ENVIRONMENT PROTECTION

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AIRCRAFT EMISSION ESTIMATION UNDER OPERATIONAL CONDITIONS IN THE AIRPORT AREA

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Abstract. *The arcticle represents the results of the analysis of aircraft engine emissions measurement principles and techniques, which were implemented on the ground of measurement campaigns at major European airports. The paper is devoted to investigation of operational and meteorological conditions impact on emission indexes of aircraft engine. On the ground of analysis of CFM56-5C2 engine test for cruise and idle conditions was observed, that real operational conditions differ from certificated ones. The observed variations between determined and certificated emission indexes are most likely caused by operational (thrust) and meteorological (air temperature and humidity) conditions under real circumstances which are quite different from well defined conditions during certification procedure. Determination of emission indexes under real operational (real value of thrust) and meteorological (ambient temperature) conditions is an actual task, as input data for models and high accurate assessment of aircraft emissions contribution to total air pollution in the vicinity of airport. In addition, estimation emission indexes with taking into account engine age and its maintenance, allow to calculate precisely the emission inventories of airports.*

Keywords: air pollution monitoring; aircraft engine emission; assessment of emission indexes; emission index; environmental monitoring; emission inventory of aircraft engine.

1. Introduction

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, 3].

Aircraft (during approach, landing, taxi, take-off and initial climb of the aircraft, engine run-ups, etc.) is the dominant sources of air pollution at airports in most cases under consideration [4, 5].

According to emissions inventory results, the aircraft contribution is more than 50 % from total pollution of the airport [4, 5]. The emission inventory of aircraft emissions are usually calculated on the basis of certificated emission indexes, which are provided by the engine manufacturers and reported in the database of the International Civil Aviation Organization (ICAO) [6]. ICAO database has gained from a very limited number of newly manufactured engines during the certification process [7].

The emission indices rely on well-defined measurement procedure and conditions during 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 of an aircraft – emission of an aircraft engine might vary significantly over the years (the average period – 30 years);

• the type of an engine installed on an aircraft, which can be different from an engine operated in an engine test bed;

• meteorological conditions – temperature, humidity and pressure of ambient air, which can be different for certification conditions (temperature – 15 degrees C, pressure – 101325 Pa)

2. Analysis of the research and publications

Analysis of measurement campaigns at different European airports (London-Heathrow in 1999 and 2000, Frankfurt/Main in 2000, Vienna in 2001 and Zurich, 2003) [7]) determines, that operational procedures of aircraft are sometimes not well adapted to engine settings (thrust) and standard time operation (TIM), which are specified under ICAO engine emission certification procedure.

Thus, the aircraft engine thrust used in real operations is significantly smaller (close to 85–90 %), than what is prescribed by the ICAO (100 %) for performance and cost-efficiency reasons [7, 12]. Such inevitably may lead to overestimation of emissions of NOx from airport operations. In practice for idle/taxi mode most aircraft use a thrust of 3–4 % of m aximum instead of 7 %, this may lead to underestimation of CO and hydrocarbons [7, 12].

In Ukraine continuous measurements of airport-related emissions have not been conducted at all. And the assessment of historical, existing and/or future air pollution is implemented only by modeling techniques.

3. Task

Assessment of emission indexes of aircraft engine exhaust from measurement under operating conditions is an actual task which allows to calculate precisely the emission inventory and to improve local air quality modeling systems.

4. Determination EICO, EINO under idle operation conditions at European airports

The most part of landing/take-off cycle (LTO), the aircraft is taxing with a thrust of 7 % maximum value. Several measurement campaigns were performed for idling aircraft at different European airports (London-Heathrow in 1999 and 2000, Frankfurt/Main in 2000, Vienna in 2001 and Zurich, 2003) [7] to overcome expressed limitations of the ICAO database using non-intrusive spectroscopic methods like Fourier transform infrared spectroscopy (FTIR) [8, 9] and differential optical absorption spectroscopy (DOAS) [10].

On the ground of measurement results the emission indices for CO and NOx were calculated (1) under real operational conditions (idling, taxing and take-off) and compared to the values given in the ICAO [7].

$$EI(X) = EI(CO_2) \times \frac{M(X)}{M(CO_2)} \times \frac{Q(X)}{Q(CO_2)}, \qquad (1)$$

where M – the molecular weight;

Q – concentration (mixing ratio, column density, etc.) of the species.

