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3.7 MODELS FOR ASSESSMENT OF NO$_x$ EMISSIONS FROM TURBOFAN ENGINE OF AIRCRAFT

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Aircraft emissions are of concern due to the expansion of air traffic over the years (a mean annual rate of 5 to 7 %) and their potential impact on air quality in local, regional and global environments [1,2]. Even if in some the European hubs their capacity is close to the limit (never mind operational or environmental), the transfer of the air traffic to other airports, with less intensive traffic, but usually closer to habitation areas, once again making a rise to concerns about their LAQ tasks.

The analysis of emission inventories at major European (Frankfurt am Main, Heathrow, Zurich and etc.) and Ukrainian airports highlighted that aircraft are the dominant source of air pollution in most cases under consideration, with contribution to inventory higher than 50 % of their total values in most of the airports [3, 4]. The aircraft emission inventory is usually calculated on the basis of certificated engine emission (EE) indices, which are provided by the engine manufacturers and reported in ICAO EE database [5]. It is necessary to mention that ICAO EE database has gained from a very limited number of newly manufactured engines during the certification process [6], even someone may conclude that the best practice is included first of all.

The emission indices rely on well-defined measurement procedure and conditions during aircraft engine certification. Under real circumstances, however, these conditions may vary and deviations from the certificated emission indices may occur due to impact such factors, as:

- the life expectancy (age) of an aircraft – emission of an aircraft engine might vary significantly over the years (the average period – 30 years), usually aging aircraft/engine provides higher emission indices in comparison with same type but new ones;
- the type of an engine (or its specific modification, for example with different combustion chambers) installed on an aircraft, which can be different from an engine operated in an engine test bed (during certification);
- meteorological conditions – temperature, humidity and pressure of ambient air, which can be different for certification conditions.

The impacts of aviation emissions of NO_x, PM, and other gaseous emissions need to be further assessed and understood [1]. In respect to this anassessment of aircraft emission indices under operating conditions, also including from measurements, is an actual task, which must provide more accurate emission inventory and to improve total LAQ modeling systems.

The advanced emission model of turbofan engine (TURBOGAS emission model) was developed for assessment aircraft engine emissions with taking into account of the influence of the operational and meteorological conditions on emission indexes to calculate precisely aircraft emission inventory. Sensitivity analysis of the TURBOGAS advanced emission model to define some key parameters for the estimation of aircraft emission indexes under real operation conditions and to provide precisely aircraft emission inventory.

Aircraft main engines have received a lot of attention in sector of aviation emissions as they are the dominant airport-related source [7, 8].

There are various methodologies, to quantify aircraft emissions – each with a degree of accuracy and an inverse degree of uncertainty. The purpose and need for quantifying aircraft emissions drive the level of accuracy needed in an inventory, which in turn, determines the appropriate approach. A secondary factor is data availability [7].

Aircraft emission is function of following parameters [7, 8]:

$$Q = FF \times EI \times T \times n, \tag{1}$$

where *FF* – fuel flow rate, kg/s; *EI* – emission index, g/kg; *T* – time in mode, s; *n* – number of aircraft engines.

The basic methodologies [7, 8] rely on the two critical parameters: the fuel flow rate and the emission factor or index.

The Intergovernmental panel on Climate Change (IPCC) [8] presented a tier based approach to report the on level of accuracy and complexity of commonly available methods to compute aircraft emissions, Table1.

Tier 1 represents the simplest method used to compute the emissions of different pollutants. It does not require very complex computational manipulations and the data requirements are very low. One of the main advantages is the speed of the computational procedure but, on the other hand, this category is also considered to be the least accurate among the tiers [8]. An example is the ICAO reference method.

