ENVIRONMENT PROTECTION

UDC 503.3.054:629.735.03 (045)

Oleksander Zaporozhets[1]
Kateryna Synylo[2]

MODELLING AND MEASUREMENT OF AIRCRAFT ENGINE EMISSIONS INSIDE THE AIRPORT AREA

[1,2]National Aviation University
Kosmonavta Komarova avenue 1, 03680, Kyiv, Ukraine
E-mail: [1]zap@nau.edu.ua; [2]synyka@gmail.com

Abstract. *The paper is aimed to improve complex model "PolEmiCa" by taking into account basic properties of contaminants transport and dilution by exhaust gases jet from aircraft engine near the ground. Validation of complex model "PolEmiCa" was implemented on the basis of measurement campaign at International Athens airport and International Boryspol airport.*

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

1. Introduction

Despite all the benefits that airports bring, they have significant impacts on those living nearby. Lately, this problem intensifies in connection with increasing air traffic (at a mean annual rate of 5 to 7%) and growing public awareness of local air quality around the airports [1-8]. The basic objects of attention are NO_x and fine particle matter (PM) emissions from aircraft engine emissions as initiators of photochemical smog and regional haze, which directly impact human health [9].

The aircraft is special source of air pollution due to following the features: moving source and accordingly velocity, direction and acceleration of aircraft movement has been changed in within the wide limits; presence of exhaust gases jet from aircraft engine near the ground; aircraft engine operation modes during landing take-off cycle have been changed from idle to maximum operation mode – correspondingly temperature, velocity of exhaust gases jet and emission characteristics of aircraft engine have been also changed within the wide limits. So, local and regional air pollution produced by aircraft engine emissions must be assessed by measurement and modelling methods, which provide initial information for next steps of air quality regulations (aircraft emission index and concentration of pollutant) to calculate precisely emission inventory of aircrafts and concentration field for control of sanitary-hygienic zone sizes around the airport. Both methods for determination of air quality levels must take into account expressed features aircraft, as special source of air pollution.

2. Analysis of the research and publication

During last decade a lot of studies are also focusing on the aircraft emissions impact on local and regional air quality in the vicinity of an airport [1, 2, 3, 4, 5, 6, 7, 8].

Analysis of inventory emission results at major European (Frankfurt am Main, Heathrow, Zurich and etc.) and Ukrainian airports highlighted, that aircraft (during approach, landing, taxi, take-off and initial climb of the aircraft, engine run-ups, etc.) is the dominant source of air pollution in most cases under consideration [10, 11].

3. Task

In the present study air pollutant emissions, e.g. nitrogen oxides (NO_x=NO+NO_2), were measured from passenger aircraft at Boryspol airport (Kiev) or existing emission data from Athens International Airport (AIA) were used for the improvement of complex model PolEmiCa (previous and improved version by Fluent 6.3/Gambit).

4. Complex model "PolEmiCa"

In the National Aviation University (Kyiv, Ukraine) a complex model "PolEmiCa" for assessment of air pollution and emission produced by aircraft activities inside the airport has been developed [12]. It consists of the following basic components:

1. Engine emission model – emission factor assessment for aircraft engines, including influence of operational factors;

2. Jet transport model – transportation of the contaminants by engine jets;

3. Dispersion model – dispersion of the contaminants in the atmosphere due to turbulent diffusion and wind transfer.

As was mentioned before the important feature of a researched source of emission is the presence of exhaust gases jet, which can transport contaminants on rather large distances. The value of this distance depends on engine type, operational and meteorological conditions [13].

Puffs are created by engine jets of a moving (or standing) aircraft with initial dispersion parameters σ_{0s}, which are the functions of the engine exhaust outlet parameters – diameter, velocity and temperature fig. 1. Temperature difference between jet and ambient atmosphere provides buoyancy effect for the jets and corresponding to puffs rise on a height Δh_A, which is also defined by outlet parameters. All of them are prescribed by jet transport model, which is based on semi-empirical model of turbulent jets.

The most part of LTO-cycle the aircraft is maneuvering on the ground (engine run-ups, taxing, accelerating on the runway), it is subjected to fluid flow that can create a strong vortex between the ground and engine nozzle, which have essential influence on structure and basic mechanisms (Coanda and buoyancy effects) of the engine jet of exhaust gases.

