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PolEmiCa model for local air quality assessment in airports

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1. INTRODUCTION

Aircraft engine emissions have a direct impact on air quality in local, regional and global scales. Several studies exhibited extremely high concentrations of toxic compounds (including nitrogen oxides (NO_x), particulate matter (PM_{10}, $PM_{2.5}$ and UFP), unburned hydrocarbons (UHC) and carbon monoxide (CO)) due to airport-related emissions and a significant impact on the environment (Herndon et al., 2008) and health of the people living near the airport (Peace et al., 2006).

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.) are the dominant source of air pollution in most cases under consideration (Celikel et al.,2005; Fraport review, 2014).

To assess of aircraft engine emissions contribution in local air quality (LAQ) assessment it is important to take in mind some features, which define emission and dispersion parameters of the source.

The most important feature of the aircraft, as special source of air pollution is the presence of an exhaust gases jet, which can transport contaminants over rather large distances due to the high exhaust velocities and temperatures. The extent of such a distance is defined by the engine power setting and installation parameters, mode of the aircraft movement and the meteorological parameters. The aircraft is moving source with spatially and temporally changing of velocity, acceleration and direction of the aircraft movement within wide limits inside the territory of LAQ assessment. Since the most part of landing take-off (LTO) cycle the aircraft is maneuvering on aerodrome surface (engine run-ups, taxing, accelerating on the runway etc.), the ground significantly impacts on the structure and behavior (Coanda and buoyancy effect) of exhaust gases jet.

Main purpose of the PolEmiCa is to provide the dispersion (**Pol**lution) and inventory (**Emi**ssion) **ca**lculations for the aircraft engine emission during the LTO cycle of the aircraft movement inside airport area. It includes the aircraft emission from Start-up procedures, Auxiliary Power Unit (APU) and Ground Support Equipment (GSE) also. Current version of the PolEmiCa combines the calculation for the main stationary sources (power plants, fuel farms) and road vehicles inside airport area with character toxic compounds for aircraft engine emission: CO, HC, NO_x, SO_x, PM_{10}, $PM_{2.5}$ and fuel vapors (HC). Usual practice for the Former Soviet Union countries, in particular in Ukraine today, that the air pollution must be calculated, first of all, for the stationary sources using the OND-86 method and just these data must be taken into account in procedures of zoning around the polluters, including the airport. OND-86 calculation method is mainly used for stationary sources, with some assumptions – for ground vehicles, but absolutely not appropriate for aircraft (Zaporozhets and Synylo, 2015).

The complex model PolEmiCa consists of the following basic components:

1. **engine emission model** provides emission factor assessment for aircraft engines, including influence of operational and meteorological factors;
2. **jet transport model** evaluates basic mechanisms of contaminants transportation and dilution by the jet from the aircraft engine exhaust providing basic parameters of the jet for further dispersion analyses;
3. **dispersion model** calculates the dispersion of the pollutants in the atmosphere due to turbulent diffusion and wind transfer.

PolEmiCa calculates the concentration filed inside airport area taking into account intensity of flights of airplanes, a loading factor of different taxiways and runways, and other operational circumstances. Basic expression for definition of maximum instantaneous value of concentration in grid point is a solution of turbulent diffusion equation according to Eulerian approach for moving point source with preliminary transport and dilution of contaminants by an exhaust gases jet and wing vortices. Domestic normative regulations use concentration limits with averaging interval equal to 20...30 min. These values are used for administration purpose of air pollution control, including the definition of the boundaries of sanitary protection zones around the sources of air pollution, airport are among them (Zaporozhets and Synylo, 2015).

2. EMISSION INVENTORY

Emission inventory is provided by PolEmiCa for LTO cycles of aircraft movements and for some other important sources of air pollution in airport area: Start-up procedures, APU and GSE usage, Power plants, Fuel Farms. Inventory analysis for stationary sources (Power Plant, Fuel Farm) and vehicle (Roadways and Parking facilities) is carried out in

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accordance with Ukrainian national methodology (Zaporozhets and Synylo, 2015).