Table 1

IPCC tier categorization

IPCC Tiers	Level of complexity	Level of accuracy	Example of this method
Tier 1	Low	Empirical	**ICAO**
Tier 2	Medium to High	Empirical	**BFFM2**
Tier 3	High	Modeled or measurement based	**P3T3**

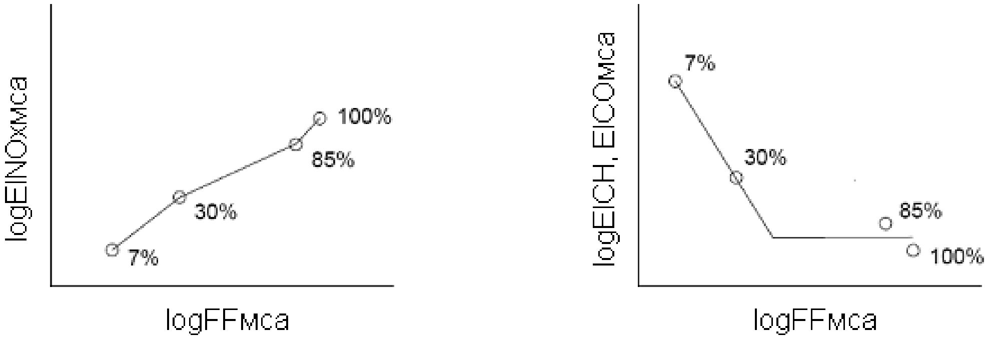
Tier 2 is known as the intermediate method [8]. It requires a higher amount of data to estimate the emissions of different types of pollutants. The related computational process will take longer but the results will provide an increased level of accuracy. An example of this tier is the Boeing Fuel Flow Method 2 (BFFM2).

The final tier (Tier 3 advanced) represents the highest level of complexity. The results generated by this method are considered to be the “most accurate” [8]. The drawback comes from the amount of data required, some of which are not in the public domain or are difficult to obtain, as it will be shown in a later section. The computational procedure is also more intensive, so it will take longer to generate the results as compared to the other two methods. An example of this tier is the P3T3 method.

Both BFFM2 and P3T3 methods have been implemented in the TURBOGAS emission model [9,10]. TURBOGAS which is an emission model of turbofan engine, and which was developed in the scope of TURBOGAS project of Clean Sky JTI company [10].

BFFM2 method is based on the evaluation of the emission index (NOx, CO and HC) of aircraft engines and the fuel flow under real meteorological and operational conditions.

The first stage of the BFFM2 model is to attempt to correct the reference values from ICAO database for “installation effects”; deviations between values from bench tested engines and those found on in service aircraft.



(*a*) (*b*)

Fig.1. Dependencies of EINOx (*a*) and EICO, EIHC (*b*) on fuel flow rate according to the ICAO bank

Secondly, the real meteorological conditions (temperature, pressure and humidity of the air) are translated into the conditions of the ISA by the formulas for correction of humidity and pressure [8, 9].

Real fuel flow value is calculated of the basis of ISA conditions by folowing conversion formula:

$$FF_{MCA} = \frac{FF}{\delta_{amb}} \times \theta_{amb}^{3,8} \times e^{0,2\times M^2}, \qquad (2)$$

where δ_{amb} – the ratio of atmospheric pressure corrected to ISA conditions; θ_{amb} – the ratio of air temperature corrected to ISA conditions; *FF* – real fuel flow rate, kg/s; *M* – Mach number.

The found values of EINOx, EICO, EIHC for ISA conditions (Fig.1) are converted into real meteorological conditions:

$$EI_{\mathrm{NO_x}} = EI_{\mathrm{NO_x}MCA} \times e^{H} \times \left(\frac{\delta^{1,02}}{\theta^{3,3}}\right)^{x}, \qquad (3)$$

$$EI_{\mathrm{HC}} = EI_{\mathrm{HC}MCA} \times \left(\frac{\theta^{3,3}}{\delta^{1,02}}\right)^{x}, \qquad (4)$$

$$EI_{\mathrm{CO}} = EI_{\mathrm{CO}MCA} \times \left(\frac{\theta^{3,3}}{\delta^{1,02}}\right)^{x}, \qquad (5)$$

where $EI_{\mathrm{NOx}MCA}$, $EI_{\mathrm{CO}MCA}$, $EI_{\mathrm{HC}MCA}$ – emission indexes are calculated under reference conditions (ICAO databank).

