

Low Emissions Combustion Technologies for Aero Gas Turbine Engines

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ABSTRACT: Aircraft engines are responsible for emitting various pollutants in the form of NO_x, CO₂, CO, UHC, SO_x and smoke in the vicinity of airports and at higher altitudes. These emissions have led to the change in earth's climate by altering the chemical and microphysical properties of the atmosphere. These pollutants produced by aircraft engines are also responsible for causing various health problems. The enactments aimed for constraining aircraft emissions have become increasingly stringent in the course of recent decades. This has resulted in the critical need of developing low emissions combustors. This report provides a comprehensive review of current modern technologies for low emissions aero gas turbine engines. The review considers current high Technologies Readiness Level (TRL) technologies and the focus of the review is placed on the working principle, advantages and disadvantages of these technologies.

KEYWORDS: Low emissions, Technologies, Aero engines, Combustion

I. INTRODUCTION

Aviation research is not only focused on how to produce larger planes with higher speeds and different shapes, but also on how to control aircraft emission levels. The aircrafts are responsible for emitting several types of pollutants in the form of Nitrogen Oxides (NO_x). These are one of the most toxic pollutants in the atmosphere. They destroy the ozone layer and cause problems to the atmosphere, such as smog. NO_x can also cause health problems such as lung irritation and lower resistance to respiratory infections. The other pollutants also have very bad effects on our health. Carbon dioxide (CO₂) and Carbon monoxide (CO) cause cardiovascular problems. Unburned Hydrocarbons (UHC) lead to visual disorders, respiratory problems and memory impairment. Sulphur oxides (SO_x) are other serious pollutants, where exposure to sulphur dioxide in the ambient air has been associated with reduced lung function. The stringent international standards aimed to reduce emission levels led to increased interest in low emission technologies. A significant development has been achieved, where over the past 40-50 years the aviation industry has been capable of reducing fuel consumption and pollutant emissions [1].

II. MODERN COMBUSTION TECHNOLOGIES

Only the design of a typical low combustor shouldn't be the primary focus. The importance of other performance interacting with the emissions should also be explored thoroughly. Therefore, the performance should not be compromised when designing a low emission combustor. The altitude-relight capability and avoidance of auto-ignition/flashback should be considered primarily during the early stage of the design. Stable combustion is critical as combustion instability could damage the hardware of the combustor and become a safety issue. Operability should be also considered as a high priority to ensure the combustor is capable of operating over a wide range of fuel-air ratios. The performance criteria such as combustion efficiency and pressure loss are always the key design considerations. This is because the combustor design has to satisfy the whole engine requirement. Pressure loss also affects the whole engine design, particularly for engine SFC. Size and weight are important for aero applications. In order to meet the durability requirement, the component should be designed to ensure they are capable of operating over thousands of hours and flight cycles. The satisfactory turbine thermal and life integrity should be also be achieved [3].

A. Rich-burn Quick-quench Lean-burn combustors (RQL)

The strategy of RQL is to reduce NO_x emissions. It effectively processes fuels of complex compositions and varying compositions. The primary zone of the combustor operates most effectively with rich mixture ratios. There are three stages, the first is a rich-burn stage, the middle is a quick-quench stage, and the last is a lean-burn stage as shown in Fig. 1. The combustion is initiated by a fuel-rich mixture in the primary zone. In the rich burn stage, production of NO_x is less due to relatively low temperatures. In the quick-quench stage, a large amount of air is introduced to mix quickly to complete the rapid transition from rich to lean burn, so as to prevent large NO_x production. Finally, the lean-burn stage is very important because it helps to achieve more CO and UHC consumption for lower NO_x. The combustor outlet temperature distribution quality is controlled by this region [1].

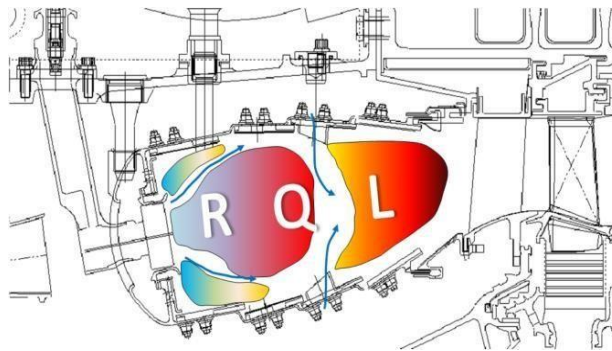


Figure 1. Schematic of RQL Combustor [2].