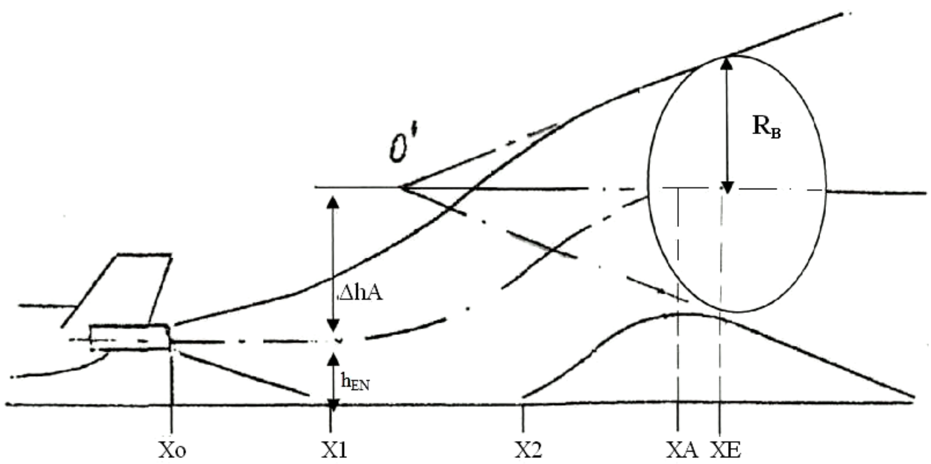

Fig. 1. Jet structure for jet transport model: Δh_A. X_A – height and longitudinal coordinate of jet axis rise due to buoyancy effect. m; h_{EN}– height of engine installation. m; R_B – radius of jet expansion. m; X_1 – longitudinal coordinate of first contact point of jet with ground; X_2 – longitudinal coordinate of a point of jet lift-off from the ground due to buoyancy effect

Complex model "PolEmiCa" has been improved in jet/plume transportation modeling by CFD code (Fluent 6.3) [14].

Using CFD codes allows us to investigate structure, properties, and fluid mechanisms of jet and also get deep understanding of contaminants transportation and dilution by jet from aircraft engine with taking into account ground impact.

Assessment of air pollution produced by aircraft engine emissions with taking into account dilution contaminants by jet and dispersion by wind and atmospheric turbulence is based on the decision of semi-empirical equation of turbulent diffusion (Eulerian approach) [12].

A basic equation of a complex model "PolEmiCa" for definition of instantaneous concentration from a moving source (from a single exhaust event) with preliminary transport on distance X_A and rise on altitude Δh_A and dilution σ_{0s} of contaminants by jet has a form:

$$c(x,y,z,t)=\frac{Q\exp\left[-\frac{(x-x')^2}{2\sigma_{x0}^2+4K_xt}-\frac{(y-y')^2}{2\sigma_{y0}^2+4K_yt}\right]}{\{8\pi^3[\sigma_{x0}^2+2K_xt]\,[\sigma_{y0}^2+2K_yt]\}^{1/2}}\times$$
$$\times\left\{\frac{\exp\left[-\frac{(z-z'-H)^2}{2\sigma_{z0}^2+4K_zt}\right]+\exp\left[-\frac{(z+z'+H)^2}{2\sigma_{z0}^2+4K_zt}\right]}{[\sigma_{z0}^2+2K_zt]^{1/2}}\right\} \quad (1)$$

where current coordinates (x', y', z') of the emission source in movement during time t':

$$x' = x_0 + u_{PL}t' + 0{,}5at'^2 + u_w(t + t');$$
$$y' = y_0 + v_{PL}t' + 0{,}5bt'^2;$$
$$z' = z_0 + w_{PL}t' + 0{,}5ct'^2,$$

(x_0, y_0, z_0) − initial coordinates of the source; (u_{PL}, v_{PL}, w_{PL}) – velocity vector components of emission source; (a, b, c) − acceleration vector components of emission source. Estimation of turbulent diffusion parameters for various atmosphere conditions is obtained as the following [15, 16, 17]:

$$u_B = \frac{u_1}{\ln^{z_1}/z_0 \times (H - 2)}\left(H \times \ln\frac{H}{z_0 e} - 2\ln\frac{z_1}{z_0 e}\right),$$

$$K_Z = \frac{K_1 \times H}{2z_1}; \quad K_X = K_0 \times U_B, \tag{2}$$

where wind speed u_1 and exchange factor K_1 correspond to altitude z_1, z_0 – roughness of the underlying surface, H - altitude.

