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Research Article

Air Quality Studies at Ukrainian Airports

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Abstract

Sustainability of aviation must be provided to limit the harmful influence and protect public health and the environment. As a rule, national and international regulations aim to reduce ambient air pollution from the aviation sector. Ukraine and other countries have historically adopted international regulations concerning air quality to protect public health and the natural environment. Local regulations also regulate it. However, these documents cover mainly stationary emission sources. In contrast, mobile sources, especially aircraft, are not considered, although, unlike most transportation modes, aircraft travel great distances at various altitudes, generating emissions that potentially impact air quality. This paper was aimed to study the principles and methods to monitor air pollution from aircraft engines at main airports of Europe, North America, and Asia. Based on measurement campaign analysis at some airports of the world and modelling results by complex model PolEmiCa (Pollution and Emission Calculation), the method and technical characteristics for measurement system detect the aircraft engine emissions. The developed practical recommendations were realised at Ukrainian airports and used for validation of model PolEmiCa. Thus, the modelling results for each engine are in good agreement with the results of measurements by the AC32M Nitrogen Oxides (NO_X) analyser system due to considering the jet and plume-regime during an experimental investigation at Boryspol airport. Analysis of measured instantaneous concentration demonstrates a high correlation with the runway movements and take-off at Zhulyany airport.

Keywords

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Air pollution
Local air quality
Monitoring of air pollution
Emission index

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1. Introduction

The Advisory Council for Aeronautics Research in Europe (ACARE) goals intend that in 2050 technologies and procedures available allow a 75% reduction in carbon dioxide (CO_2) emissions per passenger-kilometre and a 90% reduction in NO_X emissions. In addition, the perceived noise emission of flying aircraft is reduced by 65%. These are relative to the capabilities of typical new aircraft in 2000 (ACARE Goals, 2008).

The number of flights has increased by 8% between 2014 and 2017 and is forecast to grow by a further 42% between 2017 and 2040. As a result, the carbon monoxide emissions (CO) and NO_X are predicted to increase by at least 21% and 16 %. At 2040 by the European Aviation Safety Agency figures (EASA, 2019). According to the State Aviation Service of Ukraine, the total passenger traffic of Ukrainian airports in 2018 increased by 25% compared to 2017. Consequently, the future growth in

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the European aviation sector will be inextricably linked to its environmental sustainability.

Aviation must be environmentally sustainable, operating harmoniously within the constraints imposed by the need for clean air and water, limited noise impacts, and climate change, as Federal Aviation Authority declares (FAA, 2015). Air transport is committed to meeting its responsibilities for sustainable development, maximising its support for economic development, reducing its impact on the environment, and consolidating its social benefits. International Civil Aviation Organisation (ICAO) policies implement environmental policy within the two separate parts at least –globally as climate change and - locally as general provisions, noise, and local air quality. In a subject of climate change control, the recorded total CO_2 aviation emissions are approximately 2% of the global greenhouse gas (GHG) emissions (international aviation accounts for about 1.3% of total global CO_2 emissions) with an expected growth of around 3-4% per year due to traffic and proper fuel consumption growth (ICAO, 2015). There are many studies that also emphasise incredibly high concentrations of toxic compounds, including NO_X, particulate matter (PM), unburned hydrocarbons (UHC), the volatile organic compound (VOC) and CO due to airport-related emissions and their significant impact on the air quality and sufficient contribution to the public health concerns within neighbouring. Some of these primary pollutants undergo chemical and physical transformations in the atmosphere, producing other pollutants such as secondary PM and O_3. Additionally, NO_X and fine PM emissions from aircraft engine emissions can be initiators of photochemical smog and regional haze, directly impacting human health.

The problem of local/regional air pollution of airports is crucial for Ukraine in the increase of air traffic and the trend of approximation of residential areas to airports (for airports Boryspyl, Kyiv (Zhulyany), Lviv, Odessa, Kharkiv, Zaporizhzhia). By 2035, in the absence of constant efforts, it is expected that Ukrainian airports will meet environmental restrictions on the growth of air traffic. Air quality degradation in the locality of airports poses a public health hazard. The ability to quantitatively predict airport operations' air quality impacts is important for assessing airports' air quality and public health impacts today, of future developments, and for evaluating approaches for mitigating these impacts.

Criteria of civil aviation impact on air quality are determined by the requirements and recommendations of the national legislative framework (Ministry of Health of Ukraine, 2019; Air Code of Ukraine, 2011) EU requirements (art.137, 138 of Ukraine-EU Association Agreement), ICAO norms (ICAO, 1993; ICAO, 2011; ICAO, 2002).

Aircraft emissions and air pollution levels in the vicinity of the airport can be assessed through the organisation of permanent ambient air monitoring or computer modelling (or a combination of both for increased accuracy). ICAO's Airport Air Quality Guidance Manual contains advice for the assessment of airport-related air quality (ICAO, 2011).

