MODELLING OF AIRCRAFT EMISSIONS IN THE AIRPORT AREA

Ralf Kurtenbach[a)], Peter Wiesen[a)], Oleksander Zaporozhets[b)], Kateryna Synylo[b)]

[a)]University of Wuppertal, Inst. Atmos. & Environ. Res., 42097 Wuppertal, Germany

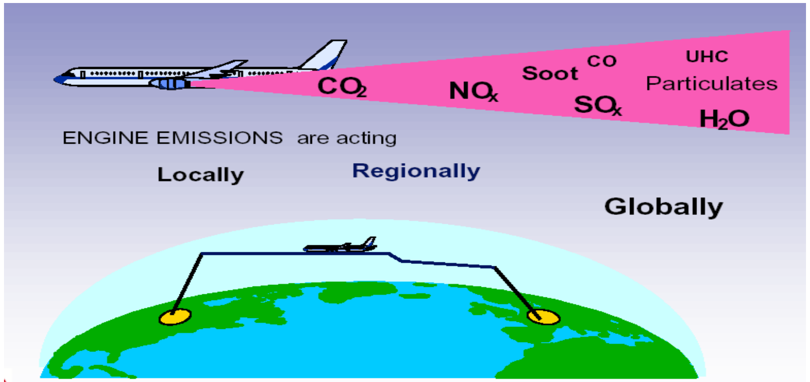
[b)] National Aviation University, Kosmonavta Komarova 1, 03058 Kyiv, Ukraine

kurtenba@uni-wuppertal.de, wiesen@uni-wuppertal.de, zap@nau.edu.ua, synyka@gmail.com

Structure

- Introduction
- Aircraft is dominant source
- ICAO tool (inventory and dispersion)
- Aircraft is special source
- Complex model PolEmiCa
- Measurement campaign at International Boryspol Airport
- Determination of EI
- Validation task
- Conclusions

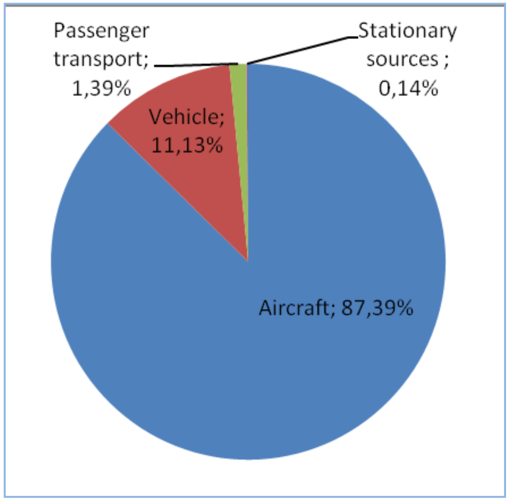
Introduction

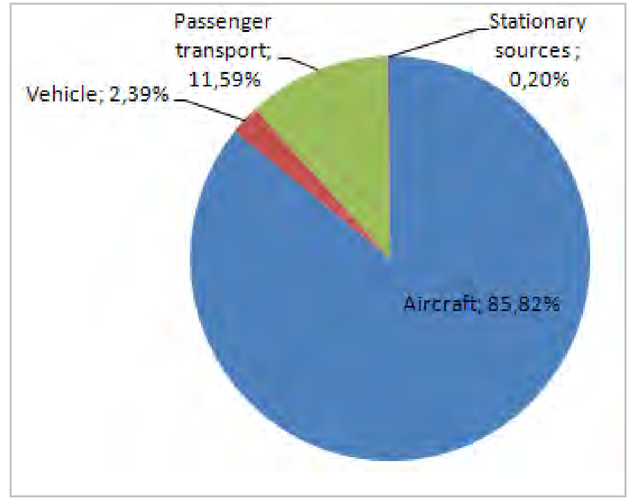


Even through all benefits that airport brings, the surrounding communities are subjected to the deterioration of air quality on local, regional and global levels

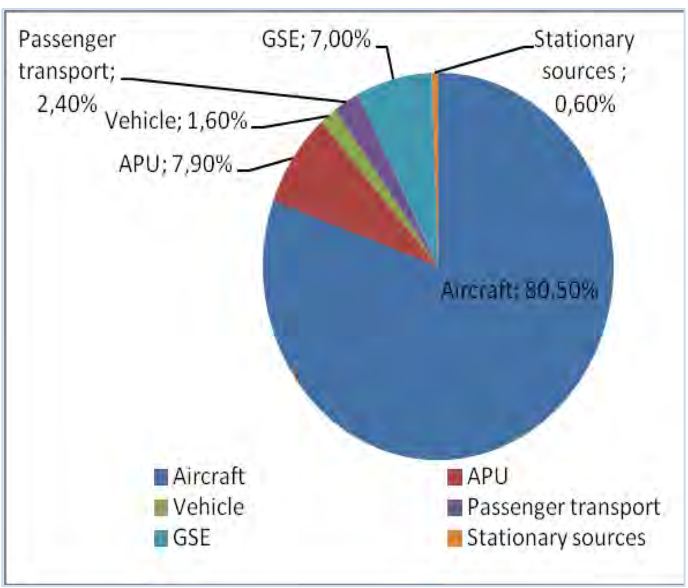
Basic objects of attention are NOx and fine PM from aircraft engines emissions as initiators of photochemical smog and regional haze, which further direct impact on human health.

