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A NO_x Emissions Correlation for Modern RQL Combustors

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Abstract

This study begins with a review of existing emissions prediction methodologies for Rich-burn Quick-quench Lean-burn combustors. The need for a simple and adaptable NO_x emissions correlation for such combustor designs as used in state-of-the-art civil turbofan engines is discussed. The derivation of a new correlation is consequently presented. 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. A case study is presented focusing on the NO_x performance of advanced future cycles relative to current and future certification limits.

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Keywords: NOx emissions; RQL; Combustor; Gas Turbine; Simulation; Aircraft Engine;

1. Introduction

Public awareness and political concern over aviation-induced pollution has increased substantially during the last 30 years; and so have the efforts to address the problem. Penner et al. [1] provide a good introduction to the impact of aviation induced emissions on the global atmosphere. A review on aero engine pollutant emissions, and some of the technologies currently under research for reducing them, is given by Wulff and Hourmouziadis [2]. For conceptual design of more environmental friendly aero engines with

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advanced technologies, the need arises for sufficiently accurate models for estimating pollutant emissions and their impact on the environment.

Prediction models of gaseous emissions for aero gas turbine combustors typically need to focus on the following pollutants: NOx, CO, unburned hydrocarbons and smoke. Lefebvre [3] 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 into the following categories [4]:

- Semi-empirical
- Phenomenological (e.g. stirred reactor networks)
- 3-D CRFD RANS (Computational Reactive Fluid Dynamics, Reynolds-Averaged Navier–Stokes equations)
- 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. An additional disadvantage of all 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 novel 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 such as the one utilized in [5], 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.

Nomenclature

CAEP	Committee on Aviation Environmental Protection
CRFD	Computational Reactive Fluid Dynamics
DLR	Deutschen Zentrums für Luft- und Raumfahrt (German Aerospace Center)
DNS	Direct Numerical Simulation
EINOx	NOx Emissions Index (g NOx / kg fuel)
ICAO	International Civil Aviation Organization
LT	Long Term
LTO	Landing and Take-Off
MT	Medium Term
NEWAC	NEW Aero engine Core concepts
RANS	Reynolds-Averaged Navier–Stokes
RQL	Rich-burn Quick-quench Lean-burn

2. Review of existing semi-empirical correlations for NO_x emissions prediction

Over the years, a large amount of semi-empirical correlations have been proposed by several authors. These models assume that the amount of NO_x is dependent on the following three factors [3]: (i) mean residence time in the combustor, (ii) chemical reaction rates, and (iii) mixing rates.

A large amount of semi-empirical correlations may be found in the literature for different combustor designs. Mellor [6] provides good insight on semi-empirical correlations derived before the 1980's. Becker and Perkavec [7], and Nicol et al. [8] provide an analytical review of various semi-empirical models derived up to the mid 1990's. For modern conventional aero engine combustors a large variety of semi-empirical correlations can be found in [9], [10] and [11].

The main disadvantage of all the above models is that they will only hold well for combustors designs of the same technology level as the original combustors that were used for deriving these correlations (via curve fitting of available experimental data). In certain occasions, though, sufficiently accurate predictions could be produced for other combustor designs if a limited amount of data is available; one would need to adapt the constants in these correlations in order to produce a good fit with the new data available [12]. On the other hand, when no experimental data are available for insight, these correlations may result in significantly inaccurate predictions.

The International Civil Aviation Organization (ICAO) maintains a large databank of NO_x emissions measurements from different types of aircraft engines [13], taken at sea level static conditions according to ICAO Annex 16 engine emissions certification procedures [14]. For predicting emissions at altitude a variety of P_3T_3 methods may be used (also known as ratio or ``reference'' methods). Although also semi-empirical in nature, they are applicable to any conventional core turbofan engine for which reference NO_x data are available; these methods essentially correct ground level measurements to an altitude condition taking into account some, or all, of the following parameters: combustor inlet temperature, inlet pressure, fuel mass flow and overall fuel to air ratio, flight Mach number and specific humidity.

