Prediction of emissions in turbojet engines exhausts: relationship between nitrogen oxides emission index ($E_{\text{INOx}}$) and the operational parameters

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Abstract

The prediction of nitrogen oxides emissions in turbojet engines exhausts remains a field of immense importance given the increasing coercive environmental requirements in relation to the emissions from turbojet engines. Emissions of nitrogen oxides (NOx) are subjected to limits fixed by legislators in a lot of countries because of their toxic character beyond specific concentrations in the air and their effects on climate change. However, analytical methods used to evaluate the quantities of the emissions are not efficiently established because of a lack of complete understanding of the phenomena governing the formation of the NOx in turbojet engines. It is a combination of chemical, thermal, and fluid dynamic processes. In this paper, a more accurate empirical correlation is determined for the prediction of nitrogen oxides emission index ($E_{\text{INOx}}$) in turbojet engines exhausts using the main combustion operational parameters. The relationship between $E_{\text{INOx}}$ and the following parameters: fuel flow rate, output power, pressure ratio, efficiency, flame temperature and combustor inlet temperature is analysed with 227 ICAO certification data measured on turbojets engines from manufacturers such as Pratt and Whitney, General Electric, CFM International and Rolls-Royce. A set of 556 test point data used to show flame and combustor inlet temperature relationship with NOx emission index is from the work of G.F. Pearce et al. on twelve gas turbine engines. From this analysis it can be noticed that the relationship between $E_{\text{INOx}}$ and flame temperature is strong but not as the relationship between $E_{\text{INOx}}$ and the combustor inlet temperature. Since the combustor inlet temperature is easier to measure, $E_{\text{INOx}}$ value can be deduce from it. By predicting NOx emissions from combustor inlet temperature we can avoid exhausts gas measurements and analysis, saving on time and money.

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1. Introduction

The prediction of nitrogen oxides (NOx) formation in turbojet engines by the chemical and the numerical simulation method didn’t produce expected results but the empirical method seems to carry a lot of hope. We look for an empirical correlation between the various reactor operational parameters and the NOx emission index with the purpose of avoiding heavy experimental equipments and time. Identification of the most important parameters of NOx emission index could allow for the reduction of NOx emissions from the conception and operation of turbojet engines. The relationship between the NOx emission index and the operational parameters is analysed and optimised by a least square method. The data used in this work is obtained from ICAO databank [1] and G.F. Pearce et al. [2]. The relationship between NOx emission index, flame temperature and inlet temperature, is evaluated on five other gas turbine engines from G.F. Pearce et al. experiments [2]. Through this analysis it is proven that a correlation linking combustor inlet temperature and NOx emission index is an efficient parameter of NOx emissions prediction without exhaust gases analysis.
1.1. Experimental data

The first piece of experimental data in this analysis is taken from ICAO data bank repertory [1]. The next set of experimental data is taken from an excellent piece of work done by Prof. D. Kretschmer and his colleagues [2] of the laboratories of Laval University and the Aeronautical Research Laboratory on the following gas turbine engines F101, J79-17A, J79-17C, PW and T56. In this work, 2200 data points were measured from 14 different experimental series. Nine different combustors of a very wide size range were investigated. Inlet temperature and pressure ranged from 290 to 851 K and from 0.1 to 1.4 MPa respectively.

2. Relationship between $m_f$ and $E_{\text{INOx}}$

The relationship between fuel flow rate and NOx emission index is analysed on 227 reactors (43 from CFMI, 80 from General Electric, 37 from Rolls-Royce and 67 from Pratt and Whitney). The results are shown in Figs. 1, 2 and 3. In Fig. 1, the relationship between $E_{\text{INOx}}$ and fuel flow rate is shown for 43 test points from CFMI engines. It is possible to observe that there is a strong relationship between fuel flow rate and $E_{\text{INOx}}$ measured during combustion operations on the same reactor. Even though this relationship is not the same in all the turbo-

Fig. 1. Relationship between $m_f$ and $E_{\text{INOx}}$ measured from 43 CFMI turbojet engines of ICAO data [1].