The limits of change of values u_1 and K_1 are certain for all classes of atmospheric stability because of long-term observations [15, 16, 17].

Validation and improvement of complex model "PolEmiCa" has been implemented on the ground of experimental investigation in Athens [18, 19] and Boryspol [20] airports.

5. Comparison of measured and calculated concentrations from aircraft emissions in Athens International Airport

Experimental investigation in Athens International Airport (AIA) was focused on concentration measurements of NO_x by chemiluminescence technique (TE42C-TL96 system) in plume from aircraft engine and estimation of emission indexes of NOx under real operation conditions (accelerating on the runway and take-off the aircraft). Basic goal of the measurement campaign was to develop a database of airport air quality and meteorological conditions that will serve as initial data for validation and improvement of modeling systems [18, 19, 21, 22].

Complex model PolEmiCa (previous version and improved by Fluent 6.3) has calculated average concentration (1 min) of the contaminants, produced by aircraft engine emission during take-off in Athens airport. Appropriate model for this case was defined as a puff-model. Puffs were assessed for each engine of the aircraft separately, because of their separate influence on averaged concentration at point of monitor installation. For every take-off different values of wind speed and wind direction were measured, so the different values for turbulent diffusion coefficients (K_X, K_Y, K_Z) were calculated and used for following concentration assessment [18, 19].

Besides, results were defined for the cases with and without jets from the engines to show that with jets they are more equal to measured data, because impact of jet basic parameters (buoyancy effect and dispersion characteristics) on concentration distribution was estimated by complex model PolEmiCa, fig. 2. Comparison between measurements and the PolEmiCa/Fluent 6.3 model is significantly better (on 20 %), because lateral wind and ground impact on jet parameters (height of buoyancy effect, jet length penetration and plume dispersions) was included in the model.

Good agreement between model results and measurements were found for most part of aircrafts, but in some cases large differences were found, e.g. B737-4Q8, B747-230, A321-211, A320-214 and B737-33A.

Possible reasons for observed differences between modeled and measured concentration of NOx:

– quite big distance is between aircraft engine and monitoring station (1000±1500 m). For example, take off of the A320-214 was defined with very small angle (6,9º) between the take-off and wind direction, so calculated distances 1486 m and 1570 m are quite big. As a result, the measured concentration of NOx in plume from aircraft engine is quite less due to previous dilution by jet and next dispersion by wind and atmospheric turbulence. So, it is difficult to estimate aircraft engine emissions contribution;

– averaging period of measured concentration (1 minute) is quite big to detect separately maximum concentration in plumes from each engine of the accelerating the aircraft and include a contribution from each engine to measured result.

Only investigation of the plume-regime was possible during the AIA campaign. Both could be investigated during the Boryspol campaign.

6. Comparison of measured and calculated concentrations from aircraft emissions in Boryspol International Airport

Motivation for organization of the measurement campaign in Boryspol airport (KBA) was an investigation of concentration distribution in both the jet- and plume-regime to accurately assess aircraft engine emissions contribution to local air pollution.

According to the expressed goal, a scheme for disposition the monitoring (stationary "A" and movable "B") stations in airport was developed with taking into account modeling results (complex model PolEmiCa) of transportation and dilution contaminants by jet from aircraft engine for differential operational and meteorological conditions, fig. 3 [20].