Fig. 2 shows a typical axial gas temperature distribution along an RQL combustor. The gas temperature peaks at the quench section, resulting in the rapid NO_x formation. GE LEC designed a series of small local cooling holes downstream of the primary holes: this effectively reduces the local peak gas as well as near wall temperatures, leading to a further reduction in NO_x and higher liner durability. Recent sector rig testing conducted by P&W indicated that the NO_x level of 72% margin to CAEP/6 was achieved [15].

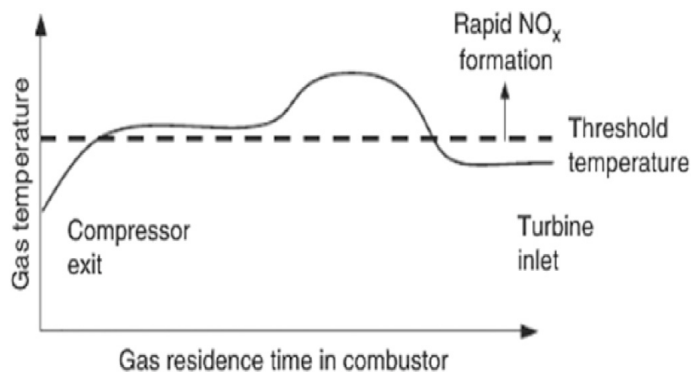


Figure 2. The Axial Gas Temperature in a Typical RQL Combustor [7].

B. Lean Premixed Prevaporised Combustors (LPP)

In LPP combustor, combustion temperature is reduced by mixing fuel and air in lean proportions before reaching combustion zone as shown in Fig. 3. The fuel is vaporized and then mixed with the air flow to create a lean and homogeneous mixture. Due to low flame temperature, there's a reduction in emission levels of NO_x. LPP Combustor consists of three main sections, where the first is for fuel injection, vaporization, and fuel-air mixing such that completed fuel evaporation and fuel-air mixing can be achieved. The second is for combustion where the flame is stabilized in the recirculation zones. The third section may comprise a conventional dilution zone. Combustor designs of this kind are very complex because they require sophisticated hardware for proper staging of the combustion process. Limited information is in the public domain, for recent LPP combustors developed in the NEWAC program. A NO_x reduction of 57% versus CAEP/2 limit is validated on a full annular combustor test.

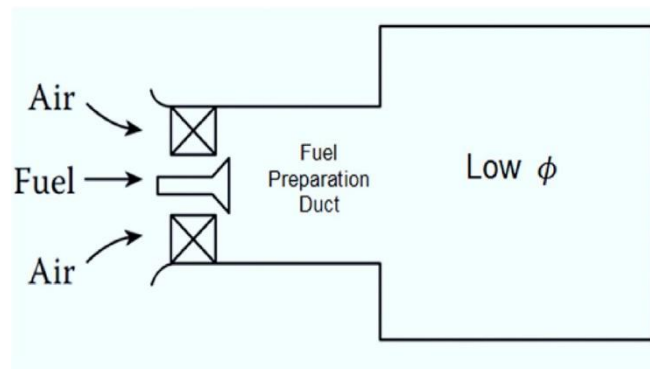


Figure 3. Schematic Concept of Lean Premix-Prevaporise Showing the Fuel and Air are Premixed Before Entering Into Combustor Zone [14].

C. Double Annular Combustors (DAC)

These combustors are based on a radially staging strategy. The combustion temperature is controlled through the use of fuel injection in multiple combustion locations. At low power settings, part of combustion zones (pilot zone, i.e. outer annulus) operates to increase the combustion efficiency and reduce CO and UHC. The pilot zones which are represented in Fig. 4 by outer circumferentially arranged circles and red color indicate the injectors are fuel filled and operating. At higher power settings, the inner annulus get fuelled and ignited. The objective is to achieve lean combustion for NO_x and smoke reduction at high power. During mid-power, part of the main zone is fuelled and operated, this aims to increase the transition efficiency. The challenges of DAC technology are excessive fuel burn due to radial profile and difficulty in cooling due to large dome surface area [11].