Measured EICO by FTIR emission and absorption spectrometry are generally slightly higher than the ICAO values, fig. 1 [7]. The differences in the CO emission indices given from FTIR emission and absorption spectrometry are caused by a different measurement principle and measurement volume. The FTIR emission spectrometry detects the exhaust of a single engine and the FTIR absorption spectrometry the exhausts of all engines behind the aircrafts. The mean difference is 20 % in order of measurement accuracy.

The largest difference between measurement data (FTIR emission and absorption spectroscopy) and emission indices of the ICAO data for CO was found for the RB211-524D4 engine due to quite long life expectancy (engine age and its maintenance) of B747-236, fig. 1. The oldest aircraft with an emission index of 52.9 g/kg was 25 years old; the other two were built in 1987 and 1983. Mean values of the measured emission indices for three engine types (CFM56-5B1, CFM-5B4/2P and CFM56-5B3/P) are nearly identical although the ICAO data of the CFM56-5B family differ by a factor of 2, fig. 2 [7].

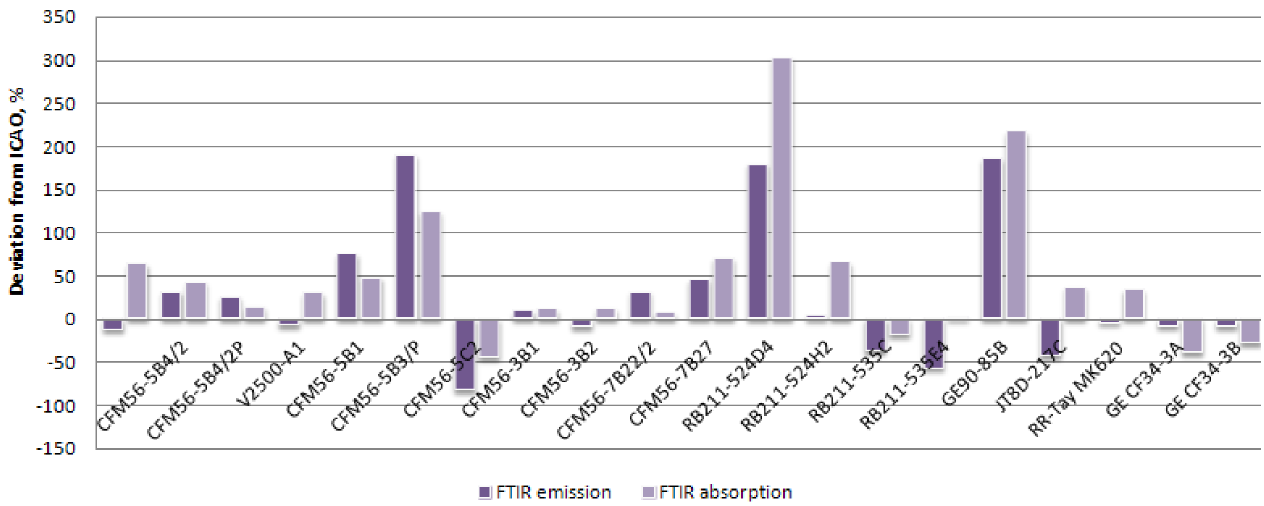


Fig. 1. Comparison measured EICO by FTIR emission and absorption spectrometry during measurement campaign for idling aircraft at European airports (London-Heathrow in 1999 and 2000, Frankfurt/Main in 2000, Vienna in 2001)