The P_3T_3 method, discussed by [15], uses combustor inlet temperature and pressure, and fuel to air ratio for correcting ground level measurements. Other similar methodologies include the Boeing2 fuel flow method ([16] and [17]) and the DLR fuel flow method ([18], [19] and [20]). These methods take advantage of the fact that P_3 and T_3 effects can be well correlated with engine fuel flow and flight conditions, at least for turbofan engines without variable geometry; they can therefore be considered as variations of the ``standard'' $P_3T_3$ method. The main advantage of fuel flow methods, compared to the ``standard'' P_3T_3 method, lays with the fact that they don't require sensitive engine performance data. On the other hand, the ``standard'' P_3T_3 method can provide predictions that reflect better the influence of engine performance on NO_x emissions, in those cases where engine performance data are available. Existing fuel flow methods are not suitable for heat-exchanged core turbofan engines, with or without variable geometry, due to the different correlation of fuel flow and flight conditions with P_3 and T_3 Finally, all these methods (``standard'' P_3T_3 and fuel flow) have one issue in common which forms their main limitation; they require $EINO_x$ measurement data at sea level static conditions to be used as reference. In those cases where reference measurement data are not available, for example during the conceptual design of a novel engine configuration, P_3T_3 methods are of limited use.

A large selection of public domain semi-empirical correlations and P_3T_3 methods, from the references discussed earlier, have been implemented in the gas turbine conceptual design tool presented and utilized in [5]. Unfortunately, each correlation is suitable only for a particular combustor concept and corporate technology level status. There is therefore a need for a NOx correlation that is suitable for a variety of past, modern and future combustor designs, and can be adapted for use within future aggressive gas turbine cycles and resulting combustor design requirements.

3. Derivation of a NO_x correlation for modern RQL combustors

As part of this work a semi-empirical correlation has been derived for modern RQL single-annular combustor designs intended for use in high overall pressure ratio gas turbine cycles. The correlation is based on a large number of engine performance data produced using an in-house library of engine performance models available to the authors, and corresponding NO_x emissions measurement data from the ICAO engine emissions databank [13]. The predictive capability of the proposed NO_x emissions correlation has also been verified within the European Union collaborative research project NEWAC, using emissions data available within the project for high overall pressure ratio turbofan designs with technology levels consistent with a year of entry into service around 2020 [21]. The proposed NO_x correlation is described by the following equation:

$$EINOx = \left(a + b \cdot e^{(c \cdot T_{31})}\right) \cdot \left(\frac{P_{31}}{P_{31,ref}}\right)^{d} \cdot e^{f \cdot (h_{SL} - h)} \cdot \left(\frac{\Delta T_{comb}}{\Delta T_{comb,ref}}\right)^{TF} \quad (1)$$

where P_{31} is in [kPa], T_{31} is in [K], h is in [kg H_2O / kg dry air], and ΔT_{comb} is in [K].

Default values for the constants and exponents in Eq. (1) are given in Table 1 and are suitable for modern civil aero engines that incorporate RQL technology combustors and are currently in production. The fit of the proposed NOx emissions correlation to measured data from the ICAO databank [13] is very good, as illustrated in Fig. 1 (a). These default values can also be considered as suitable for a high overall pressure ratio turbofan engine with an expected year of entry into service around 2020.

Table 1. Proposed NO_x emissions correlation constant and exponent default values for modern RQL combustor designs

Parameter	Default value
a	8.4
b	0.0209
c	0.0082
d	0.4
f	19
TF	0
$P_{31,ref}$ [kPa]	3000
ΔT_{comb} [K].	300
h [kg H_2O / kg dry air]	0.006344

For very aggressive future cycles, with high combustor inlet temperature and low air to fuel ratio values, the proposed correlation could very well be underpredicting NO_x emission levels. Designing a conventional rich-burn single-annular combustor for such conditions could prove a challenging task, mainly due to the limitations imposed by the need for adequate combustor liner film-cooling air as well as maintaining an acceptable temperature traverse quality [3]. For such cycles, the exponent *TF* may be used as a technology factor for adapting the proposed NO_x emissions correlation to experimental data - or results from higher fidelity NO_x prediction models - as illustrated in Fig. 1(b).