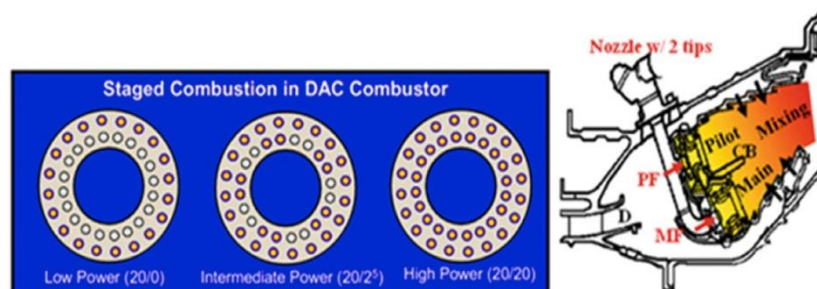


Figure 4. Combustion in Double Annular Combustor [10].

Figure 5 summarizes the ICAO LTO characteristic emissions for DAC combustors for the CFM56 series. Overall, all the DAC versions yield a similar trend for NO_x emissions. As engine OPRs increase up to around 32, the DAC combustors

demonstrate NO_x emission levels with overall 20% margin from the CAEP/6, the margin widens gradually at lower OPRs with a 40% margin obtained at OPR ¼ 24.6. This generally shows a wider NO_x margin compared to RQL combustors.

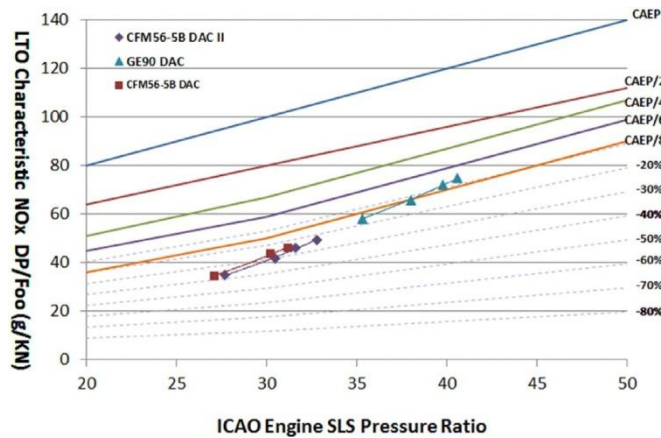


Figure 5. LTO NO_x vs Engine Pressure Ratio for DAC combustors [17].

D. Twin Annular Premixing Swirler combustors (TAPS)

The TAPS combustor concept is a lean burn system. It is composed of pilot and main stages with both concentrically mounted as shown in Fig. 6. The pilot is a rich burn configuration similar to traditional combustors. At low power operation, fuel is 100% in the pilot. At higher power fuel is split between the pilot and main. Most of the fuel is injected through the main at high power. This makes both the pilot and main mixers fuel lean. The advantage of this technology is ultra-low NO_x emissions due to premixed combustion and improved combustor exit temperature distribution [3].

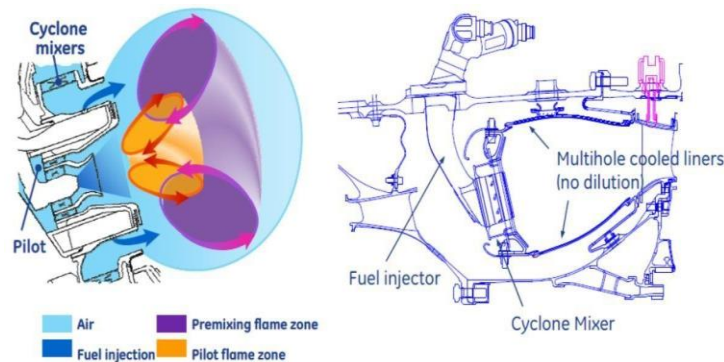


Figure 6. Cross-Section of TAPS Combustor [3].

The LTO engine testing NO_x emissions levels for current in-service TAPS combustors for different OPRs engines are summarized in Fig. 7. The Genx TAPS combustors demonstrate a remarkable NO_x emissions reduction levels. A 5 sector testing was performed that has achieved the project emissions goals of NO_x, i.e. 75% reduction relative to CAEP/6 [11].

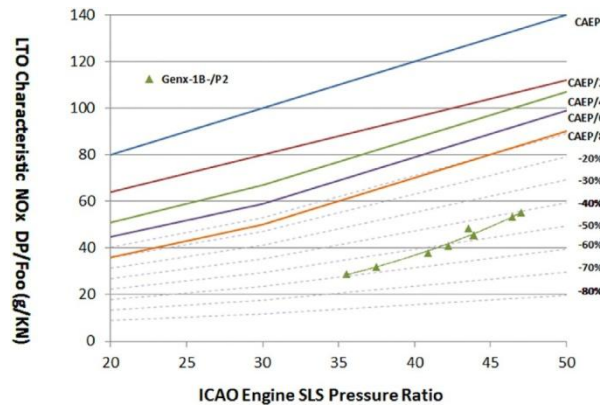


Figure 7. GENx TAPS ICAO SLS LTO NOx Emissions Level [11].