Fig. 2. Relationship between $m_f$ and $E_{\text{INOx}}$ measured from 227 ICAO data [1] on turbojet engines. $R^2 = 0.64$.

Fig. 3. Comparison between $E_{\text{INOx}}$ calculated according to correlation (2) and measured $E_{\text{INOx}}$ values from 227 ICAO [1]. $R^2 = 0.53$; SD = 23%.

The values of constants $A$ and $\alpha$ obtained by curve smoothing on the available 227 ICAO data [1] are: 20 and 0.6. $R^2$ is equal
to 0.64. The correlation is applicable to all the turbojet engines in this work. The correlation is:

\[ E_{\text{INOx}} = 20m_f0.6. \]  \hspace{1cm} (2)

### 3. Results and comments

The generalisation of correlation (2) in all the 227 turbojet engines can be considered as useful since it confirms the strong relationship between fuel flow rate and NOx emission index in the same combustion chamber as the validation of the correlation in Fig. 3 shows.

In Fig. 3, the values of \( E_{\text{INOx}} \) calculated according to correlation (2) are compared to the measured values of \( E_{\text{INOx}} \). The great majority of the points fall on the bisector line, except the high values of \( E_{\text{INOx}} \), that leave the line and move close to the \( Y \) axis. Correlation (2) has underestimated the phenomenon since the standard deviation of about 23% shows the gap between measured and calculated \( E_{\text{INOx}} \). This correlation is accurate when the number of test points, the standard deviation and the correlation index \( (R^2 = 0.53) \) are taken into account. It is necessary to analyse the relationship between \( E_{\text{INOx}} \) and those combustion parameters.

The relationship is characterised by its correlation index which is \( R^2 = 0.56 \).

#### 3.1. Relationship between \( E_{\text{INOx}} \) and \( F_{00} \)

The relationship between output power and NOx emission index on the 227 reactors used in this study is analysed by applying the same method as the previous case which was based on correlation (3) whose validation is shown in Fig. 4:

\[ E_{\text{INOx}} = F_{00}0.65. \]  \hspace{1cm} (3)

In Fig. 4, the validation of the correlation between \( E_{\text{INOx}} \) and output power is shown. The values of \( E_{\text{INOx}} \) calculated according to correlation (3) are compared to the measured values of \( E_{\text{INOx}} \). The positions of the points are not very different from those of the relationship between \( E_{\text{INOx}} \) and fuel flow. But the standard deviation of about 24% and the correlation index \( (R^2 = 0.51) \) are different from the case of fuel flow rate.

#### 3.2. Relationship between \( \pi_{00} \) and \( E_{\text{INOx}} \)

By using the same method as in the previous cases, correlation (4) shown below highlights the relationship between the compression ratio and the NOx emission index of 227 reactors used in this work.

\[ E_{\text{INOx}} = 0.6\pi_{00}^{1.2}. \]  \hspace{1cm} (4)

The validation of correlation (4) is shown in Fig. 5.

In Fig. 5, the validation of the relationship between \( E_{\text{INOx}} \) and compression ratio according to correlation (4) is shown. The values of \( E_{\text{INOx}} \) calculated according to correlation (4) are compared to the measured values of \( E_{\text{INOx}} \). The standard deviation is 29% and the correlation index \( R^2 \) is equal to 0.43. The relationship between the compression ratio and \( E_{\text{INOx}} \) is not as strong as in the previous case.

#### 3.3. Relationship between \( \eta \) and \( E_{\text{INOx}} \)

The relationship between efficiency and NOx emission index is characterised by correlation (5) below:

\[ E_{\text{INOx}} = 10^{-11} \eta^{6.985}. \]  \hspace{1cm} (5)

The relationship between efficiency and NOx emission index is shown in Fig. 6.

In Fig. 6, the positions of the points are not very different from those of the previous correlations. But the standard deviation and the correlation index \( (SD = 28\% \text{ and } R^2 = 0.51) \) are worse than the previous case.