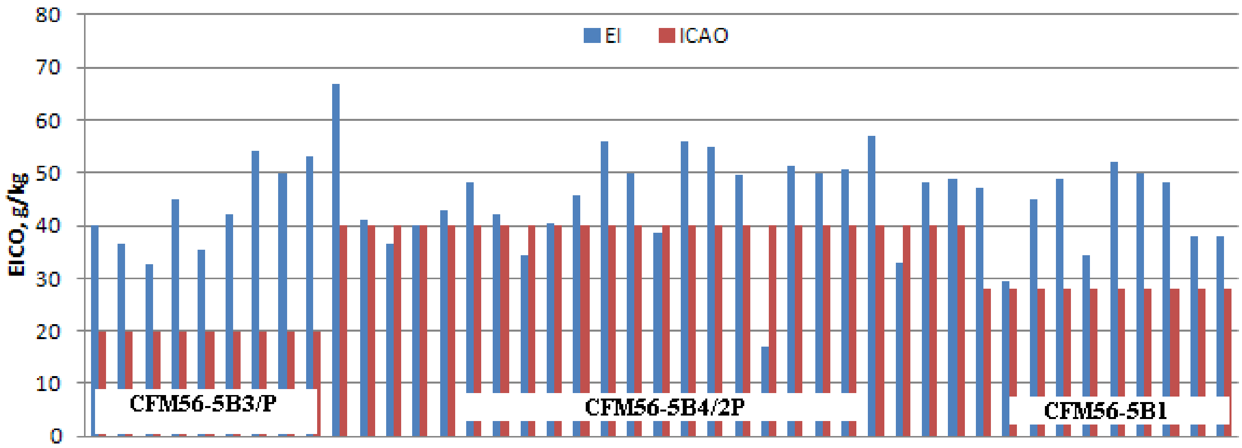


Fig. 2. Comparison EICO determined for CFM-5Bx engines with ICAO values for idling aircraft at European airports (London-Heathrow in 1999 and 2000, Frankfurt/Main in 2000, Vienna in 2001)

The relatively high variance of extreme values given as minimum and maximum value of all measured data is caused by engine-to-engine and maintenance quality, table 1.

Measured EINOx by FTIR emission spectrometry and DOAS are significantly below the ICAO values, fig.3 [7]. The emission index of NOx determined from measurements by the passive FTIR emission spectrometry is generally lower than the results given from DOAS system. This is due to the chemical transformation from NO to NO_2. The passive FTIR emission spectroscopy allow to estimate EINOx from NO concentration detected at the nozzle section of aircraft engine, while DOAS system – from NO_2 measured in the exhaust plume behind the aircraft [11].

Table 1. Measured EICO of main engines at idle thrust of different engine types by FTIR emission spectrometry and by FTIR absorption spectrometry at European airports (London-Heathrow in 1999 and 2000, Frankfurt/Main in 2000, Vienna in 2001)

Air craft	Engine	Number of tested engines	FTIR emission spectrometry EICO, g/kg			Number of tested engines	FTIR absorption spectrometry EICO, g/kg	ICAO
			Mini-mum	Maxi-mum	Mean		Mean±σ	g/kg
A320	CFM56-5B4	7	21,3	72,6	50,5	24	45,85±3,8	40,1
A321	CFM56-5B1	3	23,0	71,9	49,9	10	42,09±4,35	28,4
A321	CFM56-5B3	1	50,7	63,9	55,7	9	43,1±5,03	19,2
B737	CFM56-7B2	1	45,9	73,4	59,6	1	48,7±15,05	45,35
B747	RB211-524	1	21,0	31,2	26,0	3	37,41±15,25	9,3
B747	RB211-524	2	10,4	18,1	12,2	6	19,48±6,51	11,75
B757	RB211-535	2	11,7	12,0	11,8	11	15,41±2	18,79
B777	GE90-85B	7	2,7	64,1	39,1	6	43,35±6,21	13,67
CRJ200	CF34-3B	8	10,2	57,3	38,9	5	30,83±4,88	42,6

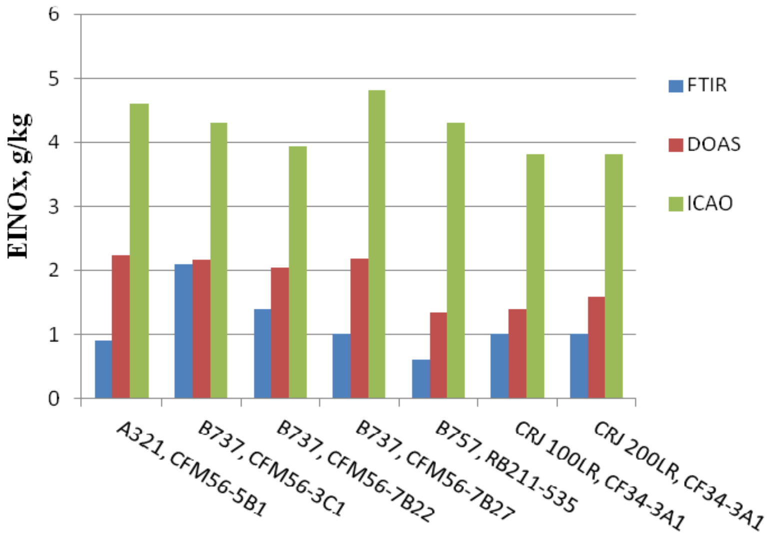


Fig. 3. Comparison measured EINOx by FTIR and DOAS with ICAO values during measurement campaign for idling aircraft at European airports

The ICAO values lies in between the measured ones (fig. 4) for idle operational conditions (engine ignition and taxing conditions) at Zurich airport [12].