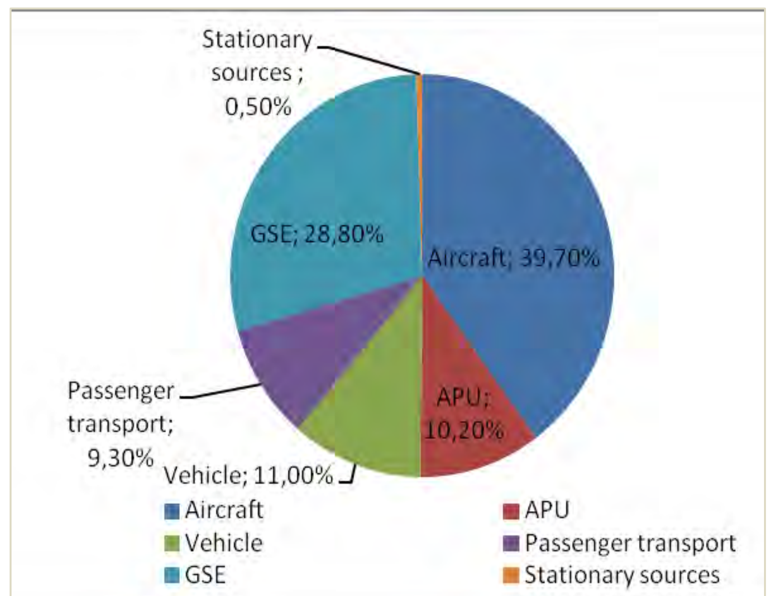
Considered problems are intensified in connection with increasing air traffic (at a mean annual rate of about 5%), rising tensions of expansion of airports and growing cities closer and closer each other and accordingly growing public concern with air quality around the airport.





The emissions inventory of NOx (a, annual emissions – 1,150 tons/year) and of PM_{10} (b, annual emissions - 7 tons/year) within International Boryspol airport with an intensity of take-offs and landings of 137 per day





The emissions inventory of NOx (a, annual emissions – 3,284 tons/year) and PM_{10} (b, annual emissions - 25 tons/year) within the International Airport Frankfurt for 2005 with an intensity of take-offs and landings of 1,300 per day

Aircraft emission inventory

The emission inventory of aircraft emissions are usually calculated on the basis of certificated emission indexes (ICAO database).
Under real circumstances, however, the operational 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)

Several measurement campaigns were performed for idling aircraft at different European airports (London-Heathrow, Frankfurt/Main, Vienna and Zurich) [*Schäfer et al.; Heland et al.*] to determine EINOx and EICO under real operation conditions.

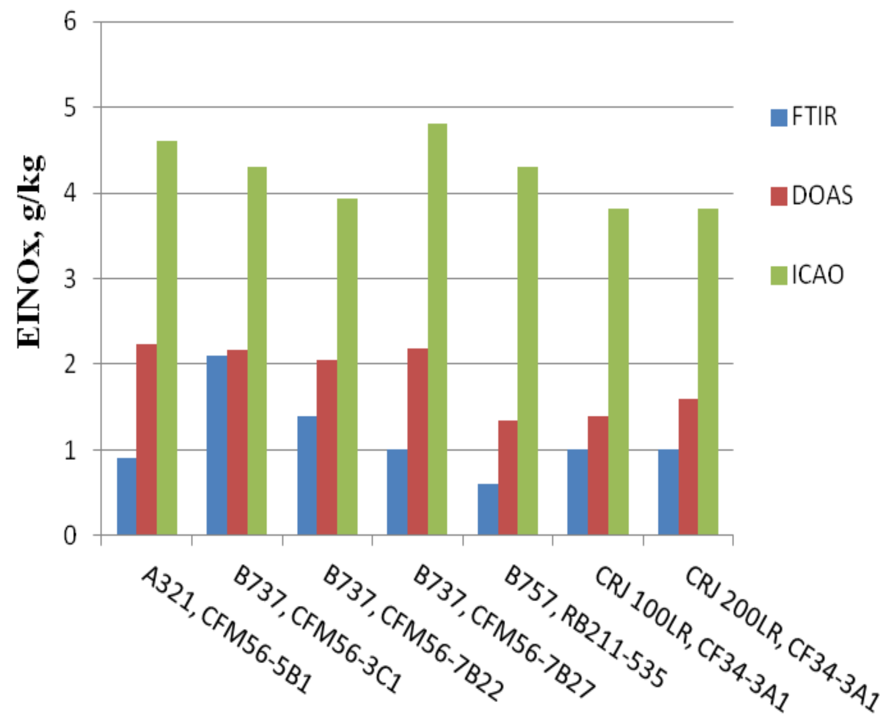


Fig.3. Comparison measured EINOx by FTIR and DOAS with ICAO values during measurement campaign for idling aircraft at European airports

