MEASUREMENT OF AIRCRAFT ENGINE EMISSIONS INSIDE 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

SUMMARY

Estimation of NO_x emission indices from passenger aircraft under real operating conditions (accelerating on the runway and taxing) at International Boryspol airport (Kyiv, Ukraine). Measured NO_x concentrations in the plume from aircraft engines were used to improve and validate the complex PolEmiCa model

Keywords: air pollution, aircraft engine emission, emission index, exhaust gases jet from aircraft engine.

INTRODUCTION

Despite the many benefits that airports bring, the surrounding communities are subjected to the deterioration of air quality. Many studies emphasize extremely high concentrations of toxic compounds (including nitrogen oxides (NO_x), particulate matter (PM), unburned hydrocarbons (UHC) and carbon monoxide (CO)) due to airport-related emissions and their significant impact on the environment [*Carslaw et al., 2006; Herndon et al., 2008*] and health of people living near the airport [*Peace et al., 2006; Jung et al., 2011*]. Analyses of health data from people living near Sea-Tac Airport in the US exhibited an increase of heart disease of 57%, cancer death of 36% and a reduction of life expectancy of 5.6 years [*Ayres E., 2001*]. Currently special attention is paid to NO_x and PM emissions from aircraft engines because of their importance for photochemical smog and regional haze, which may further impact human health [*Stedman et al., 1999*].

The analysis of emission inventories at major European (Frankfurt am Main, Heathrow, Zurich and etc.) and Ukrainian airports highlighted, that aircraft are the dominant source of air pollution in most cases under consideration [*Environmental Statement Fraport AG, 2005; Celikel et al., 2005; Umweltbericht. Fraport AG, 2008*].

During the last decade several studies were focused on the effects of aircraft emissions at ground level because they contribute significantly to air pollution at airports and nearby residential areas [*Heland et al., 1998; Popp et al., 1999; Schäfer et al., 2003; Herndon et al., 2004; Celikel et al., 2005; Schäfer et al., 2007; Johnson et al., 2008; Bossioli E. et al., 2013*]. According to the US Department of Transportation, a Boeing 747 spends an average time of 32 minutes at ground level (landing, taxiing and taking-off) and generates 87 kilograms of NO_x, which is equivalent to over 85,000 kilometers of automobile emissions [*Ayres E., 2001*].

Aircraft are a special source of air pollution due to some features. Most important is the presence of a jet of exhaust gases, which can transport pollutants over rather large distances because of high exhaust velocities and temperatures. Such a distance is determined by the engine power setting and installation parameters, mode of airplane movement and meteorological parameters. The results of jet model calculations show that, depending on initial data, the jet plumes from aircraft engines range from 20 to 1000 m and sometimes even more [*Zaporozhets and Synylo, 2005*].

Furthermore, aircraft are a moving (on the ground and in flight) pollution source with varying emission factors during landing and take-off (LTO) as well as ground operation (engine start after maintenance, run-ups to check the correct operation of the flight system). At the airport, engine operation may change from idle to maximum thrust. Accordingly, temperature, exhaust gas velocity and emissions of an aircraft engine may change within a wide range [*Zaporozhets and Synylo, 2005*].

Although certain LTO cycles have been defined, real operational conditions of aircraft do not necessarily correspond to certification procedures, in particular, by engine settings (thrust) and standard time of operation (TIM) [*Hüttig et al., 1999; Masiol et al., 2014*].

For example, for take-off the engine thrust used in real operation is often significantly smaller for performance and cost-efficiency reasons (close to 85-90%), than what is defined by the ICAO LTO cycle (100%) (*Schäfer et al., 2003; Schäfer et al., 2007, Carslaw et al., 2008; Herndon et al., 2008*). This inevitably may lead to an overestimation of NO_x emissions from aircraft. Moreover for the idle/taxi mode most aircraft use a thrust of 3-4% of maximum instead of 7% in the ICAO LTO cycle. This may lead to an underestimation of CO and hydrocarbon emissions (*Schäfer et al., 2003; Schäfer et al., 2007; Nikoleris et al., 2011*).

Quantification of the impact of airport emissions on local air quality is quite difficult due to the complexity of airport emissions and the presence of substantial levels of pollution from other sources such as major highways and roads or industrial installations. However, a reliable quantification of aircraft emissions and their contribution to overall air pollution is prerequisite for the development of cost-effective strategies to improve air quality in the vicinity of airports and to meet regulatory requirements.

Local and regional air pollution produced by aircraft emissions is assessed by measurements, which provide initial information on pollutant concentrations from which corresponding emission indices (EI) are derived. These data are then used in specific models to describe airport air quality. The model output e.g. PolEmiCa may be used for the development of certain measures to improve air quality around airports.