Therefore, based on European experience, we concluded, that idling during real operational conditions is not equal to ICAO definition. This difference is caused by thrust setting of aircraft engine under real and certificated (at 7 % of maximum thrust) idle conditions:

1. Real EICO is higher, than the ICAO ones due to lower thrust settings (engine ignition);

2. Real EICO is lower, than the ICAO ones due to higher thrust settings (taxing condition).

Thus, thrust value installed during engine exhaust certification measurements in test beds is a combination of true idling and taxing conditions.

Moreover, idle thrust differs from engine type to type and depends on ambient air conditions and hence thrust cannot be simply calculated from on-board measured parameters of an aircraft.

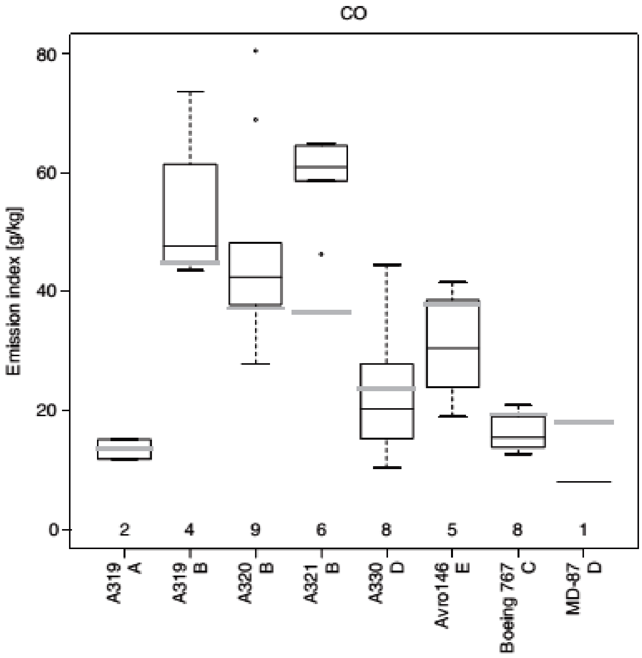


Fig. 4. Comparison measured EICO (a black vertical bar with horizontal lines of minimum, median and maximum meaning) with ICAO values (a grey horizontal bar) during measurement campaign for idling aircraft at Zurich airport. The letter adjacent to each aircraft type denotes a specific class of engines

5. Dependence emission indexes on engine age, fuel flow and ambient temperature

Measurement data of emission characteristics of 9 aircraft engine (CFM56-5C2/F) were officially obtained from Lufthansa Technik AG in Munich in order to investigate dependences of emission indexes on operational period (engine age, hours), fuel flow of engine and ambient conditions. Engine tests (26 measurements) were performed for stationary conditions on standing aircraft A340-300 (D-AIGD, D-AIGF) for different operational conditions (idle and cruise) at Munich airport during three years [1].

Concentrations of NO, NOx, CO, CO_2 and H_2O were measured at the nozzle exit of engine (or in plane parallel to engine nozzle at a distance of approximately 10 cm) by using FTIR spectrometry method [8] (with an absolute accuracy of 20 to 30 %) to determine real in-use corresponding emission indices of NO, NOx, CO, CO_2, H_2O according to equation (1) for idle (N1 =20 – 22 %), cruise (N1 = 79 – 81 %) conditions [7, 8, 13].

It should be noted that the FTIR emission spectrometry method focuses on the detection of NO in aircraft exhaust right at the engine nozzle section. While NO_X consist of both NO and NO_2, the NO_2 was not measured during the experiment at Munich airport. Therefore, the NO_X emission indexes are determined on the ground of measured values of NO only (which represent approximately 80 % of NO_X). The method was designed for accurate NO detection at high thrust levels. For low thrust operating conditions (N1 = 19.5 – 24.9 %) the NO measurements can be below the detection limits of FTIR emission spectrometry method which does not allow determining robust NO_X emission indices [7, 11, 12].