Dispersion modeling

ICAO Doc 9889 recommends few tools for dispersion calculations (EDMS, LASPORT and ALAQS-AV) for dispersion calculations.
Basically, the Gaussian plume model is used for prediction of vertical and horizontal dispersion of air pollution produced by aircraft engine emissions [ICAO Doc 9889, 2011]:

$$C(x;y;z;H)=\frac{Q}{2\cdot\pi\cdot\sigma_y\cdot\sigma_z\cdot u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\bullet\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\}$$

where C – concentration at point with coordinates (x, y, z), µg/m^3; u – wind velocity, m/s; Q – source emission rate, µg/s; σ^2_y, σ^2_z – horizontal and vertical dispersion parameters; H – effective height of source, m.

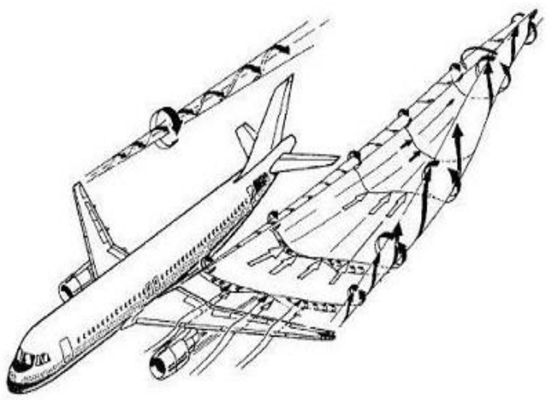
However, setting of initial plume parameters by default for various types of aircraft fleet in modeling systems is not quite reasonable. Since jet parameters (rise height Δh_A, horizontal σ^2_y and vertical σ^2_z dispersion parameters) depend on aircraft and engine type, engine operation mode and meteorological conditions.

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

AIRCRAFT IS A SPECIFIC SOURCE OF AIR POLLUTION

1. Jet of exhaust gases (with high temperature and velocity) can be transported on a rather long distance, which are defined by engine type and its installation on aircraft, operation mode and meteorological conditions;
2. Moving source of pollution and with varied emission factor during the LTO and ground running procedures;
3. The most part of 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;
4. An aircraft wake is composed of the engine jets, which are entrained into the counter-rotating wing (tip, flap) vortices, with further deflection and stretching of the plume towards the vortex centerline.

So, eliminating of fluid dynamic of jet from aircraft engine and also process of interaction between the jet and wing trailing vortex in modelling systems may overestimate the height of buoyancy exhaust gases jet , underestimate its length and radius of expansion, dispersion characteristics and contaminants concentration values.



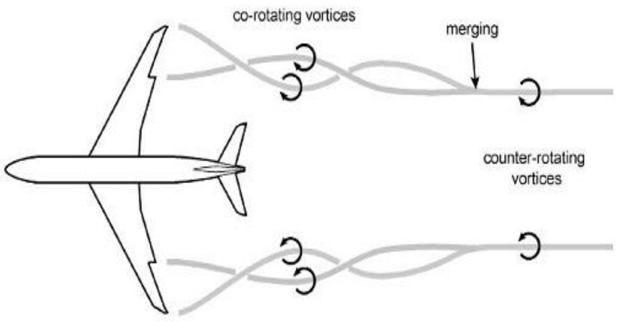


Fig. 3. Vortex wake generation behind the aircraft [F.Garnier, 2005]

COMPLEX MODEL POLEMICA

EI, Q

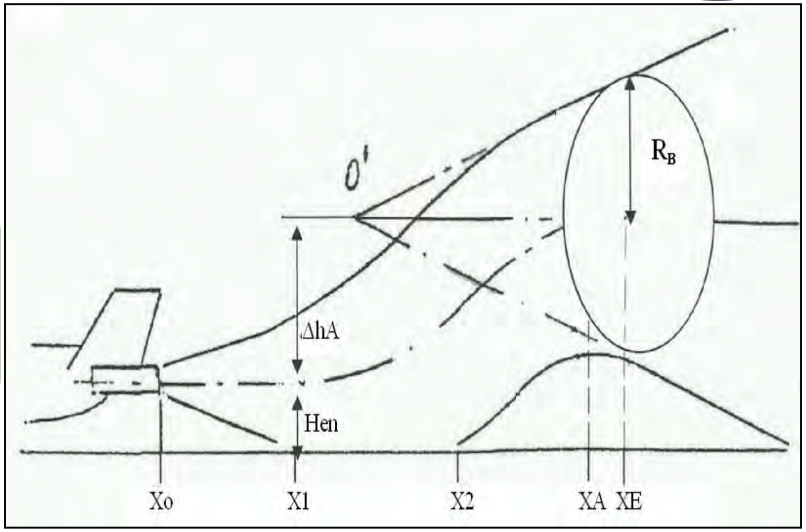
Engine emission model – emission factor assessment for aircraft engines, including influence of operational and meteorological factors.