COMPLEX MODEL POLEMICA

A complex model PolEmiCa (**Pol**lution and **Emi**ssion **Ca**lculation) for the assessment of air pollution produced inside the airport and emission inventory analyses, , has been developed at the National Aviation University (Kyiv, Ukraine) [*Zaporozhets and Synylo, 2005*]:

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

At an airport the biggest part of the LTO cycle is devoted to aircraft maneuvering on the ground (engine run-ups, taxing, accelerating on the runway). It is subjected to a fluid flow that can create a strong vortex between the ground and engine nozzle, which has essential influence on the structure and basic mechanisms (Coanda and buoyancy effects) of the jet of exhaust gases. The complex model PolEmiCa has been improved in the jet/plume transportation modeling regime by a CFD code (Fluent 6.3). Using CFD codes allow investigating structures, properties, and fluid mechanisms of the jet and also to obtain a deep understanding of pollutant transportation and dilution by the jet from an aircraft engine also taking into account interplay with the ground surface.

The assessment of air pollution produced by engine emissions, taking into account the dilution of pollutants by the jet and the dispersion by wind and atmospheric turbulence is based on a semi-empirical equation of turbulent diffusion (Eulerian approach). Contaminants are considered not being reactive. The frame of reference is set so that the wind velocity vector u_w and the *x*-axis are collinear. The *z*-axis is directed upwards and the *y*-axis completes the right-hand triple.

Thus, with the assumption that all turbulent diffusion coefficients (k_X, k_Y, k_z) are constant, a dispersion equation can be derived:

$$\frac{dc}{dt} + u_w \frac{dc}{dx} = k_x \frac{d^2c}{dx^2} + k_y \frac{d^2c}{dy^2} + k_z \frac{d^2c}{dz^2} \qquad (1)$$

where c is the pollutant concentration (mg/m^3); u_w is the wind velocity (m/s) and k_X, k_Y, *and* k_Z are the turbulent diffusion factors (m^2/s).

The basic model equation for the definition of the instantaneous concentration *c* at any time *t* at point (*x, y, z*) from a moving source from a single exhaust event has the following form (eq.2). Assessment of the instantaneous concentration has taken into account a preliminary transport of pollutants by the jet on distance X_A and rise on total altitude *H* due to buoyancy effects and dilution by jet (σ_0) [Zaporozhets and Synylo, 2005]:

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

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

where k_X, k_Y, *and* k_Z are the turbulent diffusion factors (m^2/s) for atmospheric turbulence along the three axes and Q is the emission rate (mg/s).

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:

$$x' = x_0 + u_{PL} t' + 0.5 a_{PL} t'^2 + u_w (t + t'); \qquad (3)$$

$$y' = y_0 + v_{PL} t' + 0.5 b_{PL} t'^2; \qquad (4)$$

$$z' = z_0 + w_{PL} t' + 0.5 c_{PL} t'^2 \qquad (5)$$

where x_0, y_0, *and* z_0 are the initial co-ordinates of the source (m), u_{PL}, v_{PL}, w_{PL} are vector components of the source’s speed (m/s), a_{PL}, b_{PL}, c_{PL} are vector components of the source acceleration (m/s^2) and u_w is the wind speed (m/s).

Pollutants emitted by the aircraft on the ground enter into an atmospheric surface layer (ASL) with a height h_{ASL} = 50-100 m (depending on the atmospheric stability). Within the ASL wind speed and atmospheric turbulence vary considerably with altitude.

It is possible to consider that in the ASL the wind speed varies under a logarithmic law and the factor of vertical diffusion linearly depends on the wind speed. Estimation of turbulent diffusion parameters for various atmospheric conditions is obtained as follows [*Zaporozhets and Synylo, 2005*]:

$$u_B = \frac{u_1}{\ln\frac{z_1}{z_0}(H-2)}\left(H\ln\frac{H}{z_0 e} - 2\ln\frac{z_1}{z_0 e}\right); \quad (6)$$

$$k_Z = \frac{k_1 H}{2z_1}; k_X = k_0 \cdot u_B \quad (7)$$

where the wind speed u_1 and the exchange factor k_1 correspond to the altitude z_1, z_0 is the roughness of the underlying surface and H is the altitude of averaging.

Validation and improvement of the complex model PolEmiCa has been implemented based on experimental observations at the International Boryspol Airport (IBA).

RESULT AND DISCUSSION

Experimental studies at IBA were focused on measurement of NO$_x$ concentrations in the plume of aircraft engines using the chemiluminescence technique and the estimation of NO$_x$ emission indices under real operating conditions (taxi, accelerating on the runway and take-off). The aim of the measurement campaign was to develop a data set of emission indices for different aircraft under real operating conditions. These data served as input for validation and improvement of modeling systems.