The PolEmiCa model is under evaluation procedure by MDG for mock-up airport CAEPport with given initial data for local air quality modelling (CAEP/10-MDG/8-WP/2, 2015). Total movements number according with CAEPport_Movements_v9.csv for the one calendar year is 88390 (Table 1), its distribution among the flight cases is the following.

Table 1

Flight operations distribution over aircraft groups

Aircraft group	Departures	Arrivals	Operations	Percentage, %
Large	3179	3177	6356	7.2
Medium	713	712	1425	1.6
Small	24109	24604	48713	55.1
Regional	5536	5571	11107	12.6
Business	103	113	216	0.2
Turboprop	9891	10102	19993	22.6
Piston	290	290	580	0.7
Total	43821	44569	88390	100

PolEmiCa distributes the flight operations by setting of aircraft movements separately for each aircraft group (large, medium, small, regional, business, turboprop, and piston).

The aircraft emission inventory starts with individual aircraft/engine combinations for approach or departure cycles, and generally applies the operational and emission parameters in a two-step process as follows:

1. Calculate emissions from a single aircraft/engine combination by summing the emissions from all the operating modes which constitute an LTO cycle, where emissions from a single mode could be expressed as:

$$M_{jLTO}=\sum_{i=1}^{4} EI_{ji}\times G_i \times \tau_i \times n \qquad (1)$$

where: M – emission of aircraft engine for LTO-cycle, g/s; EI – emission index for characteristic relative thrust, g/kg; G – fuel flow rate, kg/s; τ – time in mode, which is defined by ICAO LTO-cycle or by real configuration of the airport, n – number of the engines

2. Calculate total emissions by summing over the entire range of aircraft/engine combinations and number of LTO cycles for the period under consideration.

The aircraft inventory also includes start-up HC emissions, which are evaluated by art. 6.59 of ICAO Doc 9889:

$$M_{HC} = \text{rated take-off thrust (kN)}/2 + 80 \qquad (2)$$

The APU and Ground Power Unit (GPU) emissions inventory is done by PolEmiCa for CO, HC and NOx for six characteristic groups of aircraft in accordance with the sophisticated approach (art. 7.16 of ICAO Doc 9889 Airport Air Quality Manual, 1st edition, 2011). GSE emissions was done with advanced approach (art. 7.16 of ICAO Doc 9889 Airport Air Quality Manual, 1st edition, 2011).

PolEmiCa tool demonstrated a good accordance of the emission inventory for all emission sources in comparison with other LAQ models (in Table 2), which were examined during CAEP/8 and CAEP/9.

Table 2

Summary of Comparison between the tools

Substance	LASPORT	EDMS	ALAQS	ADMS	PEGAS	PolEmiCa
CO	331475	766456	285032	377899	382258	**303706**
HC	57039	111781	64780	52294	59778	**72311**
NO$_x$	328742	360286	360232	351933	383563	**375666**
SO$_x$	88501	108318	90929	86787	166303	**124012**
PM10	6297	10645	6378	7323	6867	**3639**
PM2.5	5217	9099	3095	6237	5787	**1377**

3. DISPERSION MODEL

The basic equation of the PolEmiCa model for the definition of an instantaneous concentration from a moving source (from a single exhaust event) with preliminary transport on a distance X_A and rise on an altitude Δh_A and dilution σ0s of pollutants by the jet takes a following form (3):

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

The aircraft is considered as a moving emission source, thus current co-ordinates (x’, y’, z’) of the emission source in movement during time t’ are defined as:

