MODELLING OF AIRCRAFT EMISSIONS IN THE AIRPORT AREA

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Abstract. Currently the primary subject of concern of airport air quality are the NOx and PM emissions from aircraft engines, because they are the initiators of photochemical smog and regional haze, which at further steps may impact on human health directly. The analysis of emission inventories at Ukrainian and major European airports has highlighted, that aircraft are the dominant source of air pollution in most of the cases considered. Aircraft are a special source of air pollution due to some features. To assess of aircraft engine emissions contribution in local air quality (LAQ) assessment it is important to take in mind the features, which define emission and dispersion parameters of the source. The aircraft emission inventory is usually calculated on the basis of certificated engine emission indices, which are stored in an ICAO databank. The emission indices rely on well-defined measurement procedures and conditions during aircraft engine certification. Under real real-world operating conditions, however, these conditions may be quite different and deviations from the certificated emission indices may occur. This could lead to significant differences between emissions from actual airport operations and emission inventories used in modeling airport air quality. The measured NO_x and CO_2 concentrations at Boryspol International Airport (Kyiv) were used for the improvement and validation of the complex model PolEmiCa. Comparison of measured and modeled NO_x concentration in the plumes from aircraft engines was significantly improved by taking into account the $EINO_x$ which was determined under real operating conditions.

Keywords: aircraft engine, emission index, airport air pollution, aircraft engine emissions

INTRODUCTION

Aircraft engine emissions have a direct impact on air quality in local, regional and global scales. Today the aviation sector is responsible for example for 12% of the CO_2 emissions from the transport sector, compared to 74% from road transport [ICAO report, 2013]. 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].

Aircraft are the dominant source of emissions and air pollution at airports in almost all LAQ analyses [Celikel ***et al.,*** 2005]. ICAO recommends in the Doc 9889 some tools for air quality analysis – to model emission inventory from every character groups of the spatially distributed sources as well as atmospheric concentrations resulting from emission dispersion.

Aircraft emission inventories are usually calculated on the basis of certificated engine emission (EE) indices, which are provided by the engine manufacturers and stored in the ICAO EE database. The emission indices rely on well-defined measurement procedures and conditions during aircraft engine certification. Under real-world operating conditions, however, these conditions may be quite different and deviations from the certificated emission indices may occur because of:

- **the life expectancy** (age) of an aircraft since the emission of an aircraft engine might vary significantly over the years (the average operating period – 30 years). Usually aging aircraft/engine show higher emission indices compared with same younger engine type;
- **the engine type** (or its specific modification, for example with respect to different combustion chambers) installed at an aircraft, which can be different from the same engine type operated in an engine test bed during certification;
- **meteorological conditions** – temperature, humidity and ambient air pressure, which can be different under certification conditions.

Thus, in practice 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 [Herndon ***et al.,*** 2008]. This could lead to significant differences between emissions from actual airport operations and emission inventories used in modeling airport air quality.

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]:

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

where ***C*** – concentration at point with coordinates (***x,y,z***), μg/m^3; ***u*** – velocity of moving emission source, 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.

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.

However, setting of initial plume parameters by default for various types of aircraft fleet in modeling systems recommended by ICAO Doc 9889 is not quite reasonable. Since mentioned 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.

The most important feature of the emission source under consideration is the presence of a 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 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. Corjon A. (1997) found, that the primary vortices approach the ground leading to boundary layer formation (it is a subject to an adverse pressure gradient). The newly formed vorticity separates from the ground and consists a secondary vortex, which wraps around the primary one and induces an upward velocity and causes primary vortices rebound from the ground. During take-off and landing the wings of an aircraft produce lift which in turn generates powerful trailing vortices. The engine jets are entrained into the two counter-rotating wingtip vortices, with further deflection and stretching of the plume towards the vortex centerline [Cure S., 2007].

So, eliminating of fluid dynamic of jet from aircraft engine, the ground influence on the jet structure/ its behaviour and also process of interaction between the jet and wing trailing vortex in modelling systems 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. The revealed features of aircraft, as special source of air pollution, should be included in emission and dispersion calculations of airport air quality assessment.

COMPLEX MODEL POLEMICA

The complex PolEmiCa model was developed at the Ukrainian National Aviation University for the calculation of the inventory and dispersion parameters of the aircraft engine emissions during the LTO cycle of the aircraft in the airport area. It consists of the following basic components:

1. **engine emission model** – emission factor assessment for aircraft engines, including influence operation factors;

2. **jet transport model** – transportation of the pollutants by the jet from the aircraft engine exhaust;

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

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 σ_{0s} of pollutants by the jet is [Zaporozhets, Synylo 2005, 2015]:

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

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:

$$x'=x_0+u_{PL}\cdot t'+0.5a_{PL}t'^2+u_w\cdot(t+t') \quad (3) \qquad y'=y_0+v_{PL}t'+0.5b_{PL}t'^2 \quad (4) \qquad z'=z_0+w_{PL}t'+0.5c_{PL}t'^2 \quad (5)$$

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, Synylo 2005, 2015].