2. Method

2.1. Monitoring of Airport Air Pollution

The national legislative framework does not include any norms and methods for monitoring air pollution at the civil airport in Ukraine. Nevertheless, the participation of Ukraine at the EU association supposes harmonisation of existing and implementation of new normative for environmental regulation. So, the overview of methods and basic principles was conducted to monitor air pollution at main airports of the world to accumulate best practices in this field.

Thus, permanent monitoring of aircraft engine emissions is realised John Kennedy Airport (Herndon, 2008). Spectrometry methods are used to detect the instantaneous concentration of NO_X and CO_2 in the plume from aircraft engines during both idle and take-off conditions. Thus, Tuneable Diode Laser Differential Absorption Spectroscopy (TILDAS) was used to measure NO_X and the non-dispersive infrared absorption method (LICOR). The monitoring station is positioned close to the in-use taxiway (within 300m) and the runway due to the prevailing wind. During take-off, the wind carried exhaust plumes from aircraft to the monitoring station when the aircraft had travelled approximately 300 m or the first tenth of the runway distance. Determination of NO_X concentration in aircraft emissions is based on the clear correlations between peak NO_X concentrations and aircraft's movements (Herndon, 2008).

Analysing continuous values of measured concentrations and aircraft movements, it was discovered that peaks of NO_X concentrations are correlated with aircraft take-offs at the runway, minimum values of NO_X concentrations and peaks of CO_2 concentrations have observed during aircraft taxing (fig.1).

A permanent monitoring of the extended list of the contaminants (NO_X, CO and CO_2, UHC, PM, and soot) in aircraft engine exhausts were conducted at Harts-Field-Jackson Atlanta International Airport (Herndon, 2008b). Most of the sampled plumes by TILDAS and LICOR methods during this measurement campaign were emitted from engines at maximum (take-off activity) and idle operation modes (taxing activity). The monitoring station is positioned close to the in-use taxiway (within 216 m) and the runway due to the prevailing wind.

Results of routine measurement highlight correlations between peak measured concentrations and aircraft's operation modes. The plot also expresses dependence emission index of PM on aircraft engine mode and ant correlation with black carbon emissions. So, PM emission is more significant at idle operation mode and minimum – at full operation mode. Opposite dependence is observed for black carbon.

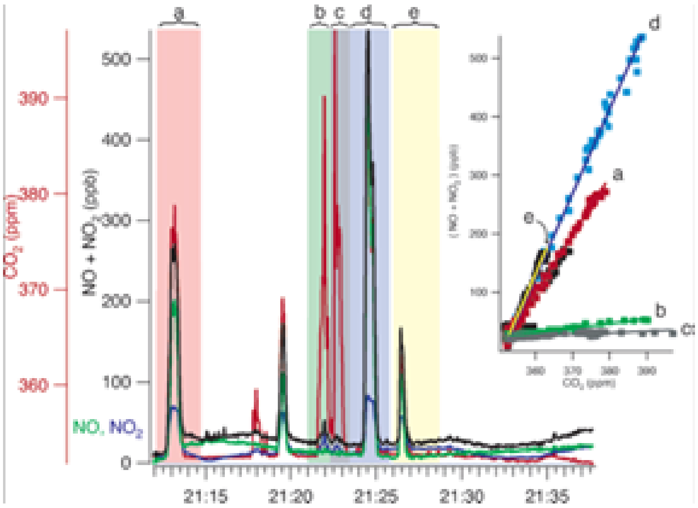


Fig. 1. Results of routine measurements of NO_X and CO_2 in aircraft engine exhaust emissions by TILDAS method (a, d, e correspond to aircraft take-off; b and c to aircraft taxi).

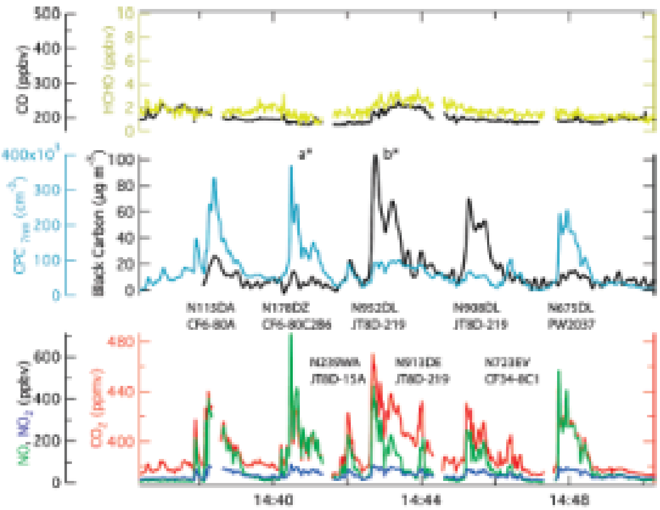
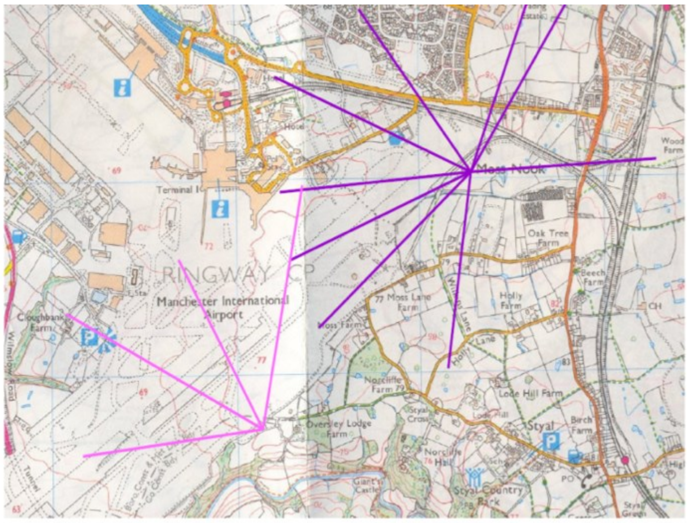