Measured emission indexes of CO, NOx were proceeded to find their dependence on operational period, fuel flow of engine and ambient temperature. Regression analysis was done for measured EINOx, EICO and engine age (t_f) with estimated statistical characteristics, table 2. Regression lines are fitted in 0,95 prediction interval via operational period (hours) of engine, fig. 5, 6. Wide range of coefficient correlation is caused by high variation of EICO, EINO depending on operational period (166–13000 hours) of tested engines.

Regression analysis was also done for measured EINOx, EICO and ambient temperature (t_a) with estimated statistical characteristics, table 3. Regression lines are fitted in 0, 95 prediction interval via ambient temperature, fig. 7, 8. Coefficient correlation is quite below 0.5, which is caused by quite small volume of random sample (36 measurements) and also accuracy of FTIR method.

Table 2. Dependencies EINO and EICO on operation hours of CFM56-5C2/F engine of A340 (D-AIGD, D-AIGF) aircraft with statistical characteristics, correlation coefficient (*r*) and coefficient of determination (R^2)

Aircraft	Operational conditions	Basic statistical characteristics						Dependence emission indexes, *EI* on operational period of aircraft engine, t_f $EI(\text{CO, NO}) = at_f + b$			
		Mini-mum	Maxi-mum	Mean	Standard deviation	Prediction interval, ± 95 %		a	b	r	R^2
D-AIGF, № 3/2	Idle, after engine test, EI_{CO}	12,5	21,0	16,74	3,66	13,36	20,13	0,0011	11,32	0,6372	0,4060
	Cruise flight, EI_{NO}	3,20	6,30	4,66	0,97	3,765	5,558	0,00026	3,36	0,580	0,3329
D-AIGD, D-AIGF	Idle, after engine test, EI_{CO}	3,30	23,00	13,96	4,79	12,313	15,60	0,00018	12,632	0,14017	0,0197
	Cruise flight, EI_{NO}	2,60	10,40	4,78	1,57	4,256	5,30	0,00003	4,585	0,064	0,0040

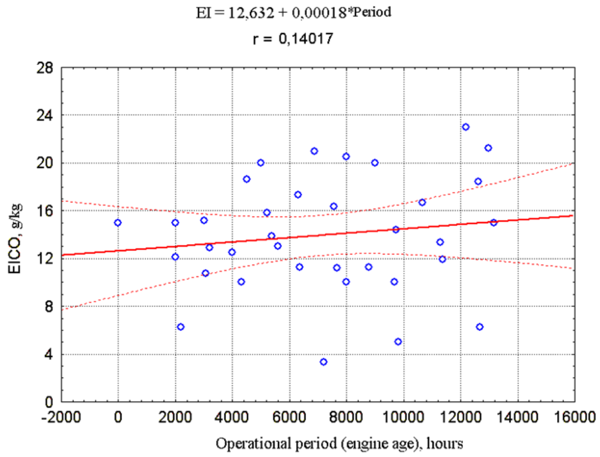


Fig. 5. Dependence of EICO on operation hours of CFM56-5C2/F engine of A340 (D-AIGD, D-AIGF) aircraft