S_j, Δh_A, X_A, σ_x, σ_y, σ_z, q

Jet model – model of air contaminants transport and dilution by exhaust gases jet. Assessment of the basic parameters of jet: length of jet penetration $\mathbf{S_j}$, height $\mathbf{\Delta h_A}$ and longitudinal coordinate $\mathbf{X_A}$ of buoyancy effect, horizontal σ^2_y and vertical σ^2_z dispersion parameters. Evaluation of concentration value in jet **q**.

q

Dispersion model – model of air contaminants dispersion in the atmosphere due to turbulent diffusion and wind transfer. Evaluation of concentration value in ambient air **q** from aircraft engine emission



Jet structure for jet transport model

Δh_A, X_A – height and longitudinal coordinate of jet axis rise due to buoyancy effect; h_{EN} – height of engine installation; R_B – radius of jet expansion; 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.

For the estimation of the height of jet rise due to buoyancy effect, the Archimedes number is used:

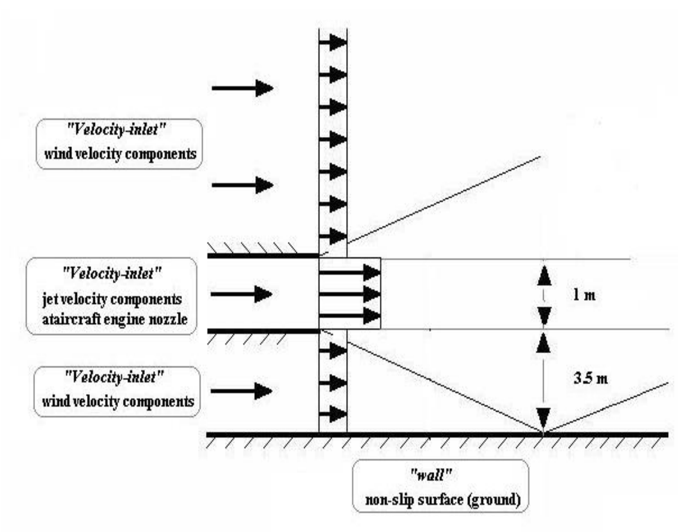
$$Ar_0 = 2 \cdot g \cdot R_0 \cdot (Q_T - 1) / U_0^2$$

$$\Delta h_A = 0.013 \cdot Ar_0 \cdot \overline{X}_A^3 \cdot R_0$$

Initial dispersion parameters (σ_{0s}) of puffs and height of jet rise Δh_A are function of **the engine exhaust outlet parameters** (diameter, velocity and temperature).

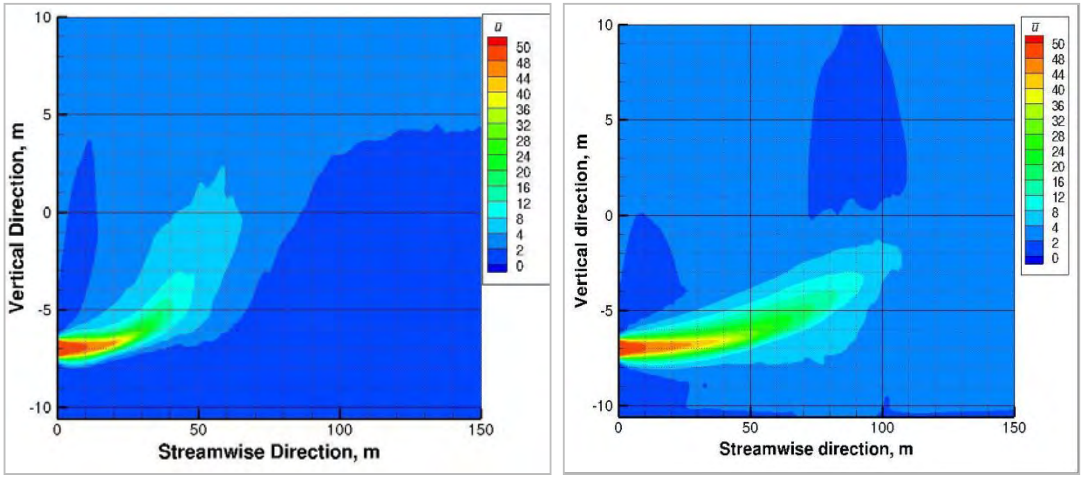
Jet model

Jet model was improved by CFD code (FLUENT 6.3/Gambit), which allow investigates and assesses structure, properties and basic fluid mechanics aspects of jet behavior.