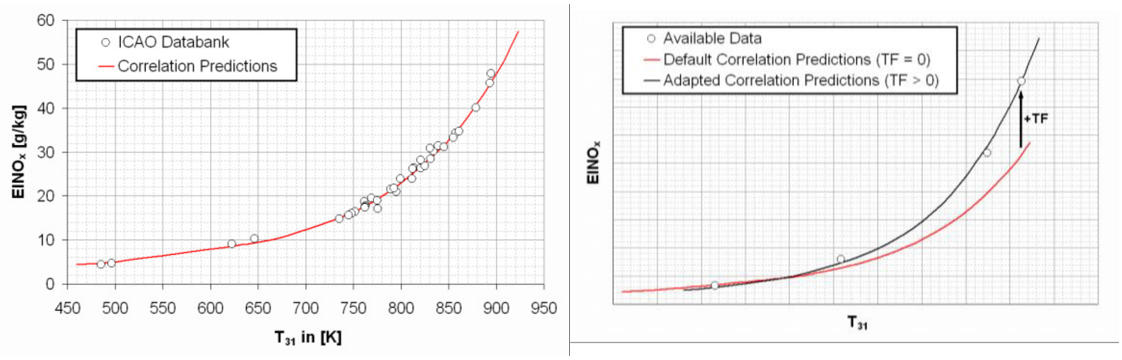

Fig. 1. (a) Fit of proposed NOx emissions correlation fit to measured data from the ICAO databank; (b) Example of using the technology factor *TF* facility to adapt the proposed NOx emissions correlation to available data.

This procedure was successfully used to adapt the default correlation to available data for some of the more aggressive cycles studied under the NEWAC project. The deviation of the proposed NO_x emissions correlation predictions from available proprietary data for the NEWAC engine configurations - and from public domain data for modern civil aero engines currently in production from the ICAO databank [13] - is well than 10% (of full scale value) and follows well the physical trends, as illustrated in Fig. 2. The accuracy of the correlation is therefore considered to be sufficient for the multi-disciplinary aero-engine conceptual design studies.

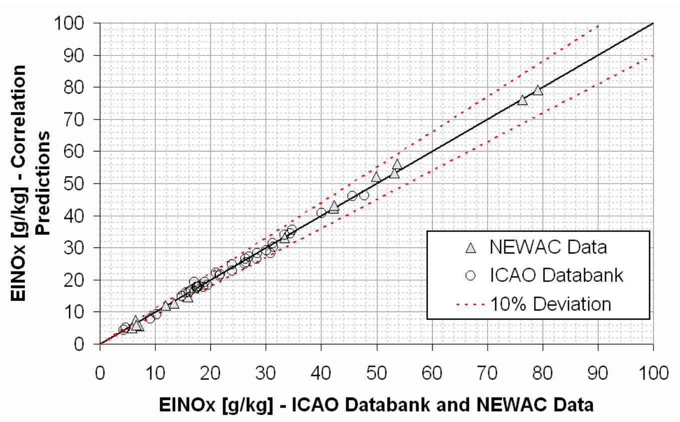

Fig. 2. Deviation of correlation predictions from available data [13]

4. Case study

The proposed correlation can be used for carrying out NOx emissions assessment of future aero-engine designs incorporating modern RQL combustors. One such assessment, focused on the prediction of NOx emissions levels for the ICAO Landing and Take-Off (LTO) cycle, is discussed in detail in [22] and shall be presented here only as a short example. The predictions from the study are compared through Fig. 3 against ICAO Annex 16 Volume II legislative limits [14], as well as the Medium Term (MT) and Long Term (LT) technology goals set by CAEP [23]. Balloons have been used to indicate the uncertainty in the NOx predictions due to the lower technology readiness level associated with the introduction of RQL combustor designs in the proposed very aggressive future cycles. The study has identified that a sufficient margin against the ICAO CAEP/6 LTO cycle NOx certification limit may be achieved for all the configurations that have been assessed assuming technology levels consistent with a year of entry into service around 2020.