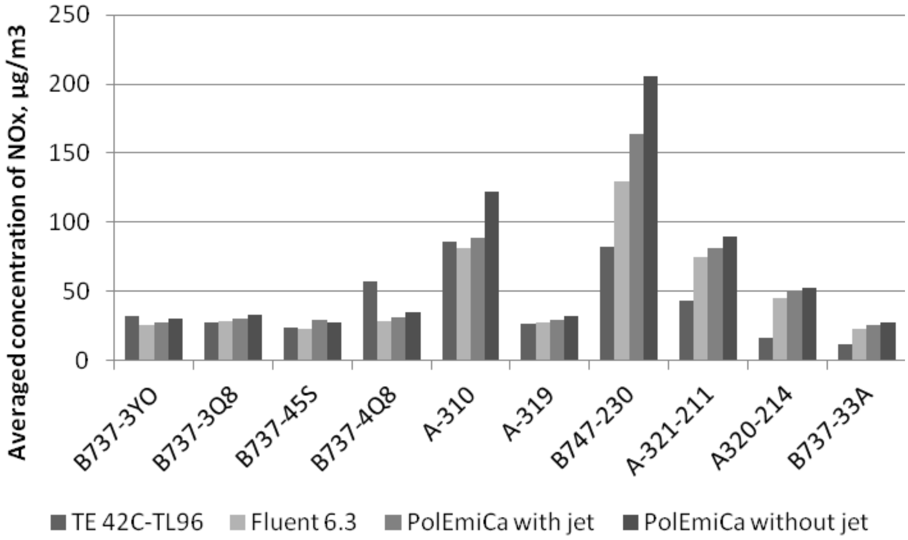

Fig. 2. Comparison of measured and modeled averaged concentrations (for period 1 min) of NOx at take-off conditions (maximum operation mode of aircraft engine)

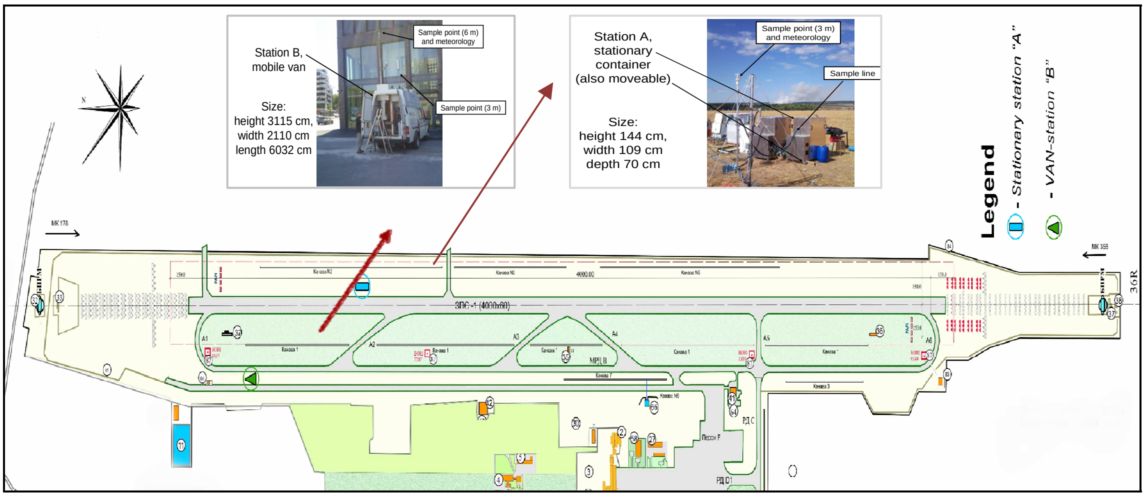

Fig. 3. Location of stationary station A and movable station B in Kyiv Boryspol airport for prevailing south-east wind direction (170°) for 13.09.2012

Stationary station A (jet regime) is displayed near runway (18L-36R) in east direction and on opposite side to taxiway A2. Mast is located at the distance of 60 m (height of sample point installation is 3 m) and measurement equipment is at the distance of 80 m from runway axis. Movable station B (plume regime) is oriented to dominant wind direction and displayed at distance 120 m from runway axis. Height of sample point installation is until 3 m, 6 m.

The monitoring stations with instrumentation of BUW were transferred from Germany to KBA:

- NO_x was measured by a chemiluminescence method (Ansyco AC 31M);
- CO_2 was measured by the non-dispersion infrared absorption method (Pewatron carbondio 1000, Licor 7100);

Ozone (O_3) was measured using a ultraviolett absorption method (Ansyco 41M);

Meteorological data; wind speed, wind direction, temperature and pressure etc. were measured by meteorological system (Thies clima).