The uncertainty of BFFM2 method for assessment of EINOx, EICO, EIHC for aircraft engines is ± 10 % due to the following factors [11]:

1) accuracy of the linear interpolation method for determining the emission index according to the certification curve is significantly reduced for operating modes of the investigated type of aircraft engine with a thrust value less than 7 %;

2) age of aircraft engine;

3) lack of information for some types of engines

Sensitivity analyses were performed for TURBOGAS emission model for aircraft A340-300 with engine CFM 56-5C2/F, using the input data for the cruising modes derived from in-flight measurements data performed by DLH [8, 12]. The averaged values used for sensitivity tasks are shown below:

− FF_{mean} = 0.816761 g/s (Min = 0.555556, Max = 1.040000, Std Dev = 0.083559).
− FF = 2938.0 kg/h = 0.8161 kg/s (FF_{ref} = 2814.48 kg/h = 0.7818 kg/s)
− For temperature Ta = 11.5° C/284.65K
− For humidity H = 65.8 %,
− For pressure Pa = 1009.7 mbar.

The objective of the sensitivity studies was to investigate the changes in output (esp. $EINO_X$) caused by variations of input data. The following parameters are studied, with step-wise variations on 2, 5 and 10 %: fuel flow, temperature, pressure, humidity [13].

The results of the sensitivity analysis of the TURBOGAS model for engine CFM56-5C2 and the appropriate dependence of EI NO_X on fuel flow and ambient atmosphere conditions are represented on the following Table 2 and plot, Fig. 2.

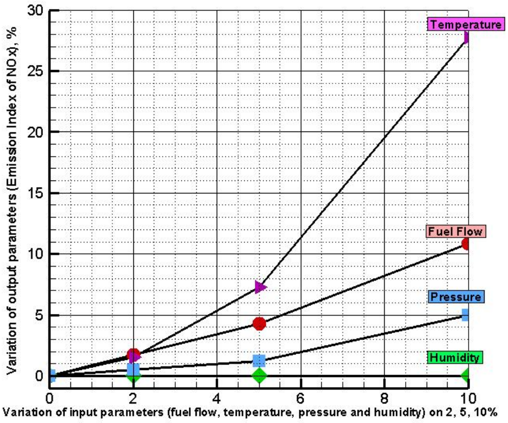


Fig. 2. $EINO_X$ variability vs input parameters for CFM 56-5C2/F

Table 2

Results from sensitivity studies for the CFM56-5C2

Parameter	**Range of parameter**	**Range of NOx (+/- % mean)**
Fuel flow	0.8161/0.8977	10.85
Ambient temperature	285 K to 313 K	27.7 %
Ambient pressure	1010 mbar to 1011 mbar	5.0 %
Ambient relative humidity	66 % to 72 %	1 %

The analysis of obtained results confirmed the sensitivity of TURBOGAS output to the fuel flow rate. The variation of this parameter on 2 % lead to the change of EI NO_x, however, the variation of input value on 10 % implied and increase of EI NO_x on 10.85 %.

Also on the ground of the results obtained and of the comparison of the resulting differences, it can be concluded that the TURBOGAS emission model was not sensitive to air pressure and humidity. That was because the changes of these parameters input by 2 % lead to variations of calculated EI NO_X lower than 2 %. Likewise the changes of input parameters by 5 % implied variations lower than 5 %. The analysis of the modeled data showed that the TURBOGAS emission model was most sensitive to ambient temperature. A change of temperature of 5 % implied an increase of EI NO_X of 7.28 %. At last the change of 10 % lead to an increase in EI NO_X of 27.72 %. Based on this last tendency it can be concluded that the TURBOGAS model was highly sensitive to the ambient temperature. Those results were in agreement with the literature on the topic: it was proved, that "humidity has the least powerful effect upon engine performances of the three ambient parameters" [14].