$$x'=x_0+u_{PL}t'+0.5a_{PL}t'^2+u_w(t+t'); \qquad (4)$$

$$y'=y_0+v_{PL}t'+0.5b_{PL}t'^2; \qquad (5)$$

$$z'=z_0+w_{PL}t'+0.5c_{PL}t'^2 \qquad (6)$$

where (x_0, y_0, z_0) are initial coordinates of the source; (u_{PL}, v_{PL}, w_{PL}) are velocity vector components of the emission source; (*a*, *b*, *c*) are acceleration vector components of the emission source; K_x, K_y, K_z. are coefficients of atmospheric turbulence (Zaporozhets and Synylo, 2005, 2015). As with any dispersion model, the initial properties of a plume are important to model its rise and location. Such plume or jet parameters, as rise height Δh_A due to buoyancy effect, horizontal σ^2_y and vertical σ^2_z dispersion parameters are needed as input to dispersion modeling of aircraft sources. **The jet transport model** evaluates basic mechanisms of contaminants transportation and dilution by jet of exhausted gases from aircraft engine and provides basic parameters of the jet for further dispersion analysis, Fig.1.

The process of contaminant transport by exhaust gases jet is described by the semi-empirical theory of turbulent jets [Abramovich G., 1960]. Buoyancy of a jet is caused by action of Archimedes forces due to excess of temperature of jet gases above air temperature, fig.1. The Archimedes number (6) is used for the estimation of the plume rise height (7) (Zaporozhets and Synylo, 2016):

$$Ar_0 = g \cdot D_0 \cdot (Q_T - 1)/U_0^2 \quad (6) \qquad \Delta h_A = 0.013 \cdot Ar_0 \cdot \overline{X_A^3} \cdot R_0 \quad (7)$$

where parameter $Q_T = T_0/T_H$ for engines currently in operation changes within the limits of 1.15- 2; $\overline{X}_A$ is the longitudinal coordinate of jet axis in relation to radius of engine exhaust nozzle, $R_0 = D_0/2$.

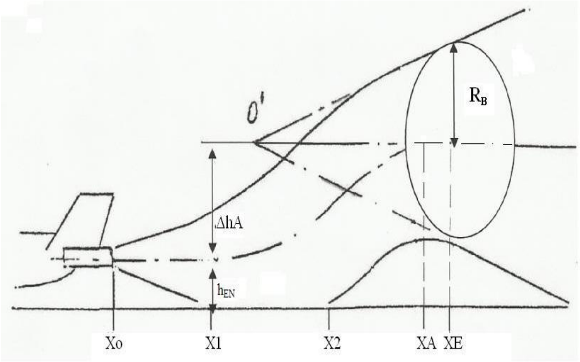


Fig. 1. Jet structure for jet transport model

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, m; X_2 – longitudinal coordinate of a point of jet lift-off from the ground due to buoyancy effect, m.

The complex model PolEmiCa has been sufficiently improved in subject of **jet transport model** by using CFD package (FLUENT 6.3) to investigate the physics and characteristics of ground vortices, which are generated between the ground surface and aircraft engine nozzle, to assess the ground surface impact on the jet structure, parameters and properties of jet development.

A three-dimensional model of a jet was generated in FLUENT 6.3 by using Large Eddy Simulation (LES) method to reveal the unsteady ground vortices and turbulence characteristics of fluid flow, investigate transient parameters of hot gases in jet and their dispersion for further concentration evaluation, Fig.2.

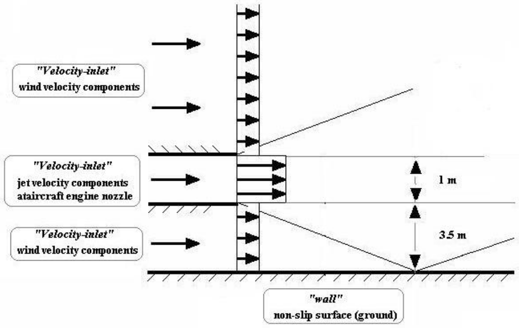


Fig.2. Boundary conditions for CFD simulations of exhaust gases jet from aircraft engine near ground

Comparison of the obtained results of numerical simulations between free and wall jets allow to reveal some differences in their structure and properties. Axial velocity profiles based on FLUENT 6.3 results demonstrate the decay rate on 40-50% higher for free jet than for the wall jet, Fig.3. Second, the potential core region is longer on 40% for the wall jet than for the free jet, Fig. 3. Third, the wall jet penetrates deeper on 50 % in comparison with wall jet. The jet arises over the ground surface due to buoyancy effect much faster (on 50%) and higher for free jet (on 30%), than in case of wall jet. The observed differences in jet's behavior can only be a consequence of the presence of a solid boundary, because other parameters are kept the same, Fig.4 (Synylo et al., 2017).

