A preliminary design of a schematic evaluation of low emission turbofan combustors

U Vamsi Krishna¹ and N V Mitrokhov ²

¹ Graduate Student, Moscow Aviation Institute (National Research University) Moscow, Russia.
² Associate Professor, Moscow Aviation Institute (National Research University ) Moscow, Russia.

E-mail: u.vamsikrishna@yahoo.com

Abstract. This paper examines low emission combustion technologies (LECT) schemes suitable to the sixth generation high-bypass Turbofan engines designed to operate on narrow-body aircraft with a rated thrust (\(F_{\text{th}}\) in kN) of 90-250 kilo-Newton(kN) and an overall pressure ratio of (\(\Pi_{\text{oo}}\) ≥ 30. The examined schemes are based on 11th regulatory standards of the Committee on Aviation Environmental Protection (CAEP). A brief overview on emissions is provided.

1. Emissions

Modern aviation engines are 80% more fuel-efficient compared to the ones produced in 1960’s. However, with the current trend of air traffic doubling at every 15 years and the concept of carbon-neutral growth that aims to keep the average global temperature increase below 2°C in accordance with the Paris agreement, there is an urgent necessity for technological improvements. According to the International Civil Aviation Organization (ICAO) and the Intergovernmental Panel on Climate Change (IPCC), the aviation industry accounts for 2 % of greenhouse gases, of which 2/3rd s are caused by international flight operations and 1/3rd is the result of airport operations. [2]

The main aviation pollutants are \(\text{CO}_2\) & \(\text{NO}_x\). \(\text{CO}_2\) production is directly related to consumption of hydrocarbon fuels. In 2015 alone, 160 Mt of fuel consumed by international aviation resulted in 506 Mt of \(\text{CO}_2\) production. It is predicted that by 2025 207 to 226 Mt of fuel required by international aviation which will result in 655 to 713 Mt of \(\text{CO}_2\) emissions [2]. In order to increase thermal efficiency of a gas turbine and to decrease the specific fuel consumption (SFC), it is essential to increase both \(\Pi_{\text{oo}}\) and \(\text{TIT}\) (Turbine Inlet Temperature). Overall pressure ratios \(\Pi_{\text{oo}}\) of 6th generation engines are in the order of 60-70 and \(\text{TIT}\) is about 2000-2100 K. With \(\text{TIT}\) of around 2000K local temperatures in the flame tube or combustion liner are elevated and this in turn enhances the rate of \(\text{NO}_x\) production. Trends of \(\text{NO}_x\) emissions are shown in fig 1. with CAEP standards. Other pollutants such as Sulphur oxides are byproducts of gases that are created because of sulphur in the fuel. UHC(Unburned Hydro Carbons), particulate matter and smoke are created because of fuel-rich pockets formed in the liner and dependent on the rate of their consumption downstream in the liner through proper mixing of secondary air.
Fig 1. Recent trends of LTO of NOx function of $\Pi_{oo}$ [2]

The CAEP 11 regulatory standards [1] are stated below as follows. The limits set are based on the maximum mass content of a pollutant ($D_p$) in grams which is the function of $F_{oo}$ and $\Pi_{oo}$. The empirical values are deduced from the CAEP emission reduction goals from earlier standards of CAEP. The emission is evaluated by the Landing and Take-off cycle (LTO).

Smoke Number or Amount of Smoke content

\[ SN \leq 83.6 \times (F_{oo})^{0.274} \text{ or 50 whichever is the lowest} \]

Hydrocarbons

\[ D_p (HC) \leq 19.6 \times (F_{oo}) \]

Carbon monoxides

\[ D_p (CO) \leq 118 \times (F_{oo}) \]

Nitroxides

\[ D_p (NOx) \leq (-9.8 + 2 \times \Pi_{oo}) \times F_{oo} ; \]
where \( \{ F_{oo} \geq 90 \text{, } 30 \leq \Pi_{oo} \geq 104.7 \} \)
applicable to engines manufactured after 2014

Non-Volatile Particle Matter (nvPM)

\[ \text{nvPM mass concentration} \leq 10(3 + 2.9 \times (F_{oo})^{-0.274}) \text{ ;} \]
applicable to engines manufactured after January 1st, 2020

2. Design of Modern Aero combustors.

Yize Liu et al [4] thoroughly examined the low emission combustion technologies (LECT) which include Rich burn Quick quench Lean burn (RQL)\(^1\), often referred as Single Annular Combustor (SAC)\(^1\), Double Annular Combustor (DAC)\(^2\), Twin Annular Premixing Swirler combustors (TAPS)\(^3\), Lean Direct Injection (LDI)\(^4\), NASA multipoint LDI5, Lean Premixed Prevaporised (LPP)\(^6\), Axially Staged Combustors (ASC)\(^7\) and Variable Geometry Combustors (VGC)\(^8\). Out of these technologies 1,2 and 3 are fully developed and in operation as of date. The other technologies, namely 4,5,6,7 and 8 are still under development and need to perform under operational conditions.