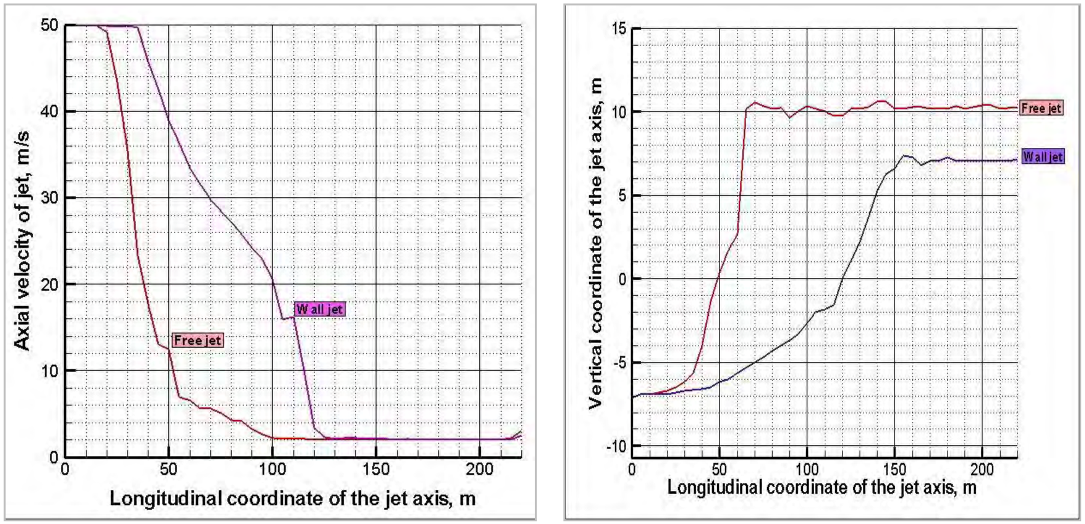
Boundary conditions for CFD simulations of the jet from aircraft engine near ground

LES method was used to investigate transient parameters of exhaust jet from aircraft engine near aerodrome's surface. Smagorinsky-Lilly model was used, as subgrid-scale model .



a) b)

Mean velocity contours in streamwise direction of free (a) and wall (b) jet



a) b)

Maximum velocity decay (a) and buoyancy effect (b) of free and wall jet

DISPERSION MODEL POLEMICA

The basic model equation for definition of instantaneous concentration *C* at any moment *t* in point (*x,y,z*) from a moving source from a single exhaust event with preliminary transport by jet on distance X_A and rise on total altitude *H* and dilution of contaminants by jet (σ_0) has a form:

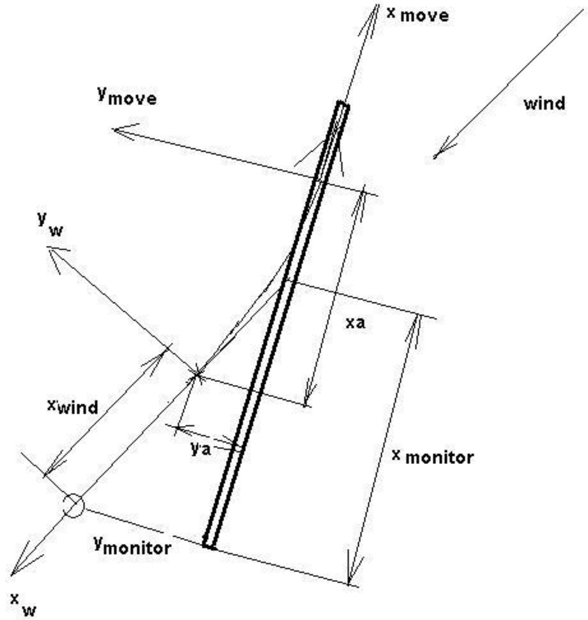
$$c(x,y,z,t) = \frac{Q\exp\left[-\frac{(x-x')^2}{2\sigma_{x0}^2+4K_x t}-\frac{(y-y')^2}{2\sigma_{y0}^2+4K_y t}\right]}{\{8\pi^3[\sigma_{x0}^2+2K_x t][\sigma_{y0}^2+2K_y t]\}^{1/2}}\times$$