These results were in line with sensitivity studies conducted by the ICAO CAEP on the AEDECAM model [15, 17] which results are summarized below (Table 3):

Table 3

Results from sensitivity studies for the AEDECAM model

Parameter	**Range of parameter**	**Range of NOx (+/- % mean)**
Ambient temperature	0 °C to 30 °C	34.53 %
Ambient pressure	950 mbar to 1025 mbar	9.04 %
Ambient relative humidity	40 % to 70 %	2.84 %

Sensitivity analysis of TURBOGAS emission model for engine JT9D-7J Sensitivity studies for the engine JT9D-7J used previously in the validation tests were implemented according to the input data named Case 5 and Case 7 (see Table 6 and Table 7) corresponding to cruise flight conditions and obtained in paper [16]:

- Case 5
  - Fuel flow, FF = 0.9028 kg/s;
  - Air temperature, T_A = 226.15K;
  - Air humidity, H = 38 %;
  - Atmospheric Pressure, Pa = 26.2kPa
- Case 7
  - Fuel flow, FF = 0.8889 kg/s;
  - Air temperature, T_A = 226.15K;
  - Air humidity, H = 43 %;
  - Atmospheric Pressure, Pa = 26.2kPa

The Turbogas model sensitivity studies were performed for a Boeing aircraft B747-200 for cruise operation mode (Case 5 / Case7). The full data of the sensitivity are shown in a tabular way in Table 4, 5. In the rest of this sub-section, only results are presented.

Table 4

Results from sensitivity studies for the JT9D-7J (case 5)

Parameter	**Range of parameter**	**Range of NOx(+/- % mean)**
Ambient temperature	226 K to 249 K	34.7 %
Ambient pressure	262 mbar to 288 mbar	7.1 %
Ambient relative humidity	38 % to 42 %	0 %

Table 5

Results from sensitivity studies for the JT9D-7J (case 7)

Parameter	**Range of parameter**	**Range of NOx (+/- % mean)**
Ambient temperature	226 K to 249 K	34.4 %
Ambient pressure	262 mbar to 288 mbar	7.1 %
Ambient relative humidity	43 % to 47 %	0 %

The results shown for case 5 and case 7 compare well with the sensitivity studies prepared for the ICAO with the support from manufacturers which reported an increase of 1.5 % in NO_X emitted per increase of 1 degree [17], Fig. 3, 4.

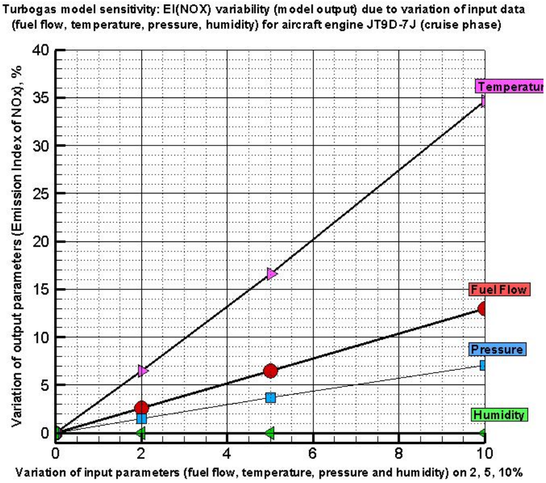


Fig. 3. $EINO_X$ variability with respect to input data Engine JT9D-7J for cruise operation mode (Case 5)

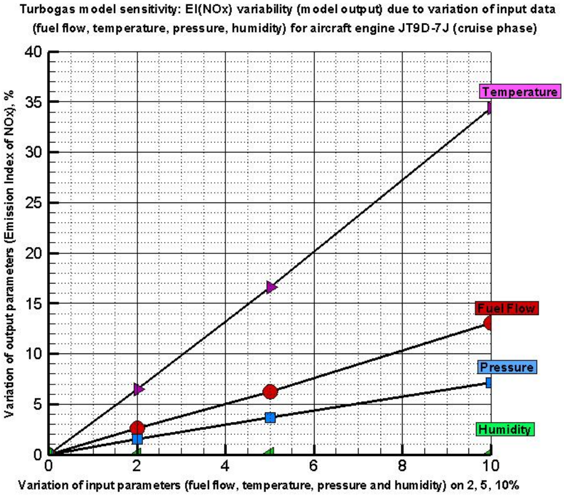


Fig. 4. $EINO_X$ variability with respect to input data Engine JT9D-7J for cruise operation mode (Case 7)

Sensitivity studies for Turbogas have been performed for a Boeing B747-200 fitted with engine P&W JT9D-7J for cruise operation mode (cases 5 & 7).