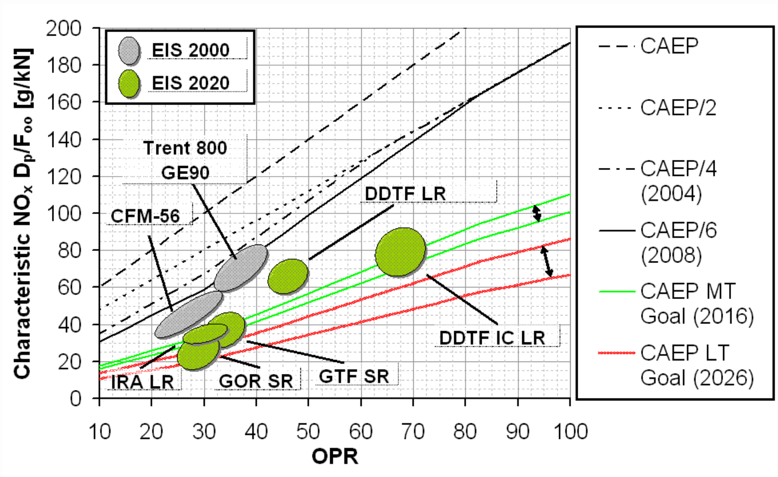

Fig. 3. NOx emissions assessment for different future aero engine design concepts

5. Conclusions

A simple and adaptable NOx emissions correlation for modern and future RQL combustors as used in state-of-the-art civil turbofan engines has been 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 NOx emissions of RQL combustors designed for very aggressive future cycles. The correlation is particularly useful for assessing the NOx performance of advanced future cycles relative to current and future certification limits.

References

[1] Penner JE, Lister DH, Griggs DJ, Dokken DJ, McFarland M. *Aviation and the Global Atmosphere: A Special Report of IPCC Working Groups I and III in Collaboration with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer*. United Kingdom: Cambridge University Press; 1999.

[2] Wulff A., Hourmouziadis J. Technology Review of Aeroengine Pollutant Emissions. *Aerospace Science and Technology* 1997; 1(8):557-572.

[3] Lefebvre A.H. *Gas Turbine Combustion.* 2nd ed. PA, USA: Taylor & Francis; 1999.

[4] Tomboulides A. Summer School on the LES of Reacting Flows. *ERCOFTAC SIG28 (presentation).* Thessaloniki, Greece; 2004.

[5] Kyprianidis K.G., Rolt A.M., Grönstedt T. Multidisciplinary Analysis of a Geared Fan Intercooled Core Aero-Engine. *Journal of Engineering for Gas Turbines and Power* 2014;136(1):011203.

[6] Mellor A.M. Semi-Empirical Correlations for Gas Turbine Emissions, Ignition, and Flame Stabilization. *Progress in Energy and Combustion Science* 1981; 6(4):347-358.

[7] Becker T., Perkavec, M.A. The Capability of Different Semianalytical Equations for Estimation of NOx Emissions of Gas Turbines. *ASME TURBO EXPO 94 Proceedings, 94-GT-282.* The Hague, The Netherlands; 1994.

[8] Nicol D.G., Malte P.C., Steele R.C. Simplified Models for NOx Production Rates in Lean-Premixed Combustion. *ASME TURBO EXPO 94 Proceedings, 94-GT-432.* The Hague, The Netherlands; 1994.