The location of the monitoring stations was defined by the prevailing wind direction. It was guaranteed, that largest part of the aircraft exhaust was scanned by NO$_x$ measurement systems.

Analysis of the data exhibited that concentration peaks for NO$_x$ and CO$_2$ are unambiguously correlated with aircraft plumes. Thus, the maximum operation mode of an aircraft engine is characterized by the highest NO$_x$ emission, while the idle mode – by a much lower NO$_x$ value, fig.1

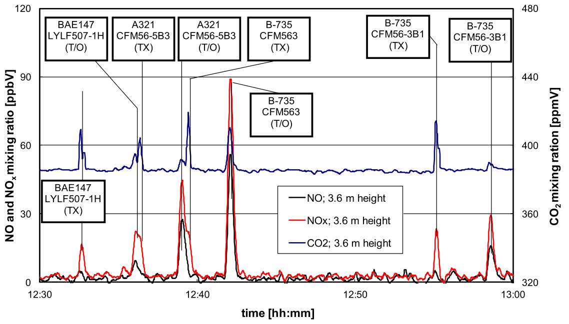

Fig.1. Background and plume concentration for NO, NO$_x$ and CO$_2$ at 3.6 m sampling height for different aircraft at take-off (T/O) and ground taxi (TX) conditions.

From the experimental data NO$_x$ emission indices were calculated (eq. 8) for different real world operating conditions such as idling, taxing and take-off. These data were compared with literature values [*Schäfer et al., 2003; Herndon et al., 2004*].

$$EI(X) = EI(CO_2) \times \frac{M(X)}{M(CO_2)} \times \frac{Q(X)}{Q(CO_2)}, \quad (8)$$

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

The EINOx from the present study were compared with ICAO values for idle and maximum engine mode. The variations between real world and ICAO certificated EIs are most likely caused by the different conditions (thrust value and air temperature) between the “real world” of the present study and the well-defined conditions during the ICAO certification procedure, fig. 2. These differences are quite important to mention, since the ICAO data are currently used to calculate aircraft emissions at airports.

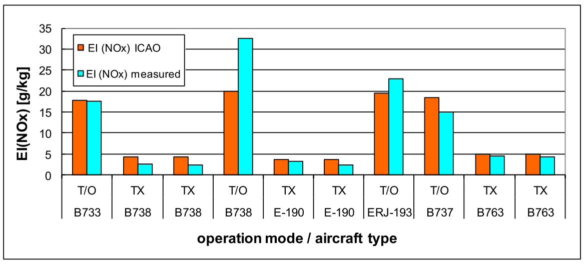

Fig.2. Comparison of measured EINOx under real world operating conditions (take-off (T/O) and taxing (TX)) with the ICAO database.

The results of the measurement campaign at IBA were used as input and validation data set for the complex model PolEmiCa. For this the period 12:30-13:00 h of the measurements was chosen. This period is characterized by 5 NO$_x$ peaks, which correspond to 5 aircrafts (BAE 147, A321, B-735) accelerating on the runway (see fig 1.)

The PolEmiCa model calculated the instantaneous concentrations using eq. 2 and assesses puffs for each engine of the aircraft separately, because of their separate influence on the averaged concentration at the monitoring stations.

As shown in fig. 3, the modeling results for each engine are in good agreement with the measurements due to:

- Taking into account the jet- and plume-regime during the experimental investigation at IBA;
- Using Fluent 6.3, which allows to improve the results by 30% (correlation coefficient, r=0.76) by taking into account lateral wind and ground impact on jet parameters.

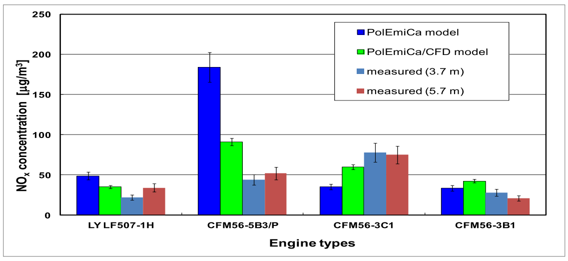

Fig.3. Comparison of the PolEmiCa standard and PolEmiCa/CFD model results with the measured NO_x concentration at different height for selected aircraft engines.

The combination of modeling and measurement methods ensured a quite accurate assessment of the contribution of aircraft emissions to total air pollution in the vicinity of the airport.