On the ground of the results obtained for case 5 and case 7, it was concluded as expected that the Turbogas model is sensitive to fuel flow. A 2 % increase in fuel flow lead to variation of EI NO_X above 2 % (resp. 2.58 % and 2.62 %) and the 5 % increase in fuel flow implied a variation of EI NO_X higher than 5 % (resp. 6.47 % and 6.26 %). At last the changes of fuel flow of 10 % lead to variation of results greater than 10 % (resp. 13.01 % and 13.03 %).

According to modelling results, Turbogas was sensitive to ambient temperature. A 2 % increase in temperature lead to variations EI NO_X of 6.49 % and 6.47 % respectively. Variations of fuel flow of 5 % implied increase in results of 16.63 % and 16.57 %. Finally, the changes of temperature of 10 % lead to variation of EI NO_X considerably more than 10 % (34.68 % and 34.39 %). Based on last tendency came to the conclusion that the Turbogas model is highly sensitive to the ambient temperature.

On the basis of modelling results and their comparison of the resulting differences it was concluded that Turbogas is not sensitive to air pressure and humidity. Since the changes of input these parameters on 2 % lead to variation of calculation results llower than 2 % and the changes of input these parameters on 5 % implies variation in results smaller that 5 %.

Those results were in agreement with the literature on the topic : it was noted in «Gas Turbines» on p.696 that «humidity has the least powerful effect upon engine performances of the three ambient parameters».

The model estimates values for P3, T3 and FAR before completing the P3T3 model and providing an estimate for NO_x emissions.

A NO_x emissions rate is calculated based on the standard P3T3 formula presented in SAE AIR 5715 [8].

$$EI_{\mathrm{NO_x}ALT} = EI_{\mathrm{NO_x}MCA} \times \left(\frac{P_{3ALT}}{P_{3MCA}}\right)^{a} \times \left(\frac{FAR_{ALT}}{FAR_{MCA}}\right) \times \exp\left(19 \times \left(h_{MCA} - h_{ALT}\right)\right) \tag{6}$$

where $P_{3\mathrm{ALT}}$ and $P_{3\mathrm{MCA}}$ – pressure at the entrance to the combustion chamber of the aircraftengine at theconsidered altitude (h_{alt}) under operational and reference conditions (h_{MCA}); FAR_{ALT} and FAR_{MCA} – fuelflowratioatthecombustionchamberunderoperationalmode at the altitude ($\mathrm{h}_{\mathrm{ALT}}$) and under reference conditions (h_{MCA}); $EI_{\mathrm{NOx}MCA}$ – emission indexes are determined by the certification curve due to ICAO databank [9].

Indicators *a* and *b* are determined on the basis of engine test. Accuracy of P3T3 method depends on the principles to determine the indicators *a* and *b* due to the formula (6). So, in the case where $a = 0.4$, the error of the emission rate of NOx is 11 % for the investigated aircraft engine and in the case of determination *a* according to the data of the experimental investigation, it reaches only 3.5 % [8].

Due to the complexity of obtaining information on the results of engine test, generalized values for these indicators are adopted. So in most works [8], a = 0.4, b = 0. The presented method for assessment the emission indexes o is characterized by highly accuracy. The implementation of this method is complicated due to the complexity of the calculation algorithm and the inaccessibility of the initial data. Currently this problem is crucial object of the research within the international projects [9] by independent calculation of pressure (P3) and temperature (T3) at the entrance to the combustion chamber according to the equations of thermodynamic calculation for the aircraft engine.

Comparison of BFFM2 and P3T3 methods for assessment of EINOx at the different altitudes is represented on Fig.5. The difference between the results for the indicated methods increases with increasing height. The observed observation is due to the effect of humidity of the atmospheric air on the value of EINOx [18].

