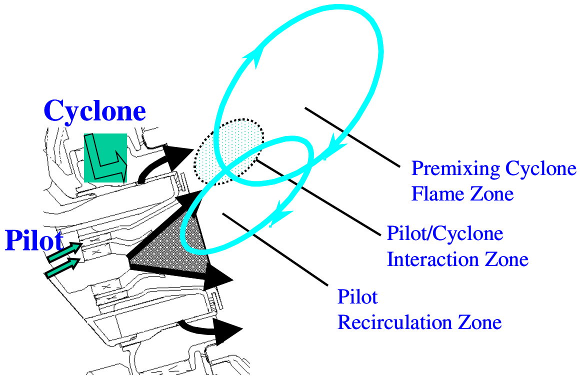


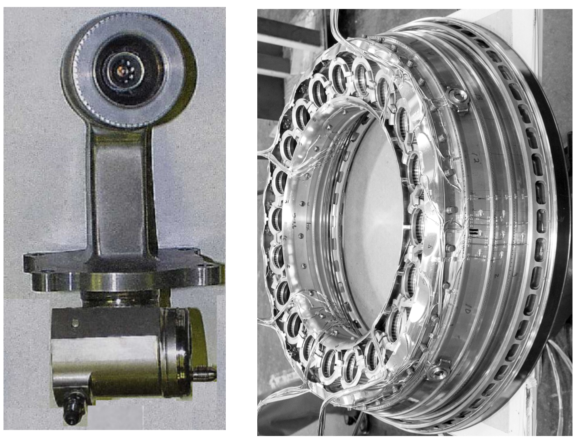
Figure 8: Rich-dome Single Annular (SAC), lean-dome Dual Annular (DAC) and lean Twin Annular Premixing Swirler (TAPS) based SAC combustion.

Twin Annular Premixing Swirler

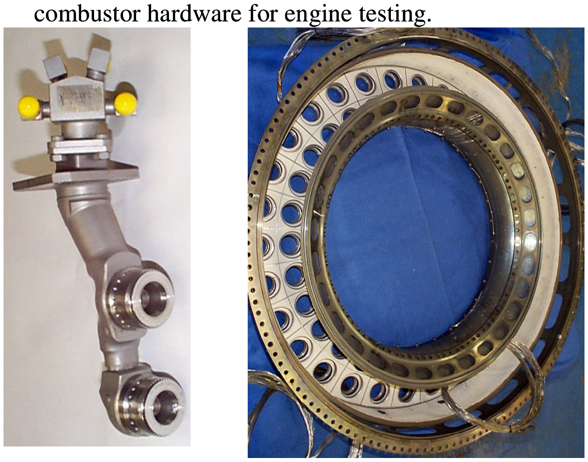
Conceptually speaking, TAPS functionality is quite simple, as shown in Figure 9, it is a premixing main



(a) TAPS mixer operating principles.



(b) Tech56/CFM SAC TAPS fuel nozzle and combustor hardware for engine testing.



(c) GE90 DAC TAPS combustor and fuel nozzle tested in a full-scale annular combustor rig to 350 psia, 1170F inlet temperature and 0.037 fuel/air ratio.

Figure 9: Twin Annular Premixing Swirler (TAPS) operating principle, full-scale fuel nozzle and combustors tested for potential application in the CFM56 and GE90 engine models.

swirler built concentrically around the well-proven swirl cup mixer, and hence the use of the word twin.

TAPS combustion system has provided many challenges for combustion, fuel nozzle and controls designers including the following:

1. Creating "flame-within-flame" that operates successfully from start to maximum power in regard to pressure drop; combustion efficiency; gaseous and smoke emissions; ignition, flame propagation, lean blowout and combustion dynamics; acceptable combustor exit temperature quality without dilution jets; desirable premixing in the main mixer without compromising robust preignition and flashback characteristics of LEC mixers.
2. Balancing tradeoffs between reliability, cost, durability, weight and complexity.
3. Fuel staging between the pilot and main; response and controllability; and nozzle purging.

An integrated team of the designers from various disciplines including combustion, controls, fuel nozzle, manufacturing process, systems and testing achieved the program objective after undertaking extensive effort in design (conceptual, preliminary and detail), hardware procurement, testing/retesting through subcomponent/component levels, involving single mixer, sector and full-scale annular, and finally an engine demonstration of the CFM TAPS system. TAPS combustion system has gone through the various technology development milestones required to achieve "New Product Introduction" readiness status TG6.

Current status of the TAPS in regard to emissions based on data presented in Figures 4, 6 and 7 is:

1. CFM TAPS meets 50% CAEP/4 NOx level at 33 OPR but exceeds 50% CAEP/6; DAC TAPS, on the other hand meets 50% CAEP/6 level up to 45 OPR; the latter is clearly more expensive than the former. Further NOx reduction technology development is therefore desirable for SAC TAPS. Analysis and preliminary testing indicate, see Figure 6, the feasibility of achieving additional 50% reduction in high-power NOx emissions.
2. LTO HC emissions of TAPS are comparable with rich-dome LEC combustion technology down to 22 OPR; no further reduction required for staying competitive.
3. LTO CO emissions levels of TAPS fall in-between low- and high-CO emissions of rich-dome SAC and lean DAC's. Of some concern is its high value for OPR<25 which can be addressed through optimizing the combustor volume, cooling level and/or technology.

4. Cruise NOx of TAPS is ~50% lower than LEC technology, especially for 40 OPR engines that are required for improving fuel burn. There is however a tradeoff between how low cruise EINOx one can achieve and still maintain >99.5% combustion efficiency.

In addition to above, as is always the case with the product introduction of new technology, will continue further evolutionary improvement in regard to cost of ownership, weight, simplicity and expanded applicability of TAPS combustion system.

SUMMARY

A brief summary has been given about environmental impact of propulsion engine gaseous emissions that provides impetus for continuous reduction in both low- and cruising-altitude NOx emissions. It appears that cruise NOx emissions reduction is more important than LTO NOx. Discounting credit for improved fuel consumption over the last 20 years, LEC technology has demonstrated ~20% reduction in the take-off NOx emissions even when we allow consideration for higher operating pressure being proportional to $\sqrt{P3}$. On the other hand, the rich-dome LEC has increased cruise EINOx (operating from 30 to 40 OPR) by 50 to 100%.

A break-through low-emissions technology is therefore needed in order to maintain a sum zero impact on environment. A summary of propulsion engine emissions technology was presented including status and plans for further improving emissions of the Twin Annular Premixing Swirler, TAPS.

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