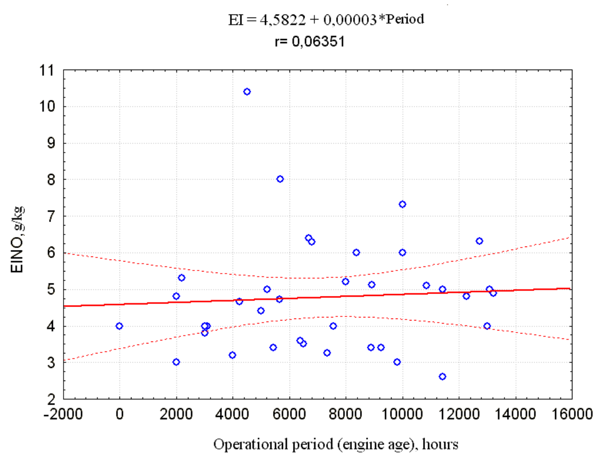


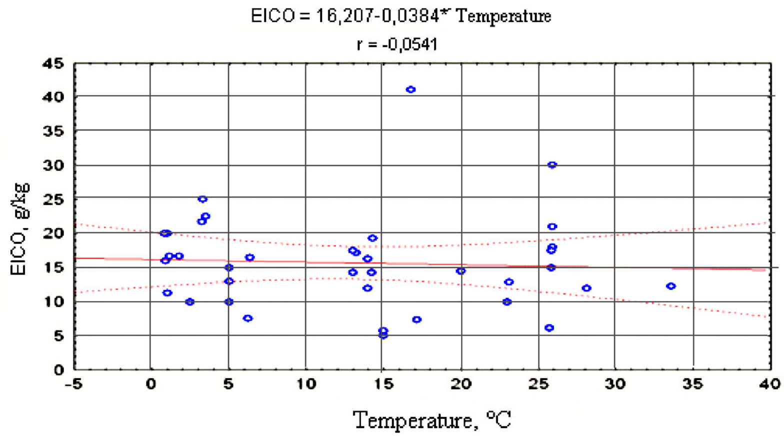
Fig. 6. Dependence of EINO on operation hours of CFM56-5C2/F engine of A340 aircraft (D-AIGD and D-AIGF)

Finally, regression analysis was done for measured EINOx and fuel flow (FF), fig. 9. Regression lines fitted within 0.95 prediction intervals vs fuel flow (FF) for the prediction expression: EINOx = -6.0944+16.02*FF.

Index of fuel consumption varies in a number of measurements performed in the range of ± 5 %, but sometimes there is also an extreme deviation of this indicator, which may be due to sharply increased or decreased index ORES (N %) for the investigated operating mode.

Table 3. Dependencies EINO and EICO of CFM56-5C2/F engine of A340 (D-AIGD, D-AIGF) aircraft on ambient temperature with statistical characteristics (correlation coefficient (r) and coefficient of determination (R_2)

Aircraft	Operational conditions	Basic statistical characteristics						Dependence emission indexes, *EI* on ambient temperature, t_a $EI(CO, NO) = at_a + b$			
		Minimum	Maximum	Mean	Standard deviation	Prediction interval, ± 95 %		a	b	r	R^2
D-AIGF, № 4/1	Idle, before engine test, EI_{CO}	7,5	22,50	14,65	4,592	11,728	17,56	-0,095	15,89	-0,196	0,038
	Idle, after engine test, EI_{CO}	10,0	20,0	14,31	3,353	12,182	16,44	-0,062	15,12	-0,174	0,03
	Cruise flight, EI_{NO}	2,714	6,0	4,07	1,0433	3,41	4,73	-0,0045	4,13	-0,041	0,0016
D-AIGD, D-AIGF	Idle, before engine test, EI_{CO}, fig. 7, *a*	5,0	41,11	15,68	6,96	13,36	18,01	-0,038	16,19	-0,054	0,0029
	Idle, after engine test, EI_{CO}, fig. 7, *b*	6,15	24,17	14,39	3,97	13,048	15,73	-0,092	20,09	-0,22	0,050
	Cruise flight, EI_{NO}, fig. 8	2,74	10,50	4,78	1,58	4,256	5,31	0,0084	4,805	0,054	0,0029



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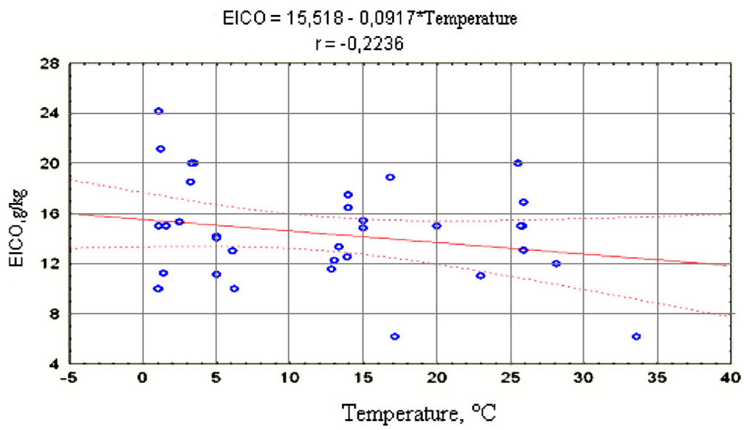

b

Fig. 7. Dependence of EICO on ambient temperature for idling conditions of CFM56-5C2/F engine of A340: *a* – before engine test; *б* – after engine test (№ 3, 4 D-AIGF, D-AIGD)