This emissions index is then converted into an emissions value by multiplying the g/kg value by the fuel flow (kg/s) for each segment.

One of the requirements of the P3T3 is the fuel-air-ratio. Establishing this ratio is in most models calculated by attempting an energy balance across the burner. However, because fuel flow is an explicit input for the Turbogas tool, this can be completed by establishing the mass of air required to achieve stoichiometric combustion. During optimum flight conditions, this is a reasonable assumption. Assuming a mean fuel composition of 13.84 % hydrogen by mass, this results in an emission index of 3.15 for CO_2 and 1.25 for H_2O (which is the value implemented in the EU ETS for aviation). Subsequently, each 1 unit of fuel requires 3.4 units of oxygen for complete combustion [18].

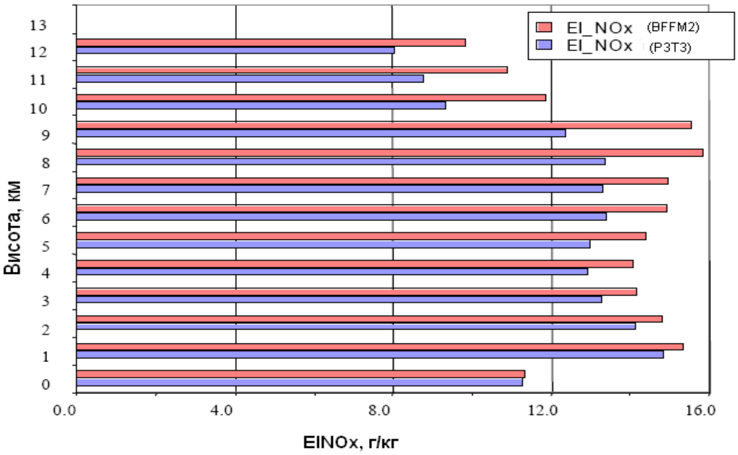


Fig. 5. Comparison of BFFM2 and P3T3 methods for assessment of EINOx at the different altitudes

Sensitivity analyses were performed for Turbogas model for engine FJ44-3A on the ground of ANP flight profile for a Citation 3 for following two points:

- **Point № 1:**
  - Fuel flow, FF = 0.153573523 kg/s;
  - Altitude, m = 457.2
  - Mach number = 0.23044085
  - Thrust, kN = 8.8442306
  - Air temperature, T_A = 284.19K;
  - Air humidity, H = 60 %;
  - Atmospheric Pressure, Pa = 942.1mbar
- **Point № 2**:
  - Fuel flow, FF = 0.1272584 kg/s;
  - Altitude, m =3048.00
  - Mach number = 0.44015261
  - Thrust, kN = 7.63414211
  - Air temperature, T_A = 268.34K;
  - Air humidity, H = 60 %;
  - Atmospheric Pressure, Pa = 696.80mbar

Aim of sensitivity studies is to investigate the changes in output (EINOx) caused by variation of input data. The following parameters are studied, with step-wise variations of 2, 5 and 10 %: fuel flow, temperature, pressure, Mach number and thrust. Obtained results of the sensitivity tests are collected in following tables correspondingly for Point 1 and Point 2 [19].

Table 6

Results from sensitivity studies for the FJ44-3A (point1)

Parameter	**Range of parameter**	**Range of NOx (+/- % mean)**
Ambient temperature	11.2 ºC to 39.6 ºC	30.70 %
Ambient pressure	942.1 mbar to 1036.3	4.84 %
Ambient relative humidity	60.0 % to 66 %	1 %

Table 7

Results from sensitivity studies for the FJ44-3A (point1)

Parameter	**Range of parameter**	**Range of NOx (+/- % mean)**
Ambient temperature	-4.7 °C to 22.17 °C	12.70 %
Ambient pressure	696.80 mbar to 766.48	4.30 %
Ambient relative humidity	60.0 % to 66 %	0.5 %

The results of TURBOGAS model sensitivity and found dependence of EINOx on ambient conditions (temperature, humidity and pressure) is represented on the plot1 for considered cases, Fig.6, 7.