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, namely – height (Δh_A) and longitudinal coordinate (X_A) of buoyancy effect, length of jet penetration and final jet flux three-dimensional spreading (σ_x; σ_y; σ_z), fig.1.

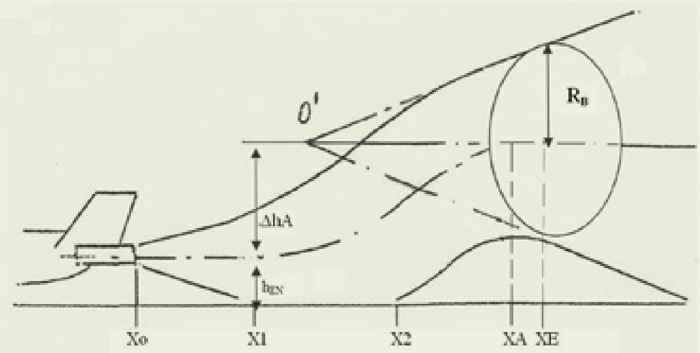

Fig. 1. Jet structure for jet transport model

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 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 et al., 2005]:

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

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, $R_0 = D_0/2$.

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 flux structure, parameters and basic mechanisms 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.

The complex model PolEmiCa also has been improved in field of the jet interaction with wing trailing vortexes during the take-off stage to assess the impact of wing vortices on the jet parameters (buoyancy height, horizontal and vertical deviation) and the contaminant dilution process. It was found, that wing trailing vortexes effect causes the expansion of horizontal dispersions of jet and decrease of buoyancy effect height.

RESULTS AND DISCUSSIONS

Experimental studies at International Boryspol Airport (IBA) were focused on the measurement of NO_x concentrations in aircraft plumes, both the jet- and dispersion-regime of aircraft engines, under real operating conditions (taxi, landing, accelerating on the runway and take-off) [Synylo et al., 2016].

On the basis of the measured NO_x and CO_2 concentrations in the jet from aircraft engines, the EINOx have been calculated under real operational conditions. The results of the measured NO_x concentrations in the plumes from aircraft engines for take-off conditions at IBA were used for the improvement and validation of the complex model PolEmiCa. Comparison of measured and modeled concentrations of NO_x was significantly improved by taking into account the determined $EINO_x$, see figure 2. The modeled concentrations included the impact of ground and wing trailing vortices on the jet parameters (buoyancy height, horizontal and vertical deviation).

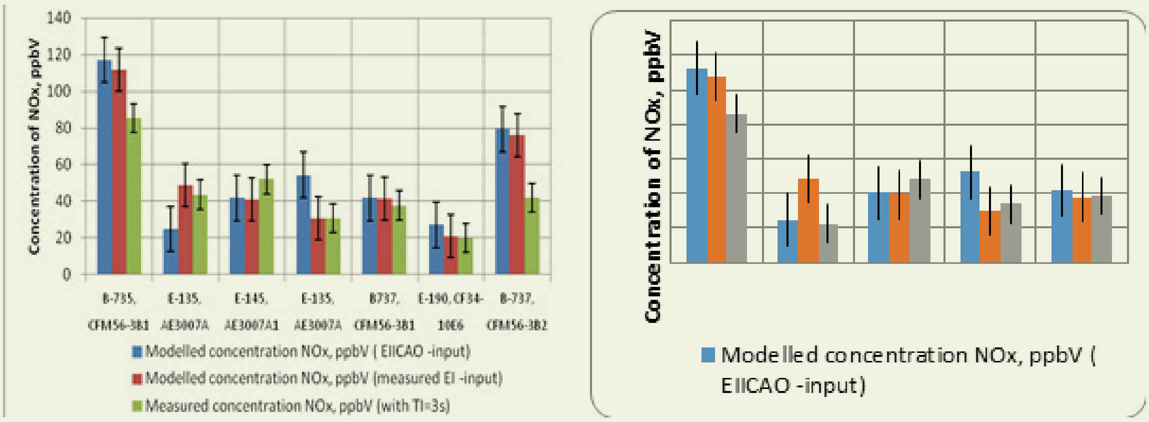

Fig.2. Comparison measured and modeled concentration of NOx in the jet from aircraft engine at down station B (a – height of sample = 3.6 m) and up station B (b – height of sample = 5.7 m)

The measurement systems applied in the field campaigns allowed the determination of EI, e.g. for NO_x under real operating conditions and to improve the emission inventory of aircraft engines for further modeling tasks. Such an approach has been proven to be successful at Boryspol airport.

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