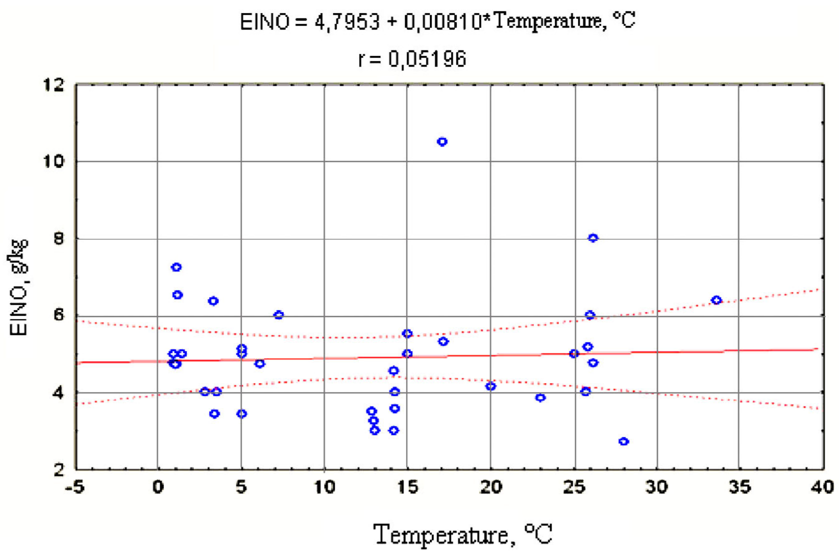

Fig. 8. Dependence of EINO on ambient temperature for cruise conditions of CFM56-5C2/F engine of A340 (№ 3, 4 D-AIGF, D-AIGD) aircraft

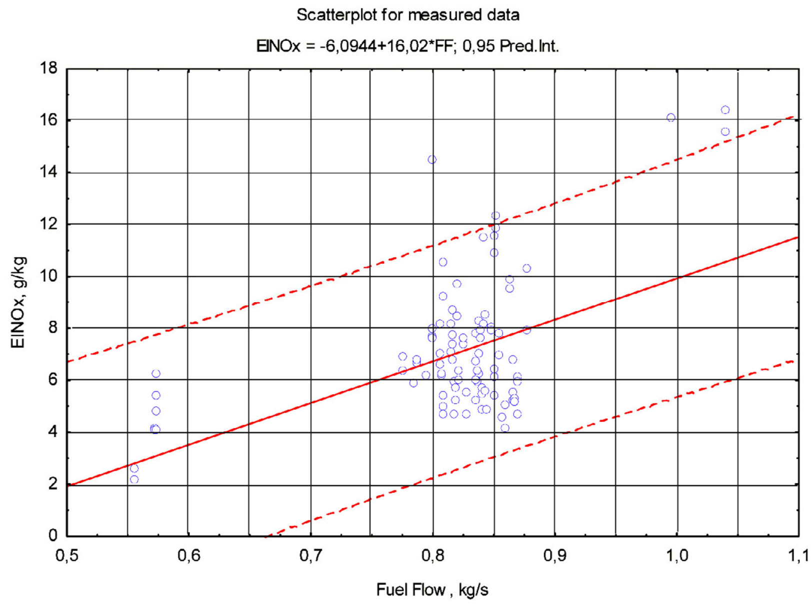

Fig. 9. Dependence of EINOx on measured Fuel Flow for cruise conditions of CFM56-5C2/F engine of A340 (№ 3, 4 D-AIGF, D-AIGD) aircraft

6. Comparison emission indexes with ICAO values

As cruise flight is displayed between "approach" and "climb-out" stages of ICAO cycle, EINOx were estimated on the basis of fuel flow rate [13]. At cruise conditions, mean value of determined EINOx is about 50% lower than ICAO value, table 4.

A similar approach was used to estimate EICO for idle conditions under real value of fuel rate.

Since the average value of the actual fuel rate was only 78 % (FF = 329 kg/h) on the ICAO value (FF = 423 kg/h), respectively, calculated emissions indices are equal only 44 % (EICO = 15.1 g/kg) of ICAO ones (EICO = 34 g/kg).

Analysis results of emission measurement data for aircraft engine concluded that method, which takes into account the influence of the real operational (fuel flow rate, operation period of engine/age and its maintenance) and ambient temperature on emission indexes, allows to get more accurate results of emission inventory of aircraft engines.