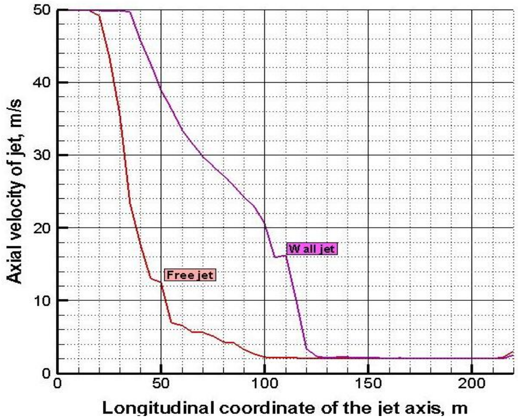


Fig. 3. Maximum velocity decay along the axis of the free and wall jet

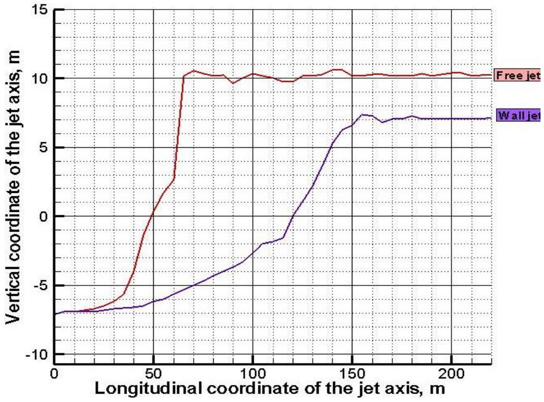
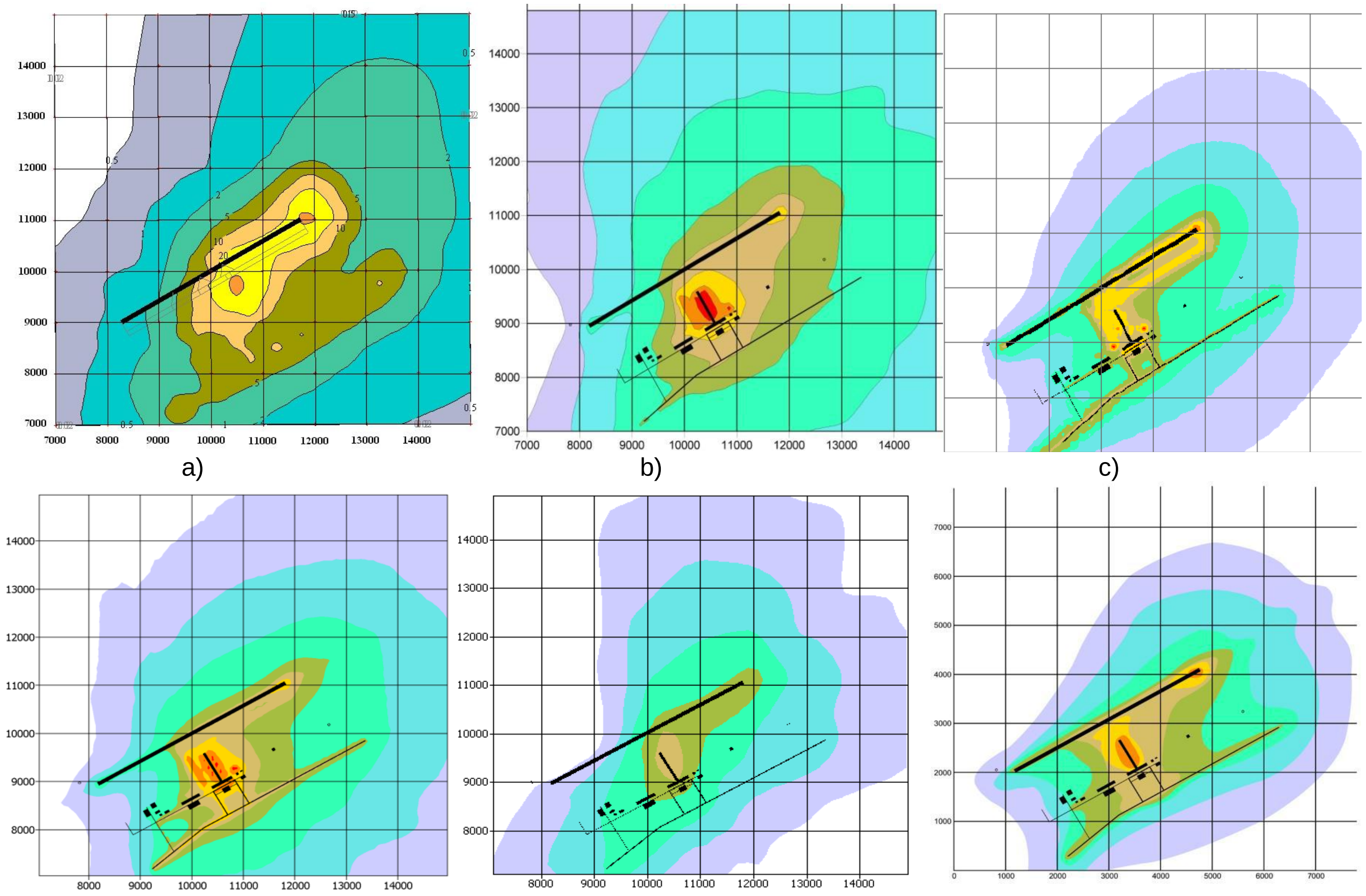