In Figs. 3, 4, 5 and 6 it is possible to notice that the values of calculated \( E_{\text{INOx}} \) are lower than the measured values; correlations (2), (4), (5) and (6) have, underestimated the phenomenon. The relationship between \( E_{\text{INOx}} \) and fuel flow output power, compression ratio and efficiency are not sufficiently strong. The analysis continues with the relationship between \( E_{\text{INOx}} \) and the two parameters of flame temperature and combustor inlet temperature.
Fig. 6. Comparison between 227 calculated by correlation (5) and measured values of EINOx: $R^2 = 0.41$; SD = 28%; ARE = 0%.

Fig. 7. Combustor flame temperature versus measured EINOx using 556 test points from five turbojet engines [2] $R^2 = 0.99$.

3.4. Relationship between $T_f$ and EINOx

The relationship between flame temperature and NOx emission index in turbojet engines is analysed with the aid of 556 test points from the work of D. Kretschmer et al. [2]. Fig. 7 shows the correlation (6) obtained with this set of data.

$$\text{EINOx} = 2 \times 10^{-83} T_f^{24.696}. \quad (6)$$

In Fig. 7, it is possible to notice that the flame temperature has a strong effect on the NOx emission index as shown by the correlation index $R^2 = 0.99$. EINOx rises very fast with the variation of flame temperature. The measurement of flame temperature being complicated.

An attempt to find the relationship between inlet temperature and NOx emission index is necessary with the expectation that it will have a stronger relationship, since it is easier to measure.

3.5. Relationship between $T_3$ and EINOx

The relationship between the combustor inlet temperature ($T_3$) and EINOx is characterised by correlation (7):

$$\text{EINOx} = 4 \times 10^{-9} T_3^{3.364}. \quad (7)$$

Correlation (7) is shown in Fig. 8.

In Fig. 8, it is possible to notice that the EINOx versus combustor inlet temperature has nearly the same curve as EINOx versus flame temperature, but combustor inlet temperature has a stronger effect on the NOx emission index compared to the effect of flame temperature, as shown by the correlation index $R^2 = 1$. EINOx rises faster with the variation of combustor inlet temperature.

Fig. 9 shows the validation of correlation (6) and (7). The square points are relative to flame temperature and the other points are relative to combustor inlet temperature. It is possible to notice that all the points fall along the first bisector.
except the high values of calculated $E_{\text{INOX}}$ of flame temperature correlation that leave the line. The flame temperature points are more scattered than the combustor inlet temperature points. This difference is shown by the standard deviation and the average relative error which are 32% and 2% for the flame temperature correlation and 24% and 3% for combustor inlet temperature correlation respectively. The measurement of flame temperature being more complicated, the relationship between combustor inlet temperature and $E_{\text{INOX}}$ is more accurate for NOx emissions prediction when we consider that its relationship is the strongest and its measurement is very easy.

4. Conclusion

The relationship between NOx emission index and operational parameters such as compression ratio, combustion efficiency, output power, flame temperature and inlet temperature in the same combustion chamber was studied and a relationship between them has been proven. The relationship between the NOx emission index and each of the parameters is shown to be a power function written as follows:

$$E_{\text{INOX}} = AX^\alpha$$

where, $X$ is the parameter analysed. The values of $A$ and $\alpha$, the correlation index, the standard deviation, and the average relative error vary according to the parameter and the turbojet engine.

The relationship between the great majority of operational parameters and NOx emission index is not strong, except temperature whose relationship with $E_{\text{INOX}}$ is very strong.

The relationship between NOx emission index and flame temperature is strong, the correlation index is 0.91. The relationship between $T_3$ and $E_{\text{INOX}}$ is better; its correlation index is 1. The combustor inlet temperature is very easy to measure.

It is therefore an efficient parameter for NOx emissions prediction as correlation (7) written below shows.

$$E_{\text{INOX}} = 4 \times 10^{-9} T_3^{3.364}.$$  

(8)

$T_3$ depends on the compression ratio, which is a well-known construction parameter. The combustor inlet temperature is the key parameter for the prediction and the evaluation of the nitrogen oxides emissions in turbojet engines.

A more efficient empirical correlation combining many operational parameters for $E_{\text{INOX}}$ emissions prediction has been determined [3] and published in another work of this research team.

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