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MODELLING AND MEASUREMENT OF NOx CONCENTRATION IN PLUME FROM AIRCRAFT ENGINE UNDER OPERATION CONDITIONS AT THE AERODROME AREA

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Abstract

Purpose: *Airport air pollution is growing concern because of the air traffic expansion over the years (at annual rate of 5 %), rising tension of airports and growing cities expansion close each other (for such Ukrainian airports, as Zhulyany, Boryspol, Lviv, Odesa and Zaporizhzhia) and accordingly growing public concern with air quality around the airport. Analysis of inventory emission results at major European and Ukrainian airports highlighted, that an aircraft is the dominant source of air pollution in most cases under consideration. For accurate assessment of aircraft emission contribution to total airport pollution and development of successful mitigation strategies, it is necessary to combine the modeling and measurement methods.* ***Methods***: *Measurement of NO_x concentration in the jet/plume from aircraft engine was implemented by chemiluminescence method under real operating conditions (taxi, landing, accelerating on the runway and take-off) at International Boryspol airport (IBA). Modeling of NO_x concentration was done by complex model PolEmiCa, which takes into account the transport and dilution of air contaminates by exhaust gases jet and the wing trailing vortexes.* ***Results***: *The results of the measured NO_x concentration in plume from aircraft engine for take-off conditions at IBA were used for improvement and validation of the complex model PolEmiCa. The comparison of measured and modeled instantaneous concentration of NO_x was sufficiently improved by taking into account the impact of wing trailing vortices on the parameters of the jet (buoyancy height, horizontal and vertical deviation) and on concentration distribution in plume.* ***Discussion***: *Combined approach of modeling and measurement methods provides more accurate representation of aircraft emission contribution to total air pollution in airport area. Modeling side provides scientific grounding for organization of instrumental monitoring of aircraft engine emissions, particularly, scheme for disposition the monitoring stations with aim to detect maximum concentration which is characterized for jets/plumes from aircraft engines.*

Keywords: aircraft engine emission; air pollution monitoring; assessment of emission indices; emission index; emission inventory of aircraft engine; environmental monitoring; wing trailing vortex.

1. Introduction

Aviation must be environmentally sustainable, operating harmoniously within the constraints imposed by the need for clean air, limited noise impacts, and a livable climate. Improvements in local air quality (LAQ) assessments are still a subject of interest to define the value of concentration of air pollution inside the airport areas [1].

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 [2].

Aircraft is a special source of air pollution due to some features.

First of all, the aircraft is moving source, result in velocity, direction and acceleration of aircraft movement has been changed in within the wide limits.

Second, the important feature is the presence of a jet of exhaust gases, which can transport contaminant on rather large distances because of high exhaust velocities and temperatures. The value of such a distance is defined by engine power setting and installation parameters, mode of an airplane movement, meteorological parameters. The results of the jet model calculations, depending on listed initial data, show that the extent of transport of the jet plumes from aircraft engines may change within the 20...1000 m and sometimes even more.

Third, the engine jets are entrained into the two counter-rotating wingtip vortices with further the deflection and the stretching of the plume towards to vortex centerline.

Fourth, the most part of landing-take-off 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 exhaust gases jet.

So, air pollution from aircraft engine emissions and engine jet behavior depend both on: number of engines, engine nozzle parameters and height of its installation, distance between engine nozzle centerlines, and where engines are mounted – on fuselage or on wing of the aircraft. To assess their contribution in LAQ assessment it is important to take in mind few features, which define emission and dispersion parameters of the source.

2. Analysis of the research and publications

A lot of theoretical and experimental investigations are focused on dynamics and mechanisms of aircraft vortex wake development [3-8]. Garnier (2005) revealed that the trailing vortex wake is generated in the boundary layer on the wing. The wingtip vortices are the results of the roll-up of the vortex sheet downstream of the wing, Fig.1. Therefore, the wake of an aircraft is composed of two counter rotating wing-tip vortices [3]. The qualitative features of the jet and trailing vortex interaction were first illustrated by Hoshizaki [4] and later by Miake-Lye [5] and Thomas Gerz [6], Tilman Dürbeck [7] Cure [8] who identified some distinct phases of aircraft wake:

- the nearfield jet regime (5s, 1 km) corresponds to the phase, where exhaust gases jets expand and mix with ambient air. While the wingtip vortices are developing and do not interact with the jet;
- the deflection regime (1 min, 10 km) corresponds to the phase of the jet entrainment into the vortex core;
- the shearing regime (1.5 min, 20 km) corresponds to the phase of the jet diffusion due to turbulence and buoyancy effects.

was already entrained by vortex wake at a distance of only one-half wingspan downstream.