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

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

$$y' = y_0 + v_{PL}t' + 0.5bt'^2$$

$$z' = z_0 + w_{PL}t' + 0.5ct'^2$$

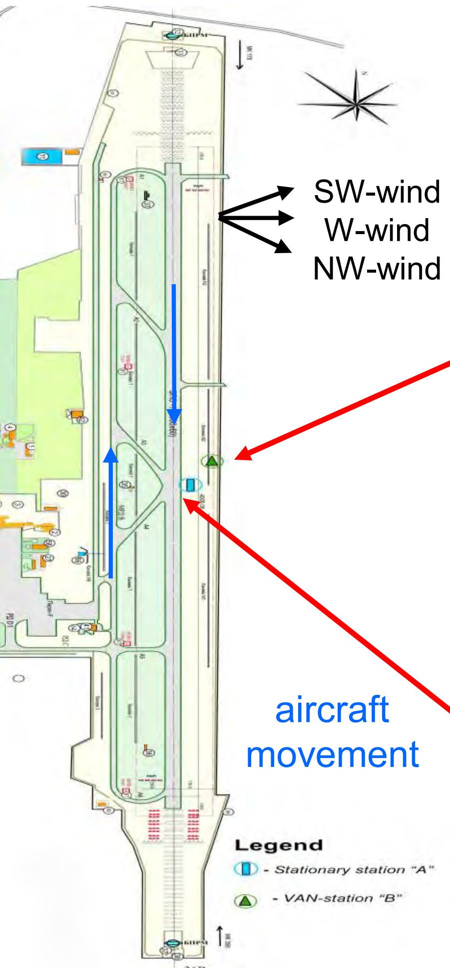


$$T_{w\max} = (X_{w\max} - X_{1w})/U_s \qquad T_{wind} = \frac{X_{wind}}{U_w} - \sqrt{X_{wind}\frac{dKx}{U_w^3}}$$

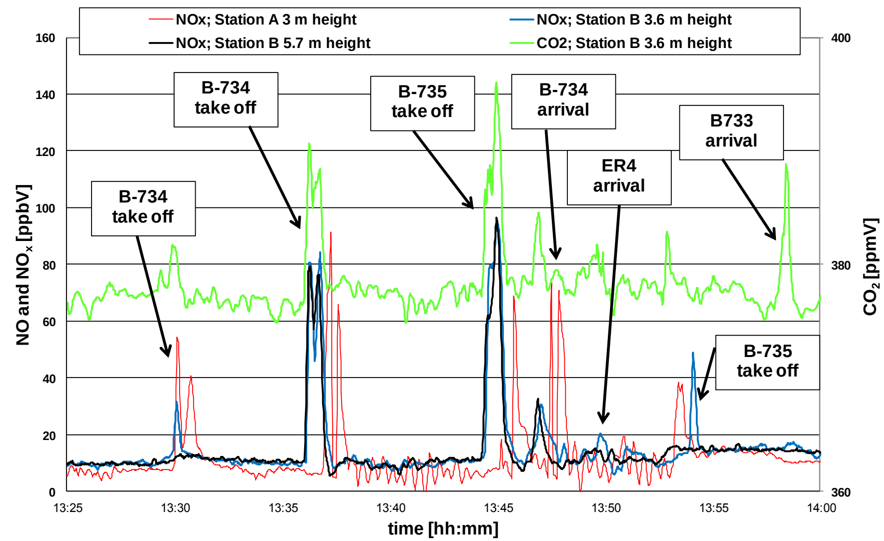
$$X_{wind} = X_{Rw} - X_{w\max}$$

where X_{wind} – the distance of the contaminants transport by the wind to monitoring station

MEASUREMENT CAMPAIGN AT INTERNATIONAL BORYSPOL AIRPORT



Measurement sites A und B: stationary station A is located close-by the runway (30 m for sample mast) and mobile station B at 110 m from the runway due to prevailing wind direction.



Background and plume concentration for NO, NOx, CO_2 at stationary station A and mobile station B at landing, take-off conditions and the prevailing wind direction

The highest aircraft engine NO_x emissions were observed for take-off conditions while much lower NO_x values were observed under landing conditions.

DETERMINATION OF EINOX UNDER LANDING AND TAKE-OFF CONDITIONS AT INTERNATIONAL BORYSPOL AIRPORT

On the basis of the measured NO_x, CO_2 concentrations in the jet from aircraft engines, the EINOx have been calculated under real operational conditions (landing and take-off) :

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

where *M* denotes the molecular weight and *Q* denotes mixing ratio of the corresponding species.

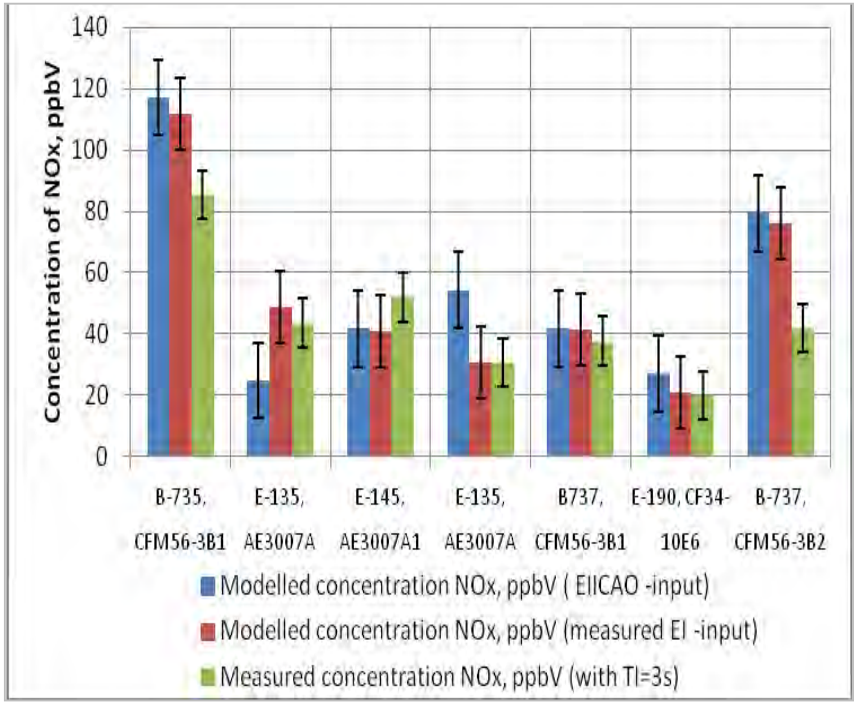
The uncertainty of $EINO_x$, arising from processing of the measurement data, was calculated by the following equation:

$$EINO_x uncert = \sqrt{\left(\frac{\left[\Delta CO_2 \cdot 0.1 + DL_{CO_2}\right]^2}{\left[\Delta CO_2\right]^2} + \frac{\left[\Delta NO_x \cdot 0.1 + DL_{NO_x}\right]^2}{\left[\Delta NO_x\right]^2} \right)} \cdot EINO_x$$

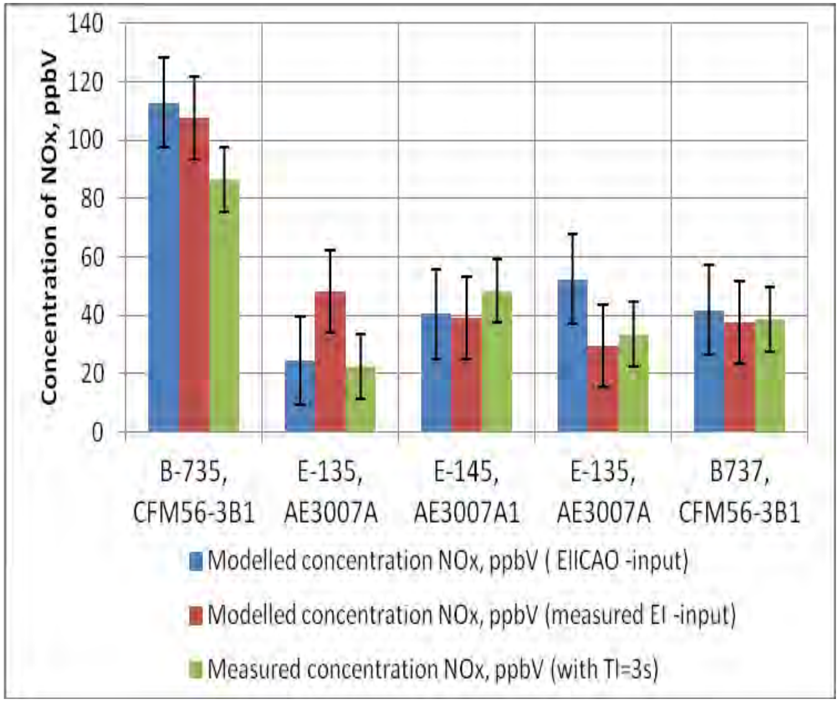
Determined $EINO_x$ on the basis of the measured (M) NO_x concentration in the plume from an aircraft engine at take-off (T/O) conditions in comparison with ICAO

№	Sta-tion	Aircraft/ Engine Type	Oper a tion	ICAO $EINO_x$[g/kg]	M $EINO_x$ [g/kg]	U $EINO_x$ [g/kg]
24	A	E135, AE3007A1P	T/O	20.8	≥3.7 (DL)	-
	B, up	E135, AE3007A1P	T/O	20.8	10.2	11.0
	B, down	E135, AE3007A1P	T/O	20.8	14.4	5.7
25	A	E190, CF34-10E6	T/O	19.0	5.2	5.2
	B, up	E190, CF34-10E6	T/O	19.0	≥8,3 (DL)	-
	B, down	E190, CF34-10E6	T/O	19.0	14.2	11.4
29	A	B-735, CFM-56-3B1	T/O	17.7	≥8.6 (DL)	-
	B, up	B-735, CFM-56-3B1	T/O	17.7	20.0	5.8
	B, down	B-735, CFM-56-3B1	T/O	20.7	15.3	4.2
36	A	E-145 AE3007A	T/O	20.5	3.6	4.3
	B, up	E-145 AE3007A	T/O	20.5.	11.5	1.6
	B, down	E-145 AE3007A	T/O	20.5	19.3	10.5
42	A	B-737 CFM56-3B2	T/O	19.4	6.8	4.9
	A	B-737 CFM56-3B2	T/O	19.4	≥3.7 (DL)	-
	B, up	B-737 CFM56-3B2	T/O	19.4	≥24.1 (DL)	-
	B, down	B-737 CFM56-3B2	T/O	19.4	18.6	2.6
52	B, up	E-145 AE3007A1/1	T/O	20.9	23.2	23.5
	B, down	E-145 AE3007A1/1	T/O	20.9	18.5	6.3