Fig. 4. Buoyancy effect of free and wall jet: longitudinal and vertical coordinate of jet axis

PolEmiCa dispersion results for CAEPport are quite comparable with EDMS, ADMS, LASPORT results (Fig. 5).

The differences in the calculated concentrations between the models arise as a consequence of both differences in emissions, which can be broadly estimated from the emission totals, and differences in their models' formulation, including the representation of emission sources, treatment of meteorology and dispersion (Zaporozhets, 2015)



a) b) c)

d) e) f)

Figure 5: Dispersion results for CAEPport: annual mean NOx concentration contours (µg/m3) – all sources: a – PolEmiCa; b – EDMS; c – ADMS; d – LASPORT; e) ALAQS; f) PEGAS

4. THE VERIFICATION OF THE POLEMICA MODEL WITH MEASUREMENTS DATA

The verification of the PolEmiCa model with measurements data was done initiatively for trials made in airports of Athen (Greece, 2007) and Boryspol (Ukraine, 2012). In both cases the comparisons were quite good showing appropriate correspondence of the model to subject of assessment.

The measured NOx concentrations (averaged for 1 min) measured by the NOx analyzer in aircraft engine plume while the aircraft was accelerating on the runway during take-off stage were compared with calculated NOx concentrations by the complex PolEmiCa model (Synylo et al., 2015).

Comparison between calculated and measured NOx concentrations (averaged for 1 min) in aircraft engine plume under real operation conditions (aircraft accelerating on the runway during take-off stage of flight) at Athens airport is shown in Table3 and Fig.6.

For each take-off different values of the wind speed and the wind direction were measured by an ultrasonic anemometer with a time resolution of 30 s. Accordingly, the different values of the diffusion coefficients (K_X, K_Y, K_Z) were calculated and used for the subsequent concentration assessment (Zaporozhets, 2005).