E. Axially Staged Combustors (ASC)

The working principle of ASC is similar to the DAC, but fuel staging is achieved through the fuel injection zones placed in the axial direction as shown in Fig. 8. Axial staging does have certain advantages over radial staging. Since the main stage is downstream of the pilot stage, ignition of the main stage directly from the pilot is both rapid and reliable. Also, the hot gas flow from the pilot into the main combustion zone ensures high combustion efficiency. The arrangement of the separation of the pilot and the main provides for efficiency and stability at low power, and stability at all operating conditions. The ASC distributes the heat release axially, reducing susceptibility to acoustics. One of the main advantages of this technology is the lower level of NOx at high power that can be achieved for reduced time.

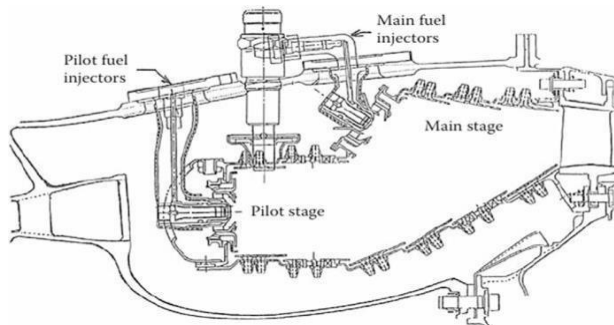


Figure 8. Schematic of Axially Staged Combustor [9].

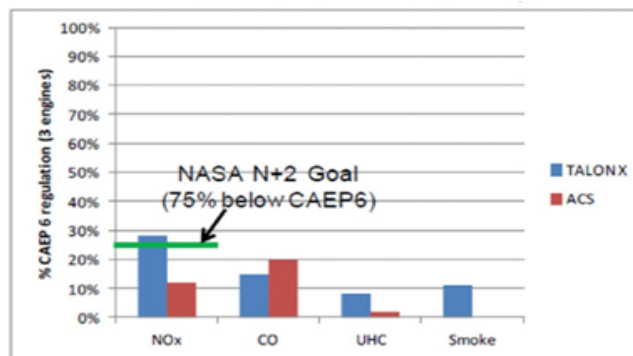


Figure 9. P&W ASC and new TALON X3 experimental Cup Test [13].

The ACS combustor 3-sector rig testing was completed at NASA Advanced Subsonic Combustion Rig (ASCR). The test yields very low NO_x emissions for the LTO NO_x emissions and has been verified to be 88% as shown in Fig. 9, relative to CAEP/6 for Phase I and 76% relative to CAEP/6 for Phase II, thereby exceeding the ERA project goal of 75% reduction [13].

F. Variable Geometry Combustors (VGC)

VGC is an unconventional method of reducing engine emissions and increasing combustion efficiency based on the distribution of air among the individual combustor zones. This technology provides the flexibility to control the airflow distribution inside a combustor and therefore has the ability to reduce the emissions on both high and low operating conditions without losing combustor performance. The air flow splitter as shown in Fig. 10 is driven by a hydraulic system and is allowed translational movement (moves forward and backwards) to vary the cross-sectional area and hence the air flow ratio into the primary zone. At lower power conditions, the degree of opening of the splitter increases the quantity of air diverted backwards to create a high primary fuel to air ration (FAR) [10]. As power is increased, the splitter opens, introducing more air into the primary zone to achieve low FAR, such that lean combustion is achieved for the purpose of NO_x and smoke reduction.

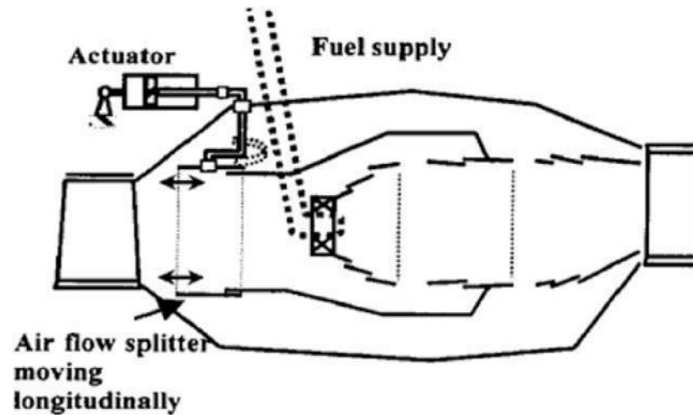


Figure 10. Variable Geometry Combustor Concept and Schematics [13].