Table 4. Emission indexes of CFM56-5C2/F engine according to engine test for cruise, idling conditions and comparison with ICAO values

№	Operational conditions	Emission sndex, g/kg			Fuel flow rate, kg/h
		EI_{CO}	EI_{NO}	EI_{NOx}	
1	Engine test for cruise regime	0,7	5,5	>8,4	3039
2	Approach stage of LTO-cycle, ICAO	1,75		10,0	1280
3	Climb stage of LTO-cycle, ICAO	0,8		25,8	3873
4	Engine test for idle mode	15,1			329
5	Idling (taxing) of LTO-cycle, ICAO	34,0			423

7. Conclusions

The observed variations between determined and certificated emission indexes are most likely caused by operational (thrust) and meteorological (air temperature and humidity) conditions under real circumstances which are quite different from well defined conditions during certification procedure. Nevertheless, these differences are important since the ICAO data [4] is currently used to calculate emissions from airports.

Determination of emission indexes under real operational (real value of thrust) and ambient temperature is an actual task, as input data for models and high accurate assessment of aircraft emissions contribution to total air pollution in the vicinity of airport. In addition, estimation emission indexes, taking into account engine age and its maintenance, allow to calculate precisely the emission inventories of airports.

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К. В. Синило. **Оцінка індексів емісії авіадвигунів за реальних експлуатаційних умов у зоні аеропорту**

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У роботі викладено результати аналізу методів, засобів та принципів вимірювання емісії авіадвигунів в умовах головних аеропортів Європи. Досліджено вплив реальних експлуатаційних та метеорологічних умов на величини індексів емісії авіадвигунів. На підставі аналізу стендових випробувань авіадвигуна типу CFM56-5C2 для крейсерського режиму та режиму малого газу встановлено кількісні залежності величин індексів емісії від температури атмосферного повітря, напрацювання та витрати палива (режиму роботи) авіадвигуна. Різниця, виявлена за результатами порівняльного аналізу виміряних індексів емісії та наданих показників ICAO, зумовлена тим, що реальні експлуатаційні умови не відповідають умовам сертифікації ICAO, зокрема за характеристиками тяги двигуна. Обґрунтовано доцільність урахування реальних експлуатаційних (показник тяги та період напрацювання авіадвигуна) та метеорологічних (температура атмосферного повітря) умов на величини індексів емісії авіадвигуна з метою вдосконалення процедури інвентаризації викидів авіадвигунів та взагалі підвищення ефективності стратегії регулювання якості повітря в межах та околиці аеропорту.

Ключові слова: екологічний моніторинг; емісія авіаційних двигунів; індекс емісії; моніторинг забруднення повітря; оцінка індексів емісії; процедура інвентаризації авіаційних двигунів.

Е.В. Синило. Оценка индексов эмиссии авиадвигателей в реальных эксплуатационных условиях в зоне аэропорта

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В работе представлены результаты анализа методов, оборудования и принципов измерения существующих систем инструментального мониторинга эмиссий авиадвигателей в главных аэропортах Европы. Приведены результаты выполненного исследования относительно влияния эксплуатационных и метеорологических условий на величины индексов эмиссии авиадвигателя. На основании анализа стендовых испытаний авиадвигателя типа CFM56-5C2 для крейсерского режима и режима малого газа были установлены зависимости индексов эмиссии от температуры атмосферного воздуха, расхода топлива и наработки авиадвигателя. Таким образом, реальные эксплуатационные условия отличаться от сертификационных условий авиадвигателей, в частности, по показателю тяги. Оценка индексов эмиссии авиадвигателей с учетом реальных эксплуатационных (показатель тяги) и метеорологических условий (температура атмосферного воздуха) является актуальной задачей, которая обеспечивает достоверные исходные данные для моделей загрязнения воздуха аэропортов и позволяет усовершенствовать процедуру инвентаризации выбросов авиадвигателей. Таким образом, оценка индексов эмиссии в реальных условиях обеспечивает достоверную оценку составляющей выбросов авиадвигателей в общем загрязнении воздуха аэропорта.

Ключевые слова: инвентаризация выбросов авиационных двигателей; индекс эмиссии; мониторинг загрязнения воздуха; оценка индексов эмиссии; экологический мониторинг; эмиссия авиационных двигателей

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