Table 3

Comparison measured and calculated concentration (averaged for 3 s) of NOx in plume from aircraft engine under take-off conditions

	Aircraft	Engine	Calculated concentration		Measured concentration	
			NOx (delta), µg/m3		NOx (delta), µg/m3	
			with jet	without jet	value	error
1	B737-3YO	CFM56-3C1	27,43	30,01	31,8	3,2
2	B737-3Q8	CFM56-3B2	30,7	33,50	28,0	2,8
3	B737-45S	CFM56-3B2	29,76	27,95	23,6	2,4
4	B737-4Q8	CFM56-3B2	31,28	34,93	56,9	5,7
5	A-310	CF6-80C2A8	88,86	122,12	86,1	8,6
6	A-319	CFM56-5B5	29,85	32,27	26,9	2,7
7	B747-230	CF6-50E2	163,63	205,37	82,5	8,2
8	A-321-211	CFM56-5B-3	81,78	89,74	43,3	4,3
9	A320-214	CFM56-5B-4	49,99	52,29	16,4	1,6
10	B737-33A	CFM56-3B1	25,5	27,95	11,5	1,1

Besides, results were defined for the cases with and without jets from the engines to show that with jets they are more equal (on 17%) to measured data, because impact of jet basic parameters (buoyancy effect and dispersion characteristics) on concentration distribution was estimated by complex model PolEmiCa, Table 3. 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, Fig.6.

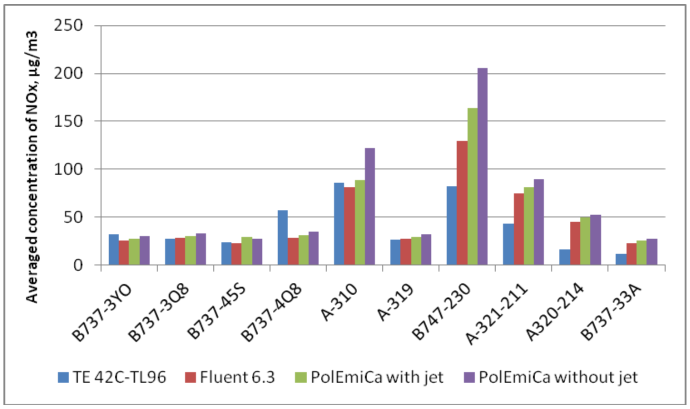


Fig. 6. Comparison of measured and modeled averaged concentrations of NOx (for period 1 min) under take-off conditions

Good agreement between model results and measurements were found for several aircraft, however, for some aircraft significant differences were observed, e.g. B737-4Q8, B747-230, A321-211, A320-214 and B737-33A.

Possible reasons for the observed differences between modeled and measured NOx concentration are as follows:

1. The quite **big distance** between aircraft engine and monitoring station (1000-1500 m). As a result, the measured NOx concentration in the plume is quite low due to previous dilution by the jet, the wind and atmospheric turbulence;
2. The **averaging period** for the measured concentration (1 minute) is quite long for the detection of the separate maximum concentrations in the plumes from each single engine of the accelerating aircraft and to include their contribution to the measurement data;
3. **Emission factor**. The values of emission indices for aircraft engines from ICAO certification data base were used for the model. These emission indices were defined for an ambient temperature of 15°C. But in the case of the measurement campaign at AIA the air temperature was 26.8°C. Such a temperature difference could have an effect on the input and output of model and composes 10 % of the accuracy.

Experimental studies at International Boryspol Airport (IBA) were focused on the measurement of NO_x concentrations in aircraft plumes under real operating conditions (taxi, landing, accelerating on the runway and take-off). A stationary station A was set up (jet-regime) close-by the runway (30 m) with a mast height of 3.0 m. A mobile station B (dispersion-regime) was set up at a distance of 110 m from the runway and its location was oriented to match the prevailing wind direction (north-west, west, south-west) and with measuring heights of 3.6 and 5.7 m, respectively. Fig.7 shows the measurement location set up at A and B (Synylo et al., 2016). The chosen positions of the stations guaranteed, that the most significant sector of the aircraft exhaust for taxing, landing and take-off conditions was scanned by the measurement systems.