ELAN analyzers are used for measurement of the mass concentration of CO, NO, NO_2 by a electrochemical method [Moscow, Russia]

Analysis of the results of measurement data at the station "B" observed that a lot of peak concentrations are clearly correlated with aircraft plumes. Maximum operation mode of aircraft engine is characterized by the highest value of NO_x, while the idle operation mode – higher value of CO_2, fig.4.

These results of measured concentration (NO, NOx, CO_2) provide the possibility to calculate NOx emission indexes for real operation conditions on the ground of equation [4]:

$$EI(X) = EI(CO_2) \times \frac{M(X)}{M(CO_2)} \times \frac{Q(X)}{Q(CO_2)}, \qquad (3)$$

where M denotes the molecular weight and Q denotes concentrations (mixing ratios, column densities, etc.) of the species.

Determined EINOx under real operational conditions compared with ICAO values for idle and maximum engine mode. The observed variations between real and certificated EI are most likely caused by conditions under real circumstances, which are different from well defined conditions during certification procedure, fig. 5. Nevertheless, these differences are important since the ICAO data is currently used to calculate emissions from airports.

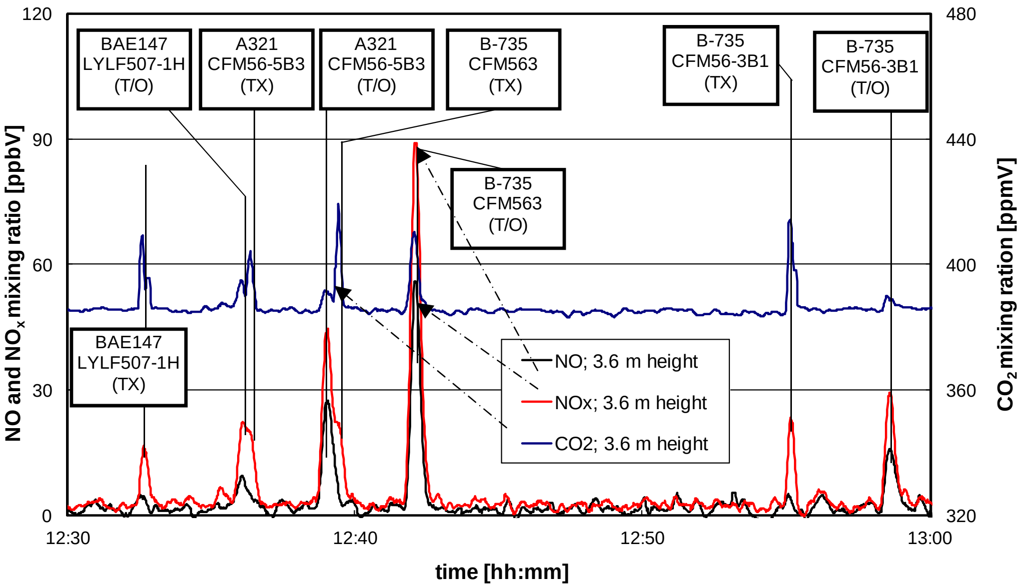

Fig. 4. Background and plume concentration for NO, NO_x and CO_2 at mobile station B for different aircraft at take-off (T/O) and ground taxi (TX) conditions