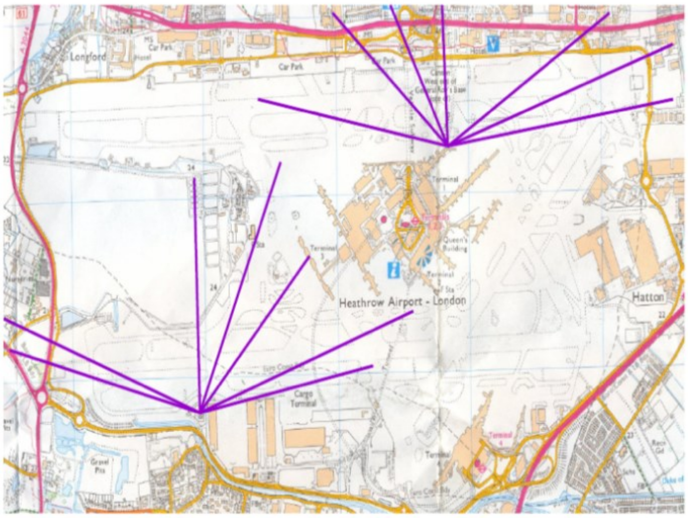
Fig. 2. Time series results of concentration measurements of NO_X, CO, CO_2, PM and soot in sampled plumes from 8 aircraft engines (CF6, CF-34, JT8D-19, PW-2037)

Permanent monitoring of air pollution during take-off and landing aircraft activities is implemented by LIDAR (Light Detection and Ranging) system at Manchester and Heathrow airports (Graham, 2008). This system operates in the optical spectral range, where intense laser pulses interact with particles and molecules of the atmosphere. From the backscattered intensity and travel time, LIDAR provides detailed information on aerosols and clouds, water vapour, atmospheric trace gases, and wind speed and direction can be directly obtained with high spatial and temporal resolution.

LIDAR scanning directions of air contamination producing by aircraft engine emissions inside Manchester and Heathrow airports are shown on fig.3, and 4. (Graham, 2008; Wayson, 2002) Results of LIDAR measurements allow to investigate aircraft plume behaviour (fig. 4), namely height plume rise and plume standard deviations. This data set provides accurate initial data for modelling systems of air pollution produced by aircraft engine activities. Participation of Ukraine at EU association supposes harmonisation of existing and implementation of new normative for regulation of civil aviation.



a)



b)

Fig.3. Scheme of scanning directions of Manchester (a) and Heathrow (b) Airport by LIDAR

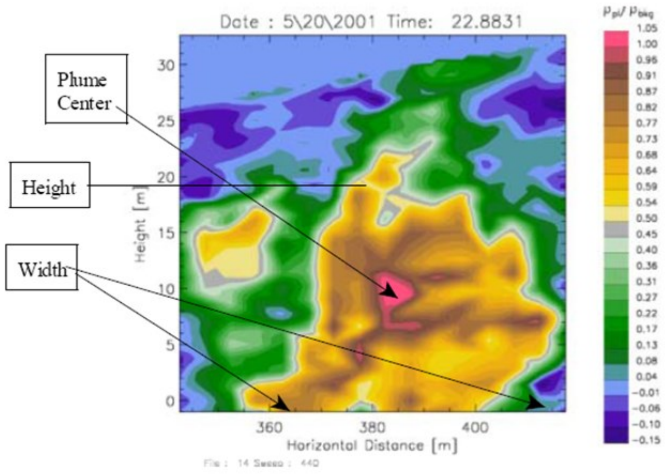


Fig.4. Example of computer enhanced LIDAR image

Most countries in Asia and the Pacific do not have air monitoring systems at airports at all. The only document that allows estimating emissions from sources of pollution is the inventory of emission sources required per ICAO policies. As instrumental monitoring is advisory, most airports ignore this issue (IQ Air, 2018). In 2018 in Southeast Asia, Jakarta registered the most polluted air in the sub-region last year. However, there are no real-time data from monitoring posts in the city. In contrast, at the Soekarno Hatta Airport, which serves Jakarta and the neighbouring cities, there are no monitoring posts.

