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On the trade-off between aviation NO_x and energy efficiency

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HIGHLIGHTS

- A NO_x emissions correlation for RQL combustors is derived; an approach for modelling LDI designs is also presented.
- Improving engine propulsive efficiency has a beneficial effect on NO_x emissions at sea level.
- Improving engine thermal efficiency has a detrimental effect on NO_x emissions for RQL combustors, but not for LDI designs.
- Future emissions certification legislation needs to become more stringent and comprehensive.

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ABSTRACT

This study aims to assess the trade-off between the ever-increasing energy efficiency of modern aero-engines and their NO_x performance. The work builds on performance models previously developed to optimise the specific fuel consumption of future aero-engine designs. As part of the present work a simple and adaptable NO_x emissions correlation for Rich-burn Quick-quench Lean-burn combustor designs is derived. The proposed model is computationally inexpensive and sufficiently accurate for use in aero-engine multi-disciplinary conceptual design tools. Furthermore, it is possible to adapt the correlation to model the NO_x emissions of combustors designed for very aggressive future cycles. An approach to lean-burn combustor NO_x emissions modelling is also presented. The simulation results show that improving engine propulsive efficiency is likely to have a benign effect on NO_x emissions at high altitude; at sea-level conditions NO_x emissions are particularly likely to reduce. Improving engine thermal efficiency however has a detrimental effect on NO_x emissions from RQL combustors, both at high altitude and particularly at sea-level conditions. LDI combustor technology does not demonstrate such behaviour. Current legislation permits trading NO_x emissions engine efficiency and hence reduce CO_2 emissions. If we are to reduce the contribution of aviation to global warming, however, future certification legislation may need to become more stringent and comprehensive.

1. Introduction

Public awareness and political concern over aviation-induced pollution has increased substantially in recent decades, driving policy and technological developments. The Intergovernmental Panel on Climate Change (IPCC) [1] provides a good introduction to the impact of aviation induced emissions on the global atmosphere; the interested reader may refer to the latest synthesis report [2]. A good review on aero engine pollutant emissions, and an introduction to some of the technologies for reducing them, is given by Wulff and Hourmouziadis [3]. Mongia [4], Matthes et al. [5], Lieuwen and Yang [6] and Masiol and Harrison [7] provide a fresh perspective on the topic and a comprehensive summary of the latest technological developments.

Overall, significant reductions in airliner fuel burn and associated CO_2 emissions have been achieved [8] in the past few decades. This has been realised primarily by reducing turbofan engine Specific Fuel Consumption (SFC). SFC is inversely proportional to both thermal and propulsive efficiency. Propulsive efficiency has been improved by increasing fan diameter and fan flow to reduce specific thrust (i.e. net thrust divided by mass flow). For very low specific thrust levels open rotor designs may be considered [9,10]. Thermal efficiency has been improved mainly by increasing the Overall Pressure Ratio (OPR) and High Pressure Turbine (HPT) rotor entry temperature T_{41} to the extent possible with current materials and design technologies. An alternative approach is the use of advanced intercooled cycles as documented by several researchers [11–18]. Intercooled-recuperated core cycles have also received significant attention [19–26]. For an extensive literature review on both core concepts the interested reader is referred to [27].