Fig.7 Location of stationary station A and movable station B at IBA

The results of the measured NO_x concentrations (averaged for 3 seconds) in the plumes from aircraft engines for take-off conditions at IBA were used for improvement and validation of the complex model PolEmiCa. As shown in Table 4 the modeling results for each engine are in good agreement with the results of measurements by the AC32M system due to taking into account the jet- and plume-regime during experimental investigation at Boryspol airport. Also 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 4

Comparison measured and calculated concentration (averaged for 3 s) of NOx in plume from aircraft engine under take-off conditions

Aircraft	AC32M			PolEmiCa CFD (Fluent 6.3)		PolEmiCa	
	Back gro-und	3 м	6 м	1 engine	All engines	1 engine	All engines
	NOx	NOx	NOx	NOx	NOx	NOx	NOx
BAE147	1,70	22,07	33,9	35,1	70,46	48,9	202,3
A321	0,72	44,00	54,2	90,85	182,90	184,2	371,2
B735	0,77	94,10	76,57	60,03	120,91	35,3	71,10
B735	1,74	29,20	23,4	42,34	85,30	33,7	67,76

Comparison of measured and modeled instantaneous concentration of NO_x was significantly improved by taking into account the interaction of the jet with wing trailing vortexes during the take-off stage, Fig. 8, 9.

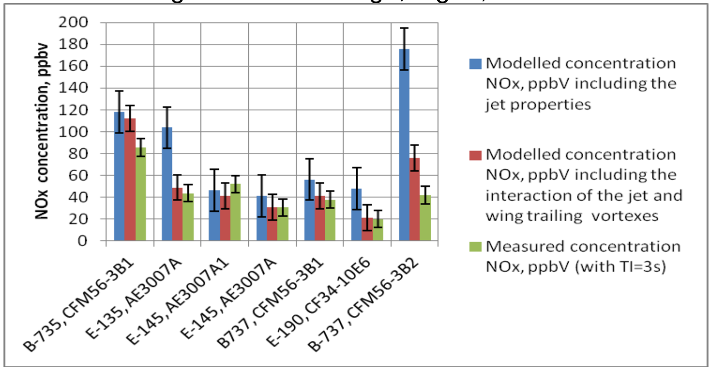


Fig.8. Comparison of the PolEmiCa (previous/improved version) results with the measured NO_x concentration from aircraft engine exhausts under maximum operation mode at station B, down.

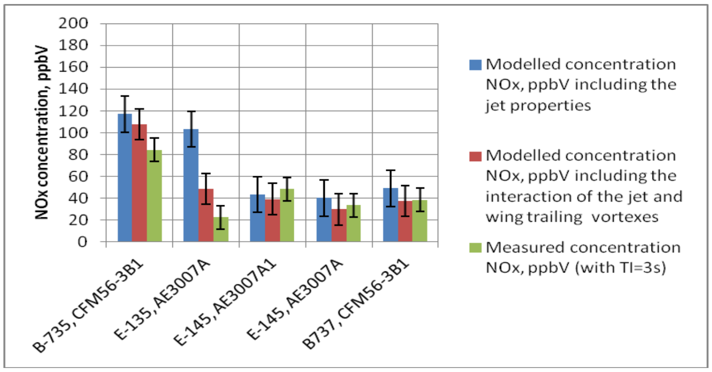


Fig.5. Comparison of the PolEmiCa (previous/improved version) results with the measured NOx concentration from aircraft engines exhausts under maximum operation mode at station B, up.

CONCLUSIONS

Considered model PolEmiCa provides the emission inventory and dispersion calculation for the aircraft engine emission during the LTO cycle and Start-up procedures, APU and GSE also. Current version of the PolEmiCa combines the calculation for the stationary sources (Power Plant, Fuel Farm) and vehicle (Roadways and Parking facilities) in accordance with Ukrainian national methodology.

The emission inventory and dispersion calculation results by PolEmiCa are quite comparable with other verified LAQ tools recommended by ICAO Doc 9889.

Validation analysis of PolEmiCa model by measurement campaign at IAA and IBA demonstrates that the measured NO_x concentrations (averaged for 3 s) are in good agreement with the modeling results for each engine.

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. Also comparison of measured and modeled instantaneous concentration of NO_x was significantly improved by taking into account the interaction of the jet with wing trailing vortexes.

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