[9] Committee of Aeronautical Technologies - Aeronautics and Space Engineering Board - Commission on Engineering and Technical Systems - National Research Council. *Aeronautical Technology for the Twenty-First Century.* ISBN 978-0-309-04732-6. Washington, D.C., USA: National Academy Press; 1992.

[10] Lecht M. Simplified NOx Emissions Prediction: Fuel Flow Methods. *The NEPAir Workshop, WP2 presenation slides.* Toulouse, France; 2002.

[11] Tilston J., Larkman J., Plohr M., Doepelheuer A., Lischer T., Zarzalis N. Future Engine Cycle Prediction and Emissions Study. *CYPRESS Final Publishable Report, Issue 2.0 (Version 3)*; 2003.

[12] Tsalavoutas A., Kelaidis M., Thoma N., Mathioudakis K. Correlations Adaptation for Optimal Emissions Prediction, *ASME TURBO EXPO 2007 Proceedings, GT2007-27060.* Montreal, Canada; 2007.

[13] International Civil Aviation Organization. ICAO Aircraft Engine Emissions Databank. *http://easa.europa.eu/document-library/icao-aircraft-engine-emissions-databank* ; Last updated March 2014.

[14] International Civil Aviation Organization. *International Standards and Recommended Practices -- Environmental Protection, Annex 16 to the Convention on International Civil Aviation, Volume II - Aircraft Engine Emissions.* 2nd edition plus ammendments. Montréal, Canada: ICAO; 2003.

[15] Norman P.D., Lister D.H., Lecht M., Madden P., Park K., Penanhoat O., Plaisance C., Renger K. Development of the Technical Basis for a New Emissions Parameter Covering the Whole Aircraft Operation: NEPAIR, Final Technical Report *NEPAIR/WP4/WPR/01*; 2003.

[16] Martin R.L., Oncina C.A., Zeeben J.P. A Simplified Method for Estimating Aircraft Engine Emissions. *Technical Report.* Boeing Company; 1994.

[17] Baughcum S.L., Tritz T.G., Henderson S.C., Pickett D.C. Boeing Method 2 Fuel Flow Methodology Description. *Scheduled Civil Aircraft Emission Inventories for 1992: Database Development and Analysis*. NASA-CR-4700. Hampton, VA, USA: NASA Langley Research Center; 1996.

[18] Deidewig F., Dopelheuer A., Lecht M. Methods to Assess Engine Emissions in Flight. *20th ICAS Congress Proceedings, Vol. I.* Sorrento, Italy; 1996.

[19] Dopelheuer A., Lecht, M. Influence of Engine Performance on Emission Characteristics. *RTO AVT Symposium on "Gas Turbine Engine Combustion, Emissions and Alternative Fuels" Proceedings, RTO-MP-14*. Lisbon, Portugal; 1998.

[20] Dopelheuer A. Aircraft Emission Parameter Modelling. *Air & Space Europe* 2000; 2(3):34-37.

[21] Kyprianidis K.G. Multi-Disciplinary Conceptual Design of Future Jet Engine Systems. *PhD thesis.* Cranfield, United Kingdom: Cranfield University; 2010.

[22] Kyprianidis K.G. Future Aero Engine Designs: An Evolving Vision. In: Benini E., editor. *Advances in Gas Turbine Technology*, Rijeka, Croatia: InTech; 2011, ch. 1, p. 3-24.

[23] Newton P., Holsclaw C., Ko M., Ralph M. Long Term Technology Goals for CAEP/7. *Presented to the Seventh Meeting of CAEP*; 2007.

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Biography

Konstantinos Kyprianidis is an Associate Professor (Docent) within the Future Energy Center at Mälardalen University (MDH). He is concurrently affiliated with Cranfield University as a scholar within the Propulsion Engineering Centre. He is active in gas turbine performance and multi-disciplinary conceptual design, NIR spectroscopy and process modelling for control optimization.