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Nomenclature

AFR	Air to Fuel Ratio
BPR	ByPass Ratio
CAEP	Committee on Aviation Environmental Protection
CO_2	carbon dioxide
CRFD	Computational Reactive Fluid Dynamics
Comb.	Combustor
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DNS	Direct Numerical Simulation
$EINO_x$	NO_x Emissions Index (g NO_x/kg fuel)
EIS	Entry Into Service
EOR	End Of Runway
Exp.	Exponent
FPR	Fan Pressure Ratio
h	Ambient humidity (kg H_2O/kg dry air)
HD	Hot-Day
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ICAO	International Civil Aviation Organization
Id.	Ideal
IPC	Intermediate Pressure Compressor
IPCC	International Panel on Climate Change
IPT	Intermediate Pressure Turbine
ISA	International Standard Atmosphere
LDI	Lean Direct Injection
LES	Large Eddy Simulation
LPT	Low Pressure Turbine
LT	Long Term
LTO	Landing and Take-Off cycle
MCR	Mid-Cruise
MT	Medium Term
NEWAC	NEW Aero engine Core concepts
n	pressure ratio split exponent
NO_x	mono-nitrogen oxides
OPR	Engine Overall Pressure Ratio
P	total pressure (Pa)
Ref.	Reference
RANS	Reynolds-Averaged Navier–Stokes
RQL	Rich-burn Quick-quench Lean-burn
SL	Sea-Level
SLS	Sea-Level Static
SFC	Engine Specific Fuel Consumption (g/(kN s))
SFN	Engine Specific Thrust (m/s)
T	total temperature (K)
T_{flame}	combustor flame temperature (K)
T_m	metal temperature (K)
TO	Take-Off
TBC	Thermal Barrier Coating
TOC	Top Of Climb
V_{id}	jet velocity from full expansion in an ideal convergent–divergent nozzle
W	mass flow
Δ	difference
2	fan entry
24	IPC entry
25	IPC delivery
26	HPC entry
3	HPC delivery
31	combustor entry
4	combustor delivery
41	HPT rotor entry
47	LPT entry temperature
8	core nozzle throat
18	bypass nozzle throat

Although CO_2 emissions per passenger-kilometer have been decreasing the same cannot be said for NO_x emissions. Aggressive turbofan designs that reduce CO_2 emissions – such as increased OPR and T_{41} designs – can increase the production of NO_x emissions due to higher flame temperatures resulting in less mixing air being available for emissions control. An important research question therefore rises:

What is the trade-off between low CO_2 and NO_x considering the influence of current emissions legislation?

For conceptual designs of more environmental friendly aero engines with advanced technologies, the need arises for sufficiently accurate models for predicting engine performance and pollutant emissions. Advanced engine performance models developed by the authors have been previously utilised for optimising aero-engine energy efficiency [27–30]. Although the optimisation results have been very promising little attention was given in these studies on the accurate prediction of gaseous pollutants other than CO_2.

Prediction models of gaseous emissions for aero gas turbine combustors typically need to focus on the following pollutants: NO_x, CO, unburned hydrocarbons and smoke. Lefebvre [31] describes thoroughly the formation mechanisms for these pollutants, focusing on the influence of various parameters such as temperature and pressure. Combustion and emissions prediction models can be divided broadly into the following categories [32]:

- Semi-empirical.
- Phenomenological (e.g. stirred reactor networks).
- 3-D CRFD RANS (Computational Reactive Fluid Dynamics, Reynolds-Averaged Navier–Stokes equations).
- 3-D CRFD LES (Computational Reactive Fluid Dynamics, Large Eddy Simulation modelling).
- Direct Numerical Simulation (DNS).

It is evident that, although direct numerical simulation is the most powerful of the above mentioned methods, the associated computational time and cost is prohibitive. Large eddy simulations offer a convenient computational trade-off between DNS and RANS, and have been used successfully for many years for studying turbulent combustion processes. A common disadvantage between all three analytical methods is the requirement for a large amount of input data (i.e. boundary conditions) that are not always readily available. Semi-empirical models are well suited for conceptual design of future aero-engine concepts, since only a limited amount of data is usually available at the beginning of such projects.

The latter constraint makes the implementation of the computationally more expensive phenomenological models, within an overarching conceptual design tool for advanced system analysis such as the ones utilised in [33–39], a fairly challenging task. For such tools, it is imperative that the different disciplines are considered at a reduced level of modelling complexity, and therefore semi-empirical models are the preferred choice.

It should be noted that developing robust and generic prediction models for NO_x emissions is not a trivial task. In the authors' view, gas turbine combustor design has for a long time been, and largely still is, characterised as a "black art"; many design principles are still based primarily on experimental observations and empirical

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