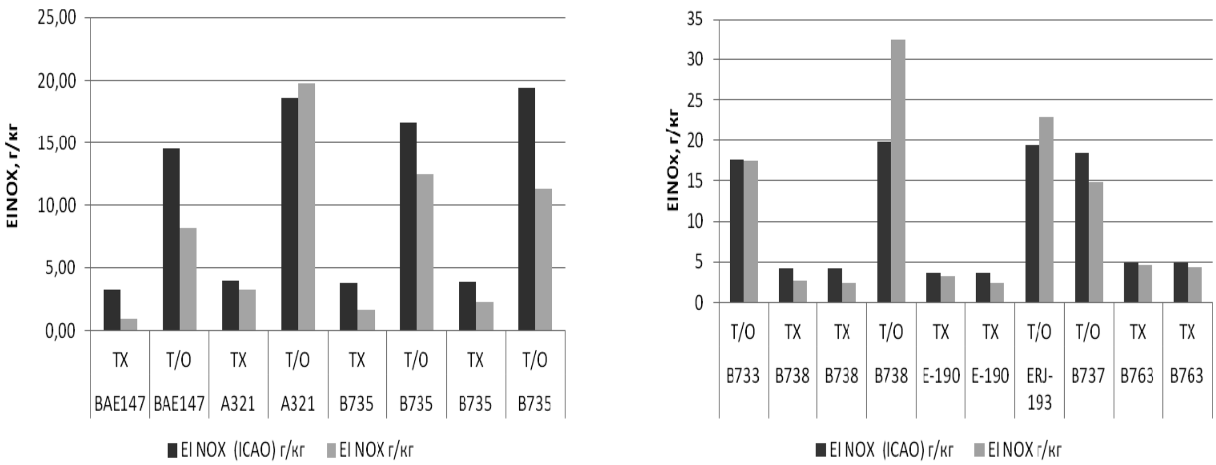

Fig. 5. Comparison of measured EINOx under real operation conditions (take-off (T/O) and taxing (TX)) with ICAO database

The period 12:30÷13.00 from 13.09.2012 of time series measurements in KBA was chosen for validation task of complex model PolEmiCa (previous version and improved by Fluent 6.3). This period is characterized by 5 peaks of NOx concentrations and corresponding to 5 aircraft departures (BAE 147, A321, B735), table 3.

As shown, the modeling results for each engine are in good agreement with the measurements results by the AC32M system. Good agreement between measurements and modelling results is explained by (fig. 6):

- Taking into account the jet- and plume-regime during experimental investigation at Boryspol airport;
- Using CFD-code (Fluent 6.3) allow to improve results on 30 % (coefficient of correlation, $r = 0{,}76$) by taking into account lateral wind and ground impact on jet parameters.

Table 3

Comparison measured and calculated concentration of NOx produced by aircraft engine emissions at accelerating stage on the runway

Time	Aircraft	Engine	Opera tion mode	AC31M			PolEmiCa Fluent		PolEmiCa	
				Back ground	3 м	6 м	1 engine	All engines	1 engine	All engines
				NOx	NOx	NOx	NOx	NOx	NOx	NOx
12:36	BAE147	LF507-1H	Take-off	1,70	22,067	33,9	35,1	70,46	48,9	202,3
12:39	A321	CFM56-5B3/P	Take-off	0,72	44,00	54,2	90,85	182,90	184,2	371,2
12:42	B735	CFM-563C1	Take-off	0,77	94,095	76,57	60,03	120,91	35,3	71,10
12:58	B735	CFM56-3B1	Take-off	1,74	29,20	23,4	42,34	85,30	33,7	67,76

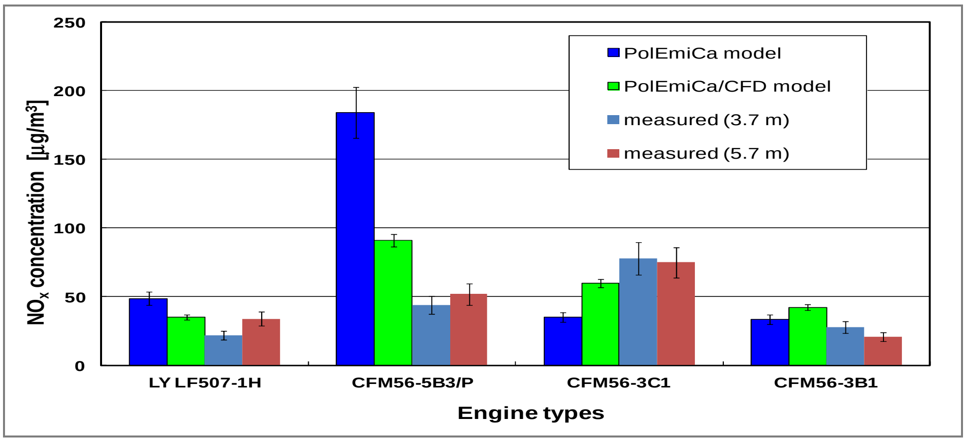

Fig. 6. Comparison of measured and modeled concentrations of NOx from aircraft accelerates on the runway (maximum operation mode of aircraft engine)

7. Conclusions

Using of calculation models allows to develop the practical recommendations for instrumental monitoring of aircraft engine emissions and to improve the assessment of its contribution to airport air pollution.