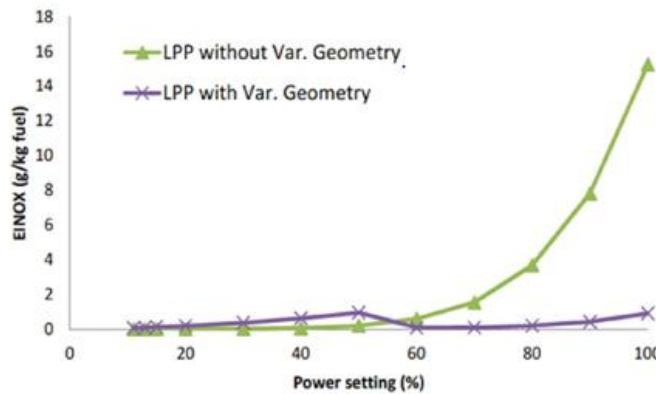


Figure 11. The Predicted EINO_x vs Power Setting for LPP with and without Variable Geometry [13].

Some of the challenges of VGS are complicated design, high cost and increased weight. LPP with variable geometry actually produces higher emissions when compared with an application with fixed geometry. The emissions prediction of variable geometry for aero application has been conducted by Pervier. Figure 11 depicts the comparison of NO_x emissions for LPP with and without variable geometry as a function of power setting. It can be noted that, at low power up to around 55%, LPP with variable geometry actually produces higher emissions than when compared with an application with fixed

geometry. The reason for this is because the air fraction to the near wall is close to stoichiometry, thereby leading to the increase in lean stability, combustion efficiency, and hence higher NO_x emissions.

G. Lean Direct Injection combustors (LDI)

Lean combustion in gas turbine combustors is fast becoming the norm due to environmental and efficiency concerns. A promising design is the lean direct injection (LDI). It has been of active interest due to its potential for low emissions under operational (high-temperature, high pressure) conditions. A schematic of Rolls Royce LDI is shown in Fig. 12. In this technology, the liquid fuel is injected from a venturi directly into the incoming swirling airstream. The swirling airflow is used both for atomizing the injected liquid and for fuel-air mixing. Auto-ignition and/or flashback are minimized since the fuel is neither premixed nor prevaporized [11]. The tests indicated NO_x levels in the region of 35%–45%, relative to CAEP/6 have been obtained. Limited emissions data is available in the public domain for LDI because it is still under development. No ICAO certified data has been produced yet [13].

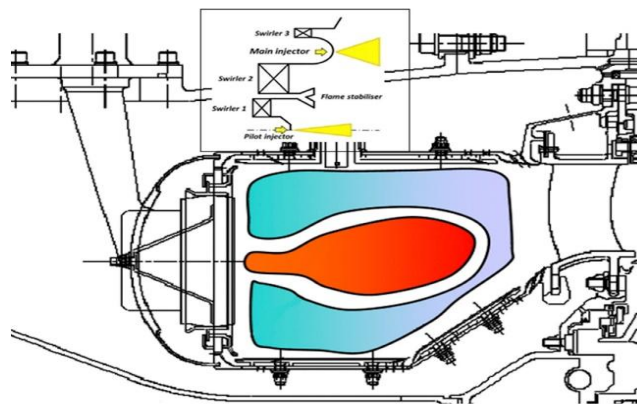


Figure 12. Schematics and Concept of RR LDI [13].

III. CONCLUSION

This paper provides a comprehensive review of low emissions combustion technologies for modern aero gas turbines. The review considers current high Technologies Readiness Level (TRL) technologies aimed at reducing emissions. It is observed that although the turbine inlet temperature is the major factor in determining the overall efficiency of the gas turbine, but higher inlet temperatures will result in larger NO_x emissions. So the essential requirement of new combustor design is a trade-off between low NO_x and improved efficiency. The current technologies employed in aero gas turbine engines show promising results in reducing NO_x emissions, but the updated regulations which include stringent standards pave way for researchers and manufacturers to improve these technologies by issuing updated versions of these technologies or creating new technologies with new concepts. Hence, there is a remarkable and continuous development in this field of research.

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