The above-mentioned design schemes majorly rely on 3 principals. Firstly, the overall equivalence ratio is maintained in the range of 0.5-0.6 for lean combustion while the local equivalence ratio of the primary zone is kept below the stoichiometric value i.e. $< 1$ so the adiabatic flame temperatures do not
attain peak value in order to reduce NOx formation. Second principal is the fuel mixture preparation. Through proper atomization of fuel and uniform mixing of air and fuel, the mixture is introduced into the chamber to maintain stable combustion throughout the operation. It is achieved through various ways such as injectors coupled with swirlers either to form a pre-mixed or pre-vaporized mixture. Thirdly, to avoid the local quenching i.e. to avoid the formation of CO oxides and other pollutants, the local flame temperature has to be maintained at above 1800K, so that upstream CO oxides and UHC can be consumed in the liner’s downstream. However, most of LECT technologies, other than SAC, do not use this technique anymore. Most of the other technologies attribute 70% of air through the combustor dome and 30% to the liner cooling.

The dome configuration plays a major role in LECT technologies. For example: DAC and TAPS schemes dome configuration is of concentric radial staging of injectors. Concentric axial staging in the ASC technology. Multipoint injection is implemented in LDI, NASA LDI and LPP technologies. Although the multipoint injection technologies anticipate the reduction of emissions compared to staging. At present the technologies are still under development it is not quite feasible to compare them. In regard to 90kN-250kN thrust class turbofan engines SAC and DAC technologies are in operational for CFM56 series. DAC configuration reduced NOx by 65% while the SAC configuration (used on the same engine) has reduced NOx by 75% in accordance with 6 CAEP standards [5]. Although SAC has shown 15% more reductions, there are high chances of CO production due to local quenching and with new regulatory measures on CO this technology is not advisable anymore.

| Technology | CFM56-5C4/P | DAC | TAPS LEAP-1B28BBJ1 |
|------------|-------------|-----|-------------------|
| BPR        | 6.8         | 5.7 | 8.3               |
| \(\Pi_\infty\) | 30.5        | 30.5| 42.0              |
| \(F_\infty\) | 149.9       | 133.5| 130.4             |

\[
\left(\frac{D_p}{F_\infty}\right)_{HC} = 6 \\
\left(\frac{D_p}{F_\infty}\right)_{CO} = 48.9 \\
\left(\frac{D_p}{F_\infty}\right)_{NOx} = 59.0 \\
SN = 15.4
\]

Table 1. Characteristic pollutant levels [3].

TAPS and DAC configurations use the concept of main and pilot burners. Pilot burner is employed for low power mode and both burners are employed for high power modes. DAC uses radially staged separate injectors, which is why the DAC configuration is heavier than the TAPS single injector. DAC scheme’s radial temperature outlet profile is not uniform during high power mode which affects the turbine’s performance and durability. Due to turbine inefficiency at an idle condition, DAC results in a 7-15% increase of SFC compared to SAC [4]. TAPS uses premixed flame, so compared to SAC and DAC that use diffusion flame, the risk of auto-ignition and flashback is low in TAPS. All technologies are at the highest combustion efficiency of 99.3-99.8 % and overall pressure losses of 4-6 %.

3. Future Work.
Thanks to this study, the DAC and TAPS schemes are shortlisted for the future Turbofan combustors for narrow-body aircraft of 90-250kN. A computer algorithm is being developed for preliminary combustor designs at the Moscow Aviation Institute. The designs are created for 140kN and \(\Pi_\infty = 41\) and Bypass ratio of 8.5 which resembles the design characteristics of a PD-14 engine. The designs for the DAC and TAPS configurations are being modified, they will be further evaluated under computer-aided analysis to verify their design performance. We believe that optimization of the DAC exit
temperature profile can be achieved by coupling the fuel injector with dual counter-rotating swirlers, which we believe will enhance the gas mixing to avail uniform exit temperature profile on a high power operation and reduce the extra SFC consumption.

4. Conclusions.
TAPS show favourable design considerations such as weight, size, low SFC consumption, especially at idle conditions, moderate risk of auto ignition and flashback. DAC exhibits some disadvantages in weight and exit temperature profile but DAC systems can be improved as they are already in service for CFM56 where the TAPS system is behind in NO\textsubscript{x} reduction by 15 % as shown in Table 1.

References

[1] International Civil Aviation Organization (ICAO) 2017 Annex-16 Volume II Aircraft Engine Emissions, 4th ed.
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