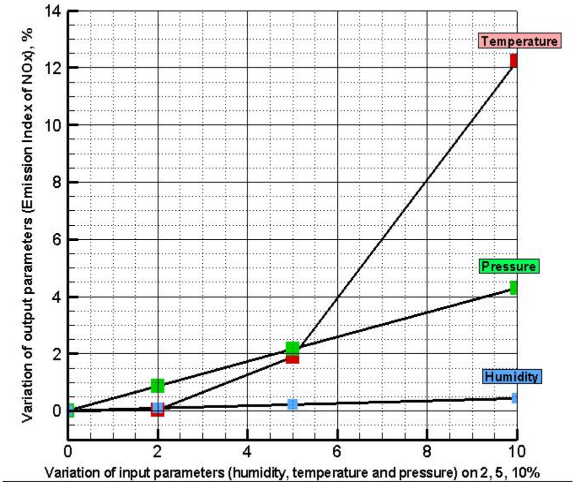


Fig. 6. EINO$_X$ variability vs input parameters for FJ44-3A (point №1)

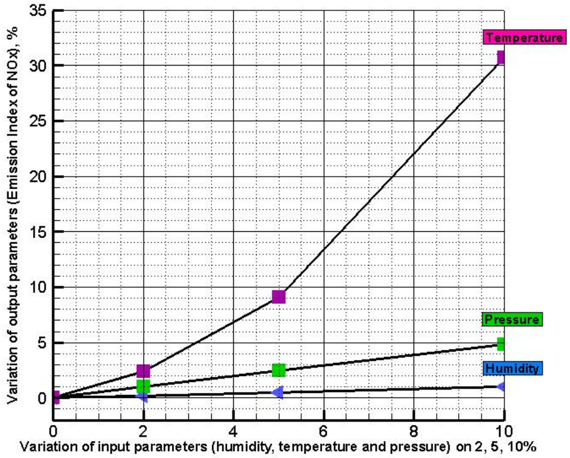


Fig. 7. EINO$_X$ variability vs input parameters for FJ44-3A (point №2)

On the ground of the results obtained for two points and of the comparison of the resulting differences it can be concluded that the Turbogas model (P3T3 method) is not highly sensitive to air pressure and humidity. That is because the changes of these parameters input by 2 % lead to variations of calculated EI NO_X lower than 2 %. Likewise, the changes of input parameters by 5 % implied variations lower than 5 %.

The analysis of the implemented tests showed, that the Turbogas model is sensitive to ambient temperature. Based on obtained results, it was found a dependence of a sensitivity level of model on altitude. As, it was observed, on altitude 457.2 m ambient temperature change on 10 % leads to an increase in EI NO_X of 12 %, while on altitude 3048.0 m – 30.7 %.

In addition, on the ground of investigation was found, that the Turbogas model (P3T3 method) is not sensitive to operational conditions at all: fuel flow, Mach number and thrust.

BFFM2 and P3T3 methods have been implemented in the TURBOGAS emission model.

Results of sensitivity analysis concluded that the emission model of turbofan engine developed to take into account the influence of the real operational (fuel flow rate) and meteorological conditions on emission indexes was robust. According to calculation results by TURBOGAS model, the fuel flow rate and ambient atmosphere conditions (air temperature, pressure and humidity) have a large impact on the EINOX. In particular the sensitivity analysis showed that the model (BFM2) is highly sensitive to the fuel flow rate (increase in $EINO_X$ on 10.85 % in case of change it on 10 %) and ambient temperature (27.72 % increase in $EINO_X$ in case of change it on 10 %).

The TURBOGAS model (P3T3 method) is not sensitive to operational conditions (fuel flow, Mach number and thrust), but it is highly sensitive to ambient temperature (1.5 to 2 % increase in EINOX per 1 degree C).