Comparison of measured and modeled concentrations of NO_x



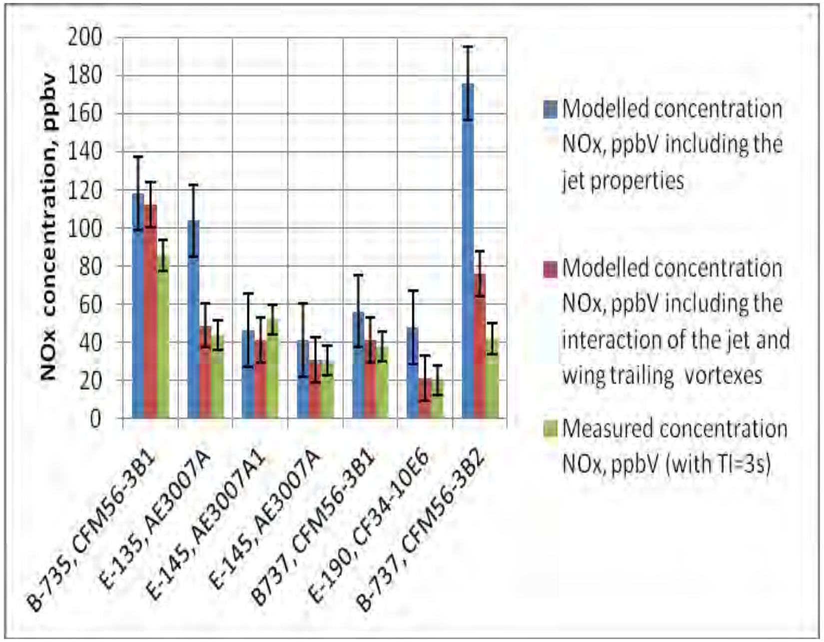
a)



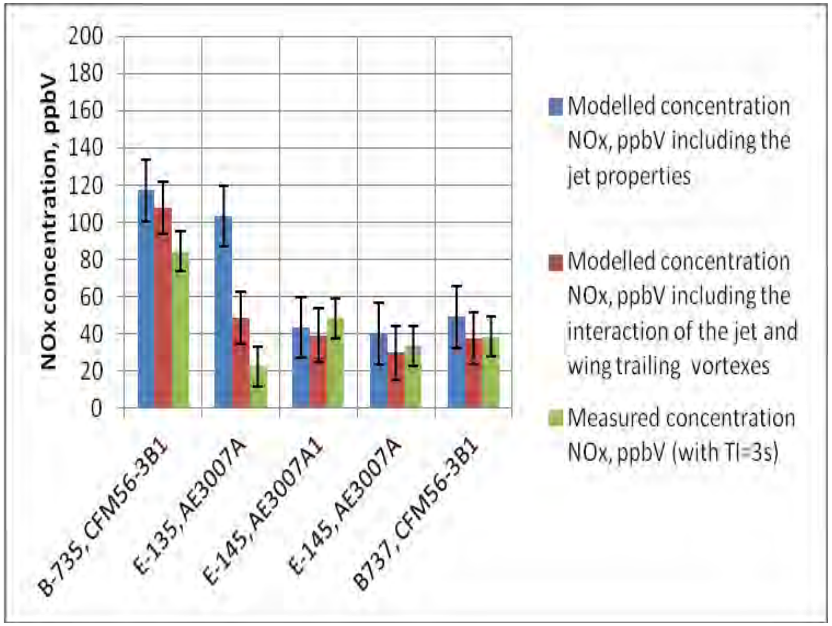
b)

Comparison of the PolEmiCa (determined EINOx and EIICAO input) results with the measured NO_x concentration in plume from aircraft engine under maximum operation mode at down station B (a – height of sample = 3.6 m) and up station B (b – height of sample = 5.7 m)

Comparison of measured and modeled concentrations of NO_x



a)



b)

Comparison of the PolEmiCa (previous and improved version) results with the measured NOx concentration in plume from aircraft engine under maximum operation mode at down station B (a – height of sample = 3.6 m) and up station B (b – height of sample = 5.7 m)

CONCLUSIONS

- Combination of measurement and modeling methods allow separate of aircraft engine emission from substantial levels of air pollution produced by other emission sources
- Comparison of measured and modeled concentrations of NOx was significantly improved by taking into account the determined $EINO_X$ under operational conditions in comparison to ICAO-input
- The measurement results correlate better with modeling ones, which includes the impact of wing trailing vortices on the jet parameters (buoyancy height, horizontal and vertical deviation) and the contaminant dilution process

Thank you for your attention!