Combined approach of modeling and measurement methods provides more accurate representation of aircraft emission contribution to total air pollution (local pollution) in the airport area. Modeling side provides scientific grounding for organization of instrumental monitoring of aircraft engine emissions, particularly, scheme for disposition the monitoring stations with the aim to detect maximum concentration, which is characterized for jets/plumes from aircraft engines and at which height should be samples the concentration in exhaust with taking into account buoyancy effect and ground impact on jets behavior. And which time integration should be installing in measurement systems fairly to detect maximum concentration in jet/plume and assess aircraft emission contribution to total air pollution inside the airport. Such approach has been realized in Boryspol airport. So, using CFD codes for modeling aims provides an accurate tool to assess and control local air pollution produced by aircraft engine emissions.

References

[1] EEA, Europe’s environment: the third assessment. – European Environmental Agency, Copenhagen, 2003.

[2] Eurocontrol Statics@Forecast Services, Long Term Forecast of Flights (2004-2025). –Brussels: ESS, 2004.

[3] IPCC, Ed. Aviation and the Global Atmosphere, Intergovernmental Panel on Global Change – Cambridge University Press: Cambridge, 1999.

[4] Aircraft emission measurements by remote sensing methodologies at airports / K. Schafer, C. Jahn, P. Sturm, B. Lechner, M. Bacher // Atmospheric Environment. – 2003. – №37. – P. 5261-5271.

[5] European scientific assessment of the atmospheric effects of aircraft emission / G. Brasseur, R. Cox, D. Hauglustaine, I. Isaksen, J. Lelieveld, D. Lister, R. Sausen, U. Schumann, A. Wahner, P. Wiesen // Atmospheric Environment. – 1998. – № 32. – P. 2329-2418.

[6] *Heland, J.* Determination of major combustion products in aircraft exhausts by FTIR emission spectroscopy / J. Heland, K. Schäfer // Atmospheric Environment. – 1998. – № 32. – P. 3067-3072.

[7] NO and NO_2 Emission Ratios Measured from In-Use Commercial Aircraft during Taxi and Takeoff / S Herndon, J.Shorter, M. Zahniser, D. Nelson, Jayne, R. Brown, R. Miake-Lye, I. Waitz, P. Silva // Environ. Sci.Technol. – 2004. – № 38. – P. 6078-6084.

[8] *Popp P. J.* Method for commercial aircraft nitric oxide emission measurements / P. J. Popp, G. A. Bishop, D. H. Stedman // Environ. Sci.Technol. – 1999. – №33. – P.1542-1544. 8

[9] *Stedman J.* Quantification of the Health Effects of Air Pollution in the UK for the Review of the National Air Quality Strategy / J. Stedman, E. Linehan; K. King //AEAT4715. – 1999: http://www.aeat.co.uk/netcen/airqual/reports/health/health2.pdf

[10] Air Quality Procedures For Civilian Airports and Air Force Bases // FAA-AEE-97-03. Final Report September 1995 – April 1997. – 210 p.

[11] *Segal H.M.* The influence of Aircraft Operations on Air Quality at Airports / H. Segal, R. Yamartino // JAPCA, v. 31. – 1981. – No 8. – P. 846-851.

[12] *Zaporozhets O.* POLEMICA – tool for air pollution and aircraft engine emission assessment in airport / O. Zaporozhets, K. Synylo // The Second World Congress “Aviation in the XXI-st century”. – Kyiv: National Aviation University, 2005. – P. 4.22–4.28.

[13] *Abramovich G.N.* The Theory of Turbulent Jets / G.N. Abramovich – MIT Press, 1984. – 243 p.

[14] *Synylo K.* Modeling comparison results of exhaust gases jet from aircraft engine by complex model “PolEmiCa” and software Fluent 6.3 / K. Synylo // Вісник НАУ. – 2009. – № 3. – P. 253–261. (Russian).

[15] *Berlyand M. E.* Modern problems of armospheric diffusion and atmosphere contamination / M. E. Berlyand. – Saint-Peterburg, 1975. – 448 p. (Russian).

[16] *Berlyand M. E.* Prediction and regulation of atmosphere pollution/ M. E. Berlyand – Saint-Peterburg, 1985. – 272 p. (Russian).

[17] Methodology of contaminant concentration calculation from aircraft engines of civil aviation – Moscow:GosNIGA, 2007. (Russian).

[18] *Zaporozhets O.* Comparison of measured and modeling concentrations of air pollution produce by aircraft engine emissions inside the airport / O. Zaporozhets, K. Synylo // Вісник НАУ. – 2009. – № 1. – P. 40–45. (Russian).

[19] *Zaporozhets O.* Monitoring and modeling of air pollution produced by aircraft engine emissions inside the Athens International Airport / O. Zaporozhets, K. Synylo // Вісник НАУ. – 2009. – № 4. – P. 59–64.

[20] *Drach O.* Monitoring of air pollution from operation of aircraft in the vicinity of airport / O. Drach, K. Synylo, K. Kazhan // AVIA 2013. – 2013. – № 5. – P. 32.9–32.11.

[21] Airport air quality studies in Athens. General concept of development of a databank / K. Schäfer, S. Emeisa, C. Jahna, M. Hoffmann, Ch. Heyder, C. Helmis, G. Scouros, H. Flocasb, Maria Tombroub // ECATS working paper, 2007.

[22] Issues related to aircraft take-off plumes in a mesoscale photochemical mode / E. Bossioli, M. Tombrou, C. Helmis, R. Kurtenbach, P. Wiesen, K. Schäfer, A. Dandou, K. Varotsos // Science of Total Environment, 456-457. – 2013. – P. 69-81.

Received 02 October 2014.

О. І. Запорожець[1], К. В. Синило[2], Моделювання та вимірювання емісій авіадвигунів в зоні аеропорту
Національний авіаційний університет, Київ, Україна, проспект Космонавта Комарова 1, 03680, Київ, Україна
E-mail: [1]synyka@gmail.com; [2]zap@nau.edu.ua

Розв’язано завдання щодо удосконалення моделі забруднення атмосферного повітря внаслідок експлуатації повітряних суден у зоні аеропорту (комплексна модель PolEmiCa) на основі розробленої моделі струменя газів від авіадвигуна поблизу поверхні аеродрому. Представлено результати перевірки достовірності вдосконаленої комплексної моделі PolEmiCa на базі результатів експериментальних досліджень в межах міжнародних аеропортів «Афіни» та «Бориспіль».

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

А. И. Запорожец[1], Е. В. Синило[2]. Моделирование и измерения эмиссий авиадвигателей в зоне аэропорта
Национальный авиационный университет, Киев, Украина, проспект Космонавта Комарова 1, 03680, Киев, Украина
E-mail: [1]synyka@gmail.com; [2]zap@nau.edu.ua

Решена проблема по усовершенствованию расчетной модели загрязнения воздуха аэропорта на основе разработанной модели струи газов от авиадвигателя вблизи поверхности аэродрома. Представлены результаты проверки достоверности усовершенствованной комплексной модели PolEmiCa на основе результатов экспериментальных исследований в международных аэропортах «Афины» и «Борисполь».

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

Zaporozhets Oleksandr (1956) D. Sc., Professor.
Director of Institute of ecological safety and Head of Chair of Safety of Human Activities, National Aviation University
Education: Kiev Institute of Civil Aviation Engineers (1978).
Reasearch area: Development of Models and Methods of Information Provision for Environment Protection from Civil Aviation Impact.
Publications: 210.
E-mail: zap@nau.edu.ua

Synylo Kateryna (1979) PhD.
Assistant of Professor, Department of Safety of Human Activity, Institute of Ecological Safety, National Aviation University
Education : Odessa Hydrometeorological Institute (2001).
Reasearch area: Methods of local air quality regulation inside the airport
Publications: 20.
E-mail: synyka@gmail.com