РЕФЕРАТ

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МОДЕЛІ ОЦІНКИ ВИКИДУ NO_x ВІД ТУРБОВЕНТИЛЯТОРНОГО АВІАДВИГУНА

Протягом останнього десятиліття багато досліджень зосереджено на оцінці впливу викидів авіаційних двигунів на місцеву та регіональну якість повітря поблизу аеропорту. Інвентаризація викидів викидів повітряних суден зазвичай обчислюється на основі сертифікованих емісійних індексів, які надаються виробниками двигунів і відображаються в базі даних Міжнародної організації цивільної авіації (ІКАО). Сертифіковані індекси емісії визначаються під час стендових випробувань. Проте в реальних умовах експлуатаційні (тяга, напрацювання двигуна та витрата палива) і метеорологічні характеристики (температура повітря, вологість і тиск) не відповідають ІКАО умовам, внаслідок чого індекси емісії вирізняються від сертифікованих величин.

Розроблена вдосконалена емісійна модель турбовентиляторного двигуна (модель викиду TURBOGAS) для оцінки викидів авіаційних двигунів з урахуванням впливу експлуатаційних та метеорологічних умов на показники викидів для створення точних кадастрів викидів повітряних суден, а також ймовірності виникнення інверсійних слідів. Обидві методи BFFM2 та P3T3 були впроваджені в моделі TURBOGAS.

Ключові слова: авіаційнийдвигун, навколишнє середовище, турбовентиляторний двигун, забрудненняатмосферного повітря, модельвикидів, емісійніiндекси.

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МОДЕЛИ ОЦЕНКИ ВЫБРОСА NO_x ОТ ТУРБОВЕНТИЛЯТОРНОГО АВИАДВИГАТЕЛЯ

В течение последнего десятилетия многие исследования также были сосредоточены на оценке воздействия выбросов авиационных двигателей на качество воздуха в зоне аэропорта и в окрестностях. Инвентаризация выбросов воздушных судов обычно рассчитывается на основе сертифицированных индексов выбросов, которые предоставляются изготовителями двигателей и заносятся в базу данных Международной организации гражданской авиации (ИКАО). Сертифицированные индексы эмиссии определяются при стендовых испытаний. Однако в реальных условиях эксплуатационные (тяга, наработки двигателя и расход топлива) и метеорологические характеристики (температура воздуха, влажность и давление) не отвечают ИКАО условиям, в результате чего индексы эмиссии отличаются от сертифицированных величин.

Усовершенствованная модель выбросов турбовентиляторного двигателя (модель выбросов TURBOGAS) была разработана для оценки выбросов авиационных двигателей с учетом влияния эксплуатационных и метеорологических условий на индексы выбросов для создания точных кадастров выбросов воздушных судов, а также вероятности появления инверсионных следов. Оба метода BFFM2 и P3T3 были реализованы в модели выбросов TURBOGAS.

Ключевые слова: авиационный двигатель, окружающая среда, турбовентиляторный двигатель, загрязнение воздуха, модель выбросов, показатели выбросов.

ABSTRACT

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MODELS FOR ASSESSMENT OF NO$_x$ EMISSIONS FROM TURBOFAN ENGINE OF AIRCRAFT

During the last decade a lot of investigations were focused on the evaluation of the impact of aircraft engine emissions on the local and regional air quality in the vicinity of the airport. The aircraft emissions inventory is usually calculated on the basis of certificated emission indices, which are provided by the engine manufacturers and reported in the database of the International Civil Aviation Organization (ICAO). The certificated emission indices rely on well-defined measurement procedures and conditions during engine test. Under real circumstances, however, operational (power setting, time-in-mode and fuel flow rate) and meteorological (air temperature, humidity and pressure) conditions may vary from ICAO definition, consequently deviations from the certificated emission indices may occur.

The advanced emission model of turbofan engine (TURBOGAS emission model) was developed for the assessment of aircraft engine emissions taking into account the influences of operational and meteorological conditions on emission indices to generate precise aircraft emissions inventories as well as contrails likelihood and lifetime. Both BFFM2 and P3T3 methods have been implemented in the TURBOGAS emission model.

Key words: aircraft engine, environment, turbofan engine, air pollution, emission model, emission indices.

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