CONCLUSIONS

The combined approach of modeling and measurement methods provides a more accurate representation of aircraft emissions to total air pollution (local pollution) at an airport. Modeling gives the scientific grounding for the measurement campaign of aircraft engine emissions, particularly, a scheme for the positioning of monitoring stations with aim to detect maximum concentration in plume from aircraft engines. The model allows to predict the sample height of the exhaust gas jet with taking into account buoyancy effects and the interplay with the ground surface.

In conclusion, it has been successfully demonstrated that the measurement systems applied in the field campaign allowed the determination of $EINO_x$ 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 IBA.

REFERENCES

Ayres E., 2001, Airports and cities: can they coexist? World Watch Institute.V.14. №4.

Bossioli E., Tombrou M, Helmis C, Kurtenbach R, Wiesen P, Schäfer K, et al., 2013, Issues related to aircraft take-off plumes in a mesoscale photochemical model. Science of the Total Environment: 456-457.

Carslaw, D.C., Beevers, S.D., Ropkins, K., Bell, M.C., 2006, Detecting and quantifying aircraft and other on-airport contributions to ambient nitrogen oxides in the vicinity of a large international airport. Atmospheric Environment 40: 5424-5434.

Carslaw, D.C., Ropkins, K., Laxen, D., Moorcroft, S., Marner, B., Williams, M.L., 2008, Near-field commercial aircraft contribution to nitrogen oxides by engine, aircraft type, and airline by individual plume sampling. Environ. Sci. Technol. 42: 1871-1876.

Celikel A, Duchene N, Fuller I, Peters S., 2005, Airport local air quality studies: concept document. EUROCONTROL Experimental Centre EEC/SEE/2005/003.

Environmental Statement 2005. Environmental Protection and Management at Frankfurt Main Airport, Fraport AG: 55–59.

Heland, J.; Schäfer, K., 1998, Determination of major combustion products in aircraft exhausts by FTIR emission spectroscopy. Atmospheric Environment 32: 3067-3072.

Herndon, S C.., Shorter, J.H., Zahniser, M.S., Nelson, D.D., Jayne, j., Brown, R.C., Miake-Lye, R.C., Waitz, I., Silva, P., Lanni, Th., Demerjian, K. and Kolb, C.E., 2004, NO and NO_2 Emission Ratios Measured from In-Use Commercial Aircraft during Taxi and Takeoff. Environmental Science & Technology 38: 6078-6084.

Herndon, S.C., Jayne, J.T., Lobo, P., Onasch, T.B., Fleming, G., Hagen, D.E., Whitefield, P.D., Miake-Lye, R.C., 2008. Commercial aircraft engine emissions characterization of in-use aircraft at Hartsfield-Jackson Atlanta International Airport. Environmental Science & Technology 42: 1877-1883.

Hüttig G, Bleschmidt F, Hotes A., 1999 Entwicklung und Erprobung einer Methode zur Bewertung der Schadstoffimmissionen in der Umgebung von Flugplätzen, Band I: Ermittlung der Emissionen, Forschungbericht.

Johnson, G.R., Mazaheri, M., Ristovski, Z.D., Morawska, L.A., 2008. Plume capture technique for the remote characterization of aircraft engine emissions. Environmental Science & Technology 42: 4850-4856.

Jung, K.H., Artigas, F., Shin, J.Y., 2011, Personal, indoor, and outdoor exposure to VOCs in the immediate vicinity of a local airport. Environ. Monit. Assess. 173: 555-567.

Masiol M., Harrison R., 2014, Aircraft engine exhaust and other airport-related contribution to ambient air pollution: a review. Atmospheric Environment 95: 409-455.

Nikoleris, T., Gupta, G., Kistler, M., 2011. Detailed estimation of fuel consumption and emissions during aircraft taxi operations at Dallas. Fort Worth International Airport. Transp. Res. D 16: 302-308.

Peace, H., Maughan, J., Owen, B., Raper, D., 2006. Identifying the contribution of different airport related sources to local urban air quality. Environ. Modell. Softw. 21: 532-538.

Popp, P. J.; Bishop, G. A.; Stedman, D. H., 1999, Method for commercial aircraft nitric oxide emission measurements. Environmental Science & Technology 33: 1542-1544

Schafer, K.; Jahn, C.; Sturm, P.; Lechner, B.; Bacher, M., 2003, Aircraft emission measurements by remote sensing methodologies at airports. Atmos. Environ. 37: 5261-5271.

Schürmann G., Schäfer K. et.al., 2007, The impact of NOx, CO and VOC emissions on the air quality of Zurich airport. Atmospheric Environment 41: 103-118.

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

Umweltbericht. Umwelterklärung 2008 mit Umweltprogramm bis 2011für den Standort Flughafen Frankfurt Main. Fraport AG: 100–104.

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