The some research studies [8, 10] have been found to get understanding on the interaction between the wing-tip vortex and the engine exhaust for the take-off and landing configuration, since it is **quite actual task** for assessment of aircraft emissions contribution to airport air pollution.

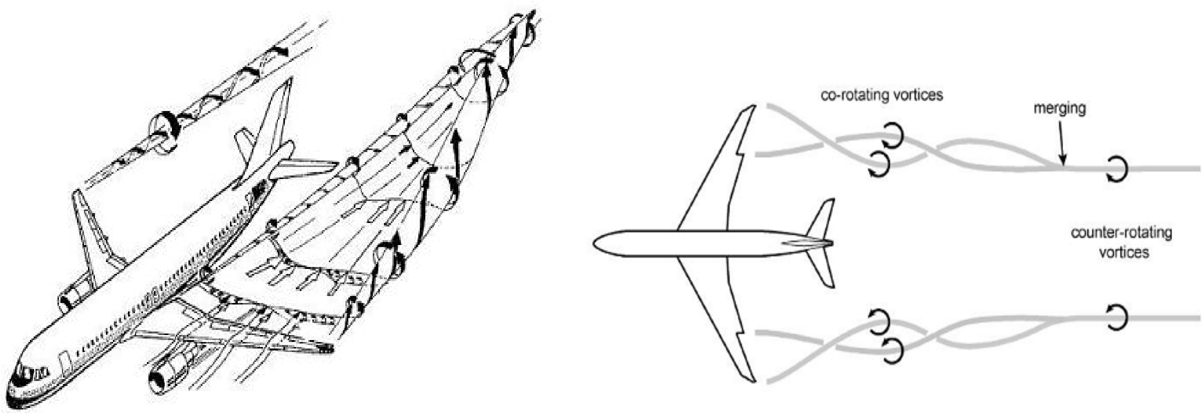
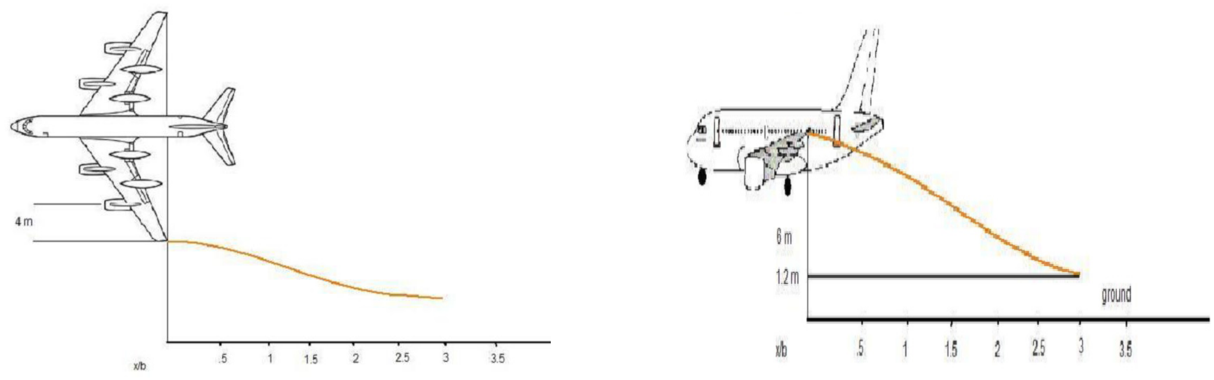


Fig. 1. Vortex wake generation behind the aircraft (F.Garnier, 2005)

The most part of the experimental and numerical simulations are devoted to the interaction of the exhaust gases jet and wing trailing vortex at cruise conditions [5, 8, 9, 10]. The strength of the vortex is higher at cruise than for the high-lift configurations. The cruise configuration was characterized by strong vortex which deflects the plume in the vortex sheet [8]. Brunet et al. [9] revealed that part of the jet The take-off configuration is characterized by full-power engines and correspondingly the high velocity of engine plume, which sufficiently impacts on the vortex flow development.

Cure [8] revealed that the vortex is deflected away from the aircraft centerline up to 2.2 m in horizontal direction (Fig.2.a) and downward to 1.2 m near the ground in vertical direction (Fig. 2.b).



a *b*

Fig. 2. Evolution of vortex core trajectory in the horizontal (a) and vertical (b) planes

Analysis of the research studies of jet and vortex iteration has highlighted the importance of the ground impact on aircraft vortex wake development at high-lift configuration. Over the last few decades, a lot of analytical and numerical studies [11, 12, 13, 14, 15, 16] have been devoted the problem of the wake vortex evolution near the ground.

Chan [11] highlighted the importance of the vortex circulation effect on pollutant dispersion and concluded the variation of pollution concentration distribution in the control volume due to the circulation of vortices near the ground.

Harvey&Perry [12] were examined the case of vortex pair approaching a no-slip wall in a viscous fluid by test in wind tunnel. On the basis of analysis of flight test data and conducted tests, it was observed, that the vortices approach the ground, it induces a cross flow and creates a boundary layer. An adverse pressure gradient causes the boundary layer to separate from the ground and roll-up into oppositely signed vortex, which causes the primary vortex to rebound from the ground [12].

So, modeling of air pollution produced by aircraft engine emissions should assess the mechanisms of the entrainment of the engine exhaust jet near the ground into the wing trailing vortex system and include their impact on contaminant concentration distribution in plume under different operation conditions. Eliminating the fluid mechanisms of aircraft wake vortex may overestimate the height of buoyancy exhaust gases jet from aircraft engine, underestimate its length and radius of expansion, dispersion characteristics and contaminants concentration values in plume.

3. Task

In the present study NO_x concentration was measured in plume from passenger aircraft at landing and take-off conditions at International Boryspol airport (IBA). Complex model PolEmiCa has been improved on the basis of the measurement campaign and by take into account an influence of the ground on jet behaviour and the interaction between the jet and the wing trailing vortex system**.**

4. Measurement results of NO_x concentration in plume from aircraft engine at International Boryspol airport

Experimental studies at IBA were focused on measurement of NO_x concentration in the plume, both the jet- and dispersion-regime of aircraft engines under real operating conditions (taxi, landing, accelerating on the runway and take-off). A stationary station A is (jet-regime) close-by the runway (30 m) with a measuring height of 3.0 m. A mobile station B (dispersion-regime) is at distance 110 m from the runway and its location is oriented due to the prevailing wind direction (north-west, west, south-west)and with a measuring height 3.6 and 5.7 m. Figure 3 shows the measurement location set up at A and B. It was guaranteed, that largest part of the aircraft exhaust at landing and take-off conditions was scanned by NO_x measurement systems.

Analysis of the data exhibited that peaks for NO_x and CO_2 concentration are unambiguously correlated with aircraft plumes.

Figure 4 shows the background and plume concentration for NO, NO_x and CO_2 at 3.6 /5.3 m sampling height for different aircraft at take-off (T/O) and landing (A) conditions.

Thus, the take-off conditions of an aircraft engine is characterized by the highest NO_x emission, while the landing conditions – by a much lower NO_x value.

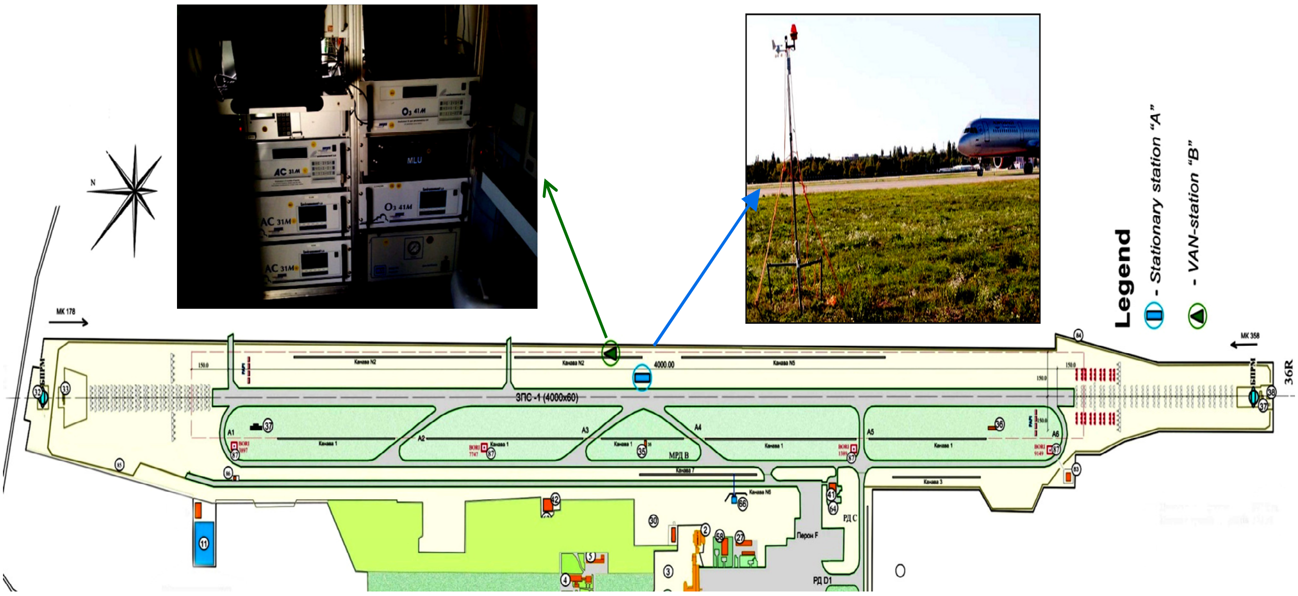


Fig. 3. Stationary station A and mobile Station B (Van), both downwind. Investigation of air contaminants transport and dilution from aircraft engine emissions at landing and take-off conditions

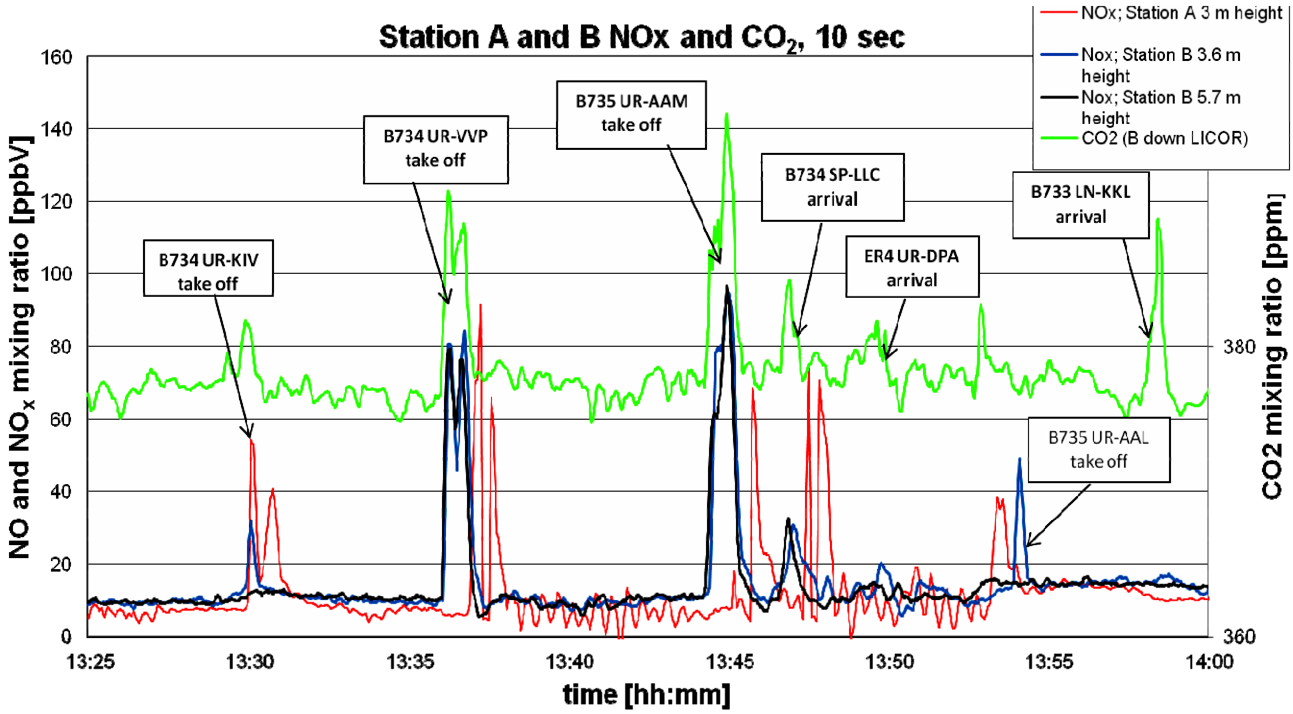


Fig.4. Background and plume concentration for NO, NO_x, CO_2 at stationary station A and mobile station B at landing / take-off conditions and the prevailing wind direction

5. Comparison of measured and calculated concentrations from aircraft emissions at Boryspol International airport

The results of the measured NO_x concentration in plume from aircraft engine for take-off conditions at IBA were used for improvement and validation of the complex model PolEmiCa. This model is developed in National Aviation University [17]. It consists of the following basic components [18, 19]:

1. **engine emission model** – emission factor assessment for aircraft engines, including influence operation factors;
2. **jet transport model** – transportation of the contaminants by jet from aircraft engine exhaust;
3. **dispersion model** – dispersion of the contaminants in atmosphere due to turbulent diffusion and wind transfer.

The complex model PolEmiCa allow to calculate the inventory and dispersion parameters of the aircraft engine emission during the landing-takeoff cycle of the aircraft in airport area [19, 20].

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 [17, 20]:

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

$$\times\left\{\frac{\exp\left[-\frac{(z-z'-H)^2}{2\sigma_{z0}^2+4K_z t}\right]+\exp\left[-\frac{(z+z'+H)^2}{2\sigma_{z0}^2+4K_z t}\right]}{[\sigma_{z0}^2+2K_z t]^{1/2}}\right\}$$

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

$$x'=x_0+u_{PL}t'+0.5at'^2+u_w(t+t');$$

$$y'=y_0+v_{PL}t'+0.5bt'^2\quad z'=z_0+w_{PL}t'+0.5ct'^2$$

(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; K_x, K_y, K_z. − coefficients of atmospheric turbulence, m/c^2.

Model calculates the coordinates (X_{wmax}; Y_{wmax}) and period of maximum concentration formation (T_{wmax}) on the runway from moment of aircraft engine run:

$$T_{w\max}=(X_{w\max}-X_{1w})/U_s$$

Also the model predicts maximum concentration distribution due to dilution by jet and diffusion by atmospheric turbulence and its detection by monitoring station (Fig.5).

Maximum value of instantaneous concentration c_{max} at the detection point of monitoring station will be derived at the moment t_{max}, which is determined by the following formula:

$$T_{wind}=\frac{X_{wind}}{U_w}-\sqrt{X_{wind}\frac{dKx}{U_w^3}}$$

where X_{wind} – the distance of the contaminants transport by the wind to monitoring station; U_w – wind velocity, m/s.

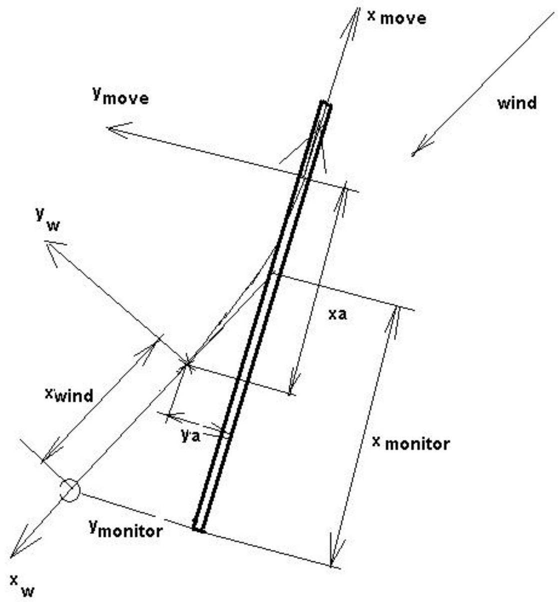


Fig. 5. Modeling scheme of transport and dilution of air contaminants by exhaust gases jet from aircraft engine and atmospheric diffusion

So, the comparison of measured and modeled instantaneous NO_x concentration was sufficiently improved by taking into account interaction of the jet with wing trailing vortexes during the take-off stage Figure 6. Wing trailing vortexes effect causes the expansion of horizontal dispersions of jet and decrease of buoyancy effect height.

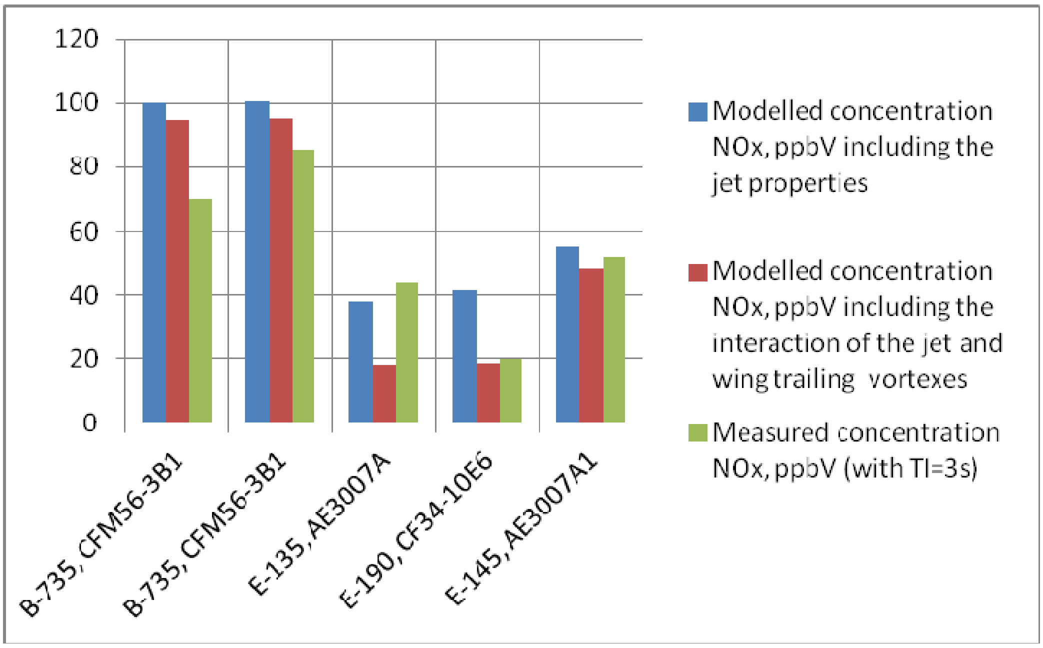


Fig. 6. Comparison of the PolEmiCa (previous and improved version) results with the measured NOx concentration from aircraft engines exhausts under maximum operation mode at International Boryspol airport

6. Conclusions

Combined approach of modeling and measurement methods provides a more accurate representation of aircraft emission contribution to total air pollution (local pollution) in airport area. Modeling side provides scientific grounding for organization of instrumental monitoring of aircraft engine emissions, particularly, scheme for disposition the monitoring stations with aim to detect maximum concentration which is characterized for jets/plumes from aircraft engines and at which height be samples the concentration in exhaust with taking into account wing-tip vortices effect and ground impact on jets behavior.

As shown from fig.6, the measurement results correlate quite good with modeling ones, which include the impact of wing trailing vortices on the parameters of the jet (buoyancy height, horizontal and vertical deviation) and contaminant dilution process.

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О.І. Запорожець[1], К.В. Синило[2]. Моделювання та вимірювання концентрацій NOx у струмені газів від авіадвигуна за експлуатаційних умов на території аеродрому

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Мета: Забруднення повітря аеропортів є актуальною проблемою через зростання обсягів авіаційних перевезень щорічно на 5%, а також у зв’язку із дедалі більшим наближенням житлових районів до аеропортів (зокрема для таких аеропортів України, як Київ («Жуляни»), Львів, Одеса, Харків, Донецьк, Запоріжжя. Аналіз результатів інвентаризації джерел викидів забруднюючих речовин (ЗР) у головних аеропортах Європи та України вказує на домінантність викидів ЗР від авіаційних двигунів (АД) у зоні аеропорту. Для успішного розв’язання зазначеної екологічної проблеми необхідно організувати контроль емісії ЗР від АД налагодженням системи інструментального моніторингу та розрахункових моделей забруднення повітря в межах та на прилеглих територіях аеропорту. **Методи**: Вимірювання NO_x концентрацій у струмені газів від авіадвигунів було виконано на базі хемілюмінесцентного методу за реальних експлуатаційних умов (руління, приземлення, розбіг уздовж злітно-посадкової смуги та зліт повітряного судна) у межах міжнародного аеропорту «Бориспіль». Розрахунок NO_x концентрацій було виконано за комплексною моделлю PolEmiCa з урахуванням процесів переносу та розбавлення домішок ЗР струменем газів від АД та вихровою пеленою від крила повітряного судна. **Результати**: Представлено результати вдосконалення комплексної моделі PolEmiCa за рахунок урахування впливу параметрів струменя (висота спливання, дисперсія меж та далекобійність), земної поверхні та вихрової пелени від крила на процеси переносу та розбавлення домішок забруднюючих речовин у викидах авіадвигунів. Наведено результати перевірки достовірності вдосконаленої комплексної моделі PolEmiCa на підставі результатів експериментального дослідження в межах міжнародного аеропорту «Бориспіль».
Отже, запропонований комбінований підхід інструментального моніторингу з розрахунковими моделями забезпечує точніше виявлення та визначення складової емісії АД у локальному та регіональному забрудненні атмосферного повітря у межах та на околиці аеропорту. Так, розрахункові моделі надають обґрунтування для схеми розміщення станцій інструментального моніторингу з метою виявлення максимальної концентрації, яка формується в струмені від кожного АД досліджуваного повітряного судна.

Ключові слова: інвентаризації авіаційних двигунів; індекс емісії; кінцевий вихор від крила; моніторинг забруднення повітря; моделювання забруднення атмосферного повітря; струмінь газів; емісія авіаційних двигунів.

А.И. Запорожец[1], Е.В. Синило[2]. Моделирование и измерения концентраций nox в струе от авиадвигателя в реальных эксплуатационных условиях на территории аэродрома

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Цель: Загрязнение воздуха аэропортов является актуальной проблемой вследствие роста объемов авиационных перевозок ежегодно на 5%, а также с тенденцией приближения жилых районов к аэропортам (в частности для Украины, это такие аэропорты, как Киев («Жуляны»), Львов, Одесса, Харьков, Донецк, Запорожье. Анализ результатов инвентаризации источников выбросов загрязняющих веществ (ЗР) в главных аэропортах Европы и Украины указывает на доминантность выбросов от авиационных двигателей в зоне аэропорта. Для успешного решения указанной экологической проблемы необходимо организовать контроль эмиссии ЗВ от АД на основе системы инструментального мониторинга и расчетных моделей загрязнения воздуха в зоне и на прилегающих к аеропорту территориях. **Методы**: Измерение NOx концентраций в струе газов от авиадвигателей было выполнено на базе хемилюминесцентного метода в реальных эксплуатационных условиях (руление, приземление, разбег вдоль взлетно-посадочной полосы и взлет воздушного судна) в зоне международного аэропорта «Борисполь». Расчет NOx концентраций выполнен на основе комплексной модели PolEmiCa, с учетом процессов переноса, разбавления примесей ЗР струей газов от АД и вихревой пеленой от крыла воздушного судна. **Результаты**: Представлены результаты усовершенствования комплексной модели PolEmiCa на основе учета влияния параметров струи (высота всплытия, дисперсия границ и дальнобойность), земной поверхности и вихревой пелены от крыла на процессы переноса и разбавления примесей загрязняющих веществ в выбросах авиадвигателей. Приведены результаты проверки достоверности усовершенствованной комплексной модели PolEmiCa на основании результатов экспериментального исследования в зоне международного аэропорта «Борисполь». Таким образом, комбинированный подход на основе инструментального мониторинга и расчетных моделей обеспечивает более точное выявление и определение составляющей эмиссии АД в локальном и региональном загрязнении атмосферного воздуха в пределах и в окрестностях аэропорта. Так, расчетные модели предоставляют обоснование для схемы размещения станций инструментального мониторинга с целью выявления максимальной концентрации ЗР в струе отработанных газов от каждого АД исследуемого воздушного судна.

Ключевые слова: инвентаризация выбросов авиационных двигателей; индекс эмиссии; концевой вихрь от крыла; мониторинг загрязнения воздуха; моделирование загрязнения атмосферного воздуха; струя газов; эмиссия авиационных двигателей.

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