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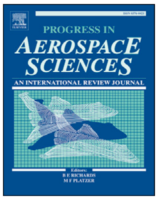

Review of modern low emissions combustion technologies for aero gas turbine engines

Yize Liu [a,*], Xiaoxiao Sun [a], Vishal Sethi [a], Devaiah Nalianda [a], Yi-Guang Li [a], Lu Wang [b]

[a] *Propulsion Engineering Centre, Cranfield University, Bedfordshire MK43 0AL, UK*
[b] *AECC Hunan Aviation Powerplant Research Institute, Zhuzhou, Hunan, China*

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ABSTRACT

Pollutant emissions from aircraft in the vicinity of airports and at altitude are of great public concern due to their impact on environment and human health. The legislations aimed at limiting aircraft emissions have become more stringent over the past few decades. This has resulted in an urgent need to develop low emissions combustors in order to meet legislative requirements and reduce the impact of civil aviation on the environment.

This article provides a comprehensive review of low emissions combustion technologies for modern aero gas turbines. The review considers current high Technologies Readiness Level (TRL) technologies including Rich-Burn Quick-quench Lean-burn (RQL), Double Annular Combustor (DAC), Twin Annular Premixing Swirler combustors (TAPS), Lean Direct Injection (LDI). It further reviews some of the advanced technologies at lower TRL. These include NASA multi-point LDI, Lean Premixed Prevaporised (LPP), Axially Staged Combustors (ASC) and Variable Geometry Combustors (VGC).

The focus of the review is placed on working principles, a review of the key technologies (includes the key technology features, methods of realising the technology, associated technology advantages and design challenges, progress in development), technology application and emissions mitigation potential. The article concludes the technology review by providing a technology evaluation matrix based on a number of combustion performance criteria including altitude relight auto-ignition flashback, combustion stability, combustion efficiency, pressure loss, size and weight, liner life and exit temperature distribution.

1. Introduction

The main pollutants emitted by aircraft are in the form of NOx (comprising NO and NO$_2$), Unburned Hydrocarbons UHC, CO, Sulphur Oxides (SOx) and Particulate matter PM that contains mainly smoke/soot. The effect of emissions on human health is summarised in Table 1 [152]. Aviation emissions generally have two main impacts: one on the local air quality, specifically in the vicinity of airports; and the second on global climate. In the vicinity of airports, the pollutant emission of primary concern is NOx (NO and NO$_2$), is produced by aircraft, ground services equipment and access road traffic. Aircraft NOx emissions contribute between 70% and 80% of total airport NOx emissions. A comprehensive global prediction of future emission trends that affect local air quality has been conducted by the Committee on Aviation Environmental Protection (CAEP) [152]. As shown in Fig. 1, results indicate that NOx emissions below 3000 feet will increase from 0.25 million metric tonnes (Mt) in 2006, as the baseline, to between 0.52Mt and 0.72Mt in 2036. NOx emitted by aircraft at low altitude contributes to the formation of the ozone that leads to human health issues and local air quality, whereas at high altitude NOx depletes ozone and results in the increase in the ground level Ultraviolet (UV) radiation.

The early combustor technology: ‘conventional’ combustors have been evolved over seven decades. Combustion is initiated in the primary zone with a fuel-air ratio close to stoichiometric value that leads to maximum heat release. Air that is initially bypassed from the combustor dome entry is then gradually admitted into the primary, secondary and tertiary zones to enable stable and complete combustion process and control of exit temperature distribution. The schematic drawing is shown in Fig. 52. Older conventional combustors contain longer liners (with length to dome ratio is greater than 2.0) hence resulting in longer residence time to assure high combustion efficiency. Pressure atomisers with diffusion based combustion were also extensively employed as it was advantageous in having wider stability limits, strong flashback resistance and improved engine operability. On the other hand, the less uniform

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* Corresponding author.
E-mail address: yizeliu.liu@cranfield.ac.uk (Y. Liu).

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Nomenclature

ACARE	Advisory Council for Aviation Research and Innovation in Europe
ACS	Axial Controlled Stoichiometry
ASC	Axially Staged Combustor
CAEE	Committee on Aircraft Engine Emissions
CAEP	Committee on Aviation Environmental Protection
CAN	Committee on Aircraft Noise
CMC	Ceramic Matrix Composite
COMAC	Commercial Aircraft Corporation of China
CRZ	Corner Recirculation Zone
DAC	Double Annular Combustor
ECCP	Experimental Clean Combustor Program
EEC	Electronic Engine Control
EI	Emission Index
ERA	Environmentally Responsible Aviation
ETS	Emissions Trading Scheme
FAA	Federal Aviation Administration
FAR	Fuel Air Ratio
FBN	Fuel Bonded Nitrogen
HC	Hydrocarbon
HSR	High Speed Research
ICAO	International Civil Aviation Organisation
IE	Independent Expert
IRA	Intercooled Recuperative
LBO	Lean Blowout
LDI	Lean Direct Injection
LEMCOTEC	Low Emission Core Engine Technology
LPP	Lean Premixed Prevaporised
LT	Long Term
LTO	Landing-takeoff
MFTF	Mixed Flow Turbofan
MLDI	Multipoint Lean Direct Injection
MRA	Multistage Radial/Axial
MT	Mid Term
NEWAC	New Aero Engine Core
NCC	National Combustion Code
OPR	Overall Pressure Ratio
OTDF	Overall Temperature Distribution Factor
PFC	Perfluorocarbon
PM	Particular Matter
PR	Pressure Ratio
P_3	Combustor inlet pressure
RQL	Rich-burn Quick-quench Lean-burn
RTDF	Radial Temperature Distribution Factor
SAC	Single Annular Combustor
SD	Stepped Dome
SFC	Specific Fuel Consumption
SLS	Sea Level Static
SN	Smoke Number
SV-LDI	Swirl-Venturi Lean Direct Injection
TAPS	Twin Annular Premixing Swirler
TALON	Technology for Advanced Low NOx
TCLA	Turbine Cooling and Leakage Air
TET	Turbine Entry Temperature
TRL	Technologies Readiness Level
T_3	Combustor inlet temperature
UHC	Unburned Hydrocarbons
UV	Ultraviolet
VGC	Variable Geometry Combustor

fuel-air mixing resulted in higher local temperature and rich stoichiometry, leading to large NOx production and soot formation. The general emissions levels for conventional combustors (thrust levels over 26.7kN) are greater than CAEP/1 or ICAO 1986 standard, as summarised in Table 2.

Over the past 40–50 years, the aviation industry has been capable of reducing fuel consumption by 70% while also limiting noise and reducing gaseous CO and HC emissions by approximately 50 and 90%, respectively [15]. This is mainly due to technology improvement in materials and cooling that enable engines to operate at higher Overall Pressure Ratios OPRs and Turbine Entry Temperatures (TET) to increase thermal efficiency which in turn reduces the engine specific fuel consumption (SFC) for economic benefit. This leads to high combustor inlet temperature and pressure. These wide environmental benefits (e.g. CO_2 reduction) achieved through higher OPR and TET therefore also led to an increase in NOx emission. Until 1970s, when larger OPR engines were developed less attention was paid to NOx emissions until serious concerns were raised by the general public on the effects of NOx on human health and climate.

These concerns gave rise to the first official aircraft emissions regulations, which were imposed in the 1960s and 1970s. Later the International Civil Aeronautics Organisation (ICAO) adopted a standard that applied to all in-production engines in 1986, namely the CAEP/1 or ICAO 1986 standard. ICAO has updated and published more stringent standards for NOx emissions during subsequent ICAO meetings. These regulations drive the development of low emissions technology and the consequence of which is that several emission reduction targets were implemented worldwide to fulfil the future legislative requirements.

The development of low emission combustor concepts for aero engines has been underway since the mid-1970s based on the experience gained from single annular conventional combustors (sometimes referred to as PreLEC, such as in Ref. [10]). The improvements of fuel injection devices along with combustion and dilution flow optimisation led to the state-of-the-art (at the time) *Low-Emissions Combustor (LEC) technology* [11–14], termed as ‘old single annular’ that is distinct from old conventional combustor, in Fig. 2 which also summarises the emissions level as a function of engine OPRs for different CAEP standards. Lean dome combustion was later followed by the creation of *Double Annular Combustor (DAC)* being considered as an alternative to LEC. The DAC technology enabled achieving up to 60% reduction from the first International Civil Aeronautics Organisation (ICAO) standard as well as a 50% reduction in cruise NOx [15]. In order to further reduce emissions, lean partially premixed combustion was introduced. This was achieved through the inception of *Twin Annular Premixing Swirler TAPS* combustors. This technology was developed later as the next generation for further emission reduction and achieved a remarkable reduction of 60% against CAEP/6. In the meantime, some advanced rich dome combustion technologies were developed based on experience gained from LEC technology. Typical examples include the Pratt & Whitney P&W TALON series and Rolls Royce Phase 5. Both TAPS and advanced rich burn technologies feature a single annular version, shown as ‘current single annular’ in Fig. 2.

Future aero gas turbines will develop technologies to improve the fuel efficiency by increasing the engine Overall Pressure Ratios OPRs (from 25 to 60–75) when compared with generation of previous engines. The higher OPRs have made it challenging to contain NOx level without changing the fuel injection concept. Therefore, some new concepts such as NASA multi-point injection are currently under development. Future high OPR engines pose a design challenge for premixed combustion due to risks of auto-ignition and flashback. These risks can be mitigated by Lean Direction Injection such as Rolls Royce LDI that is under development and approaching a Technology Readiness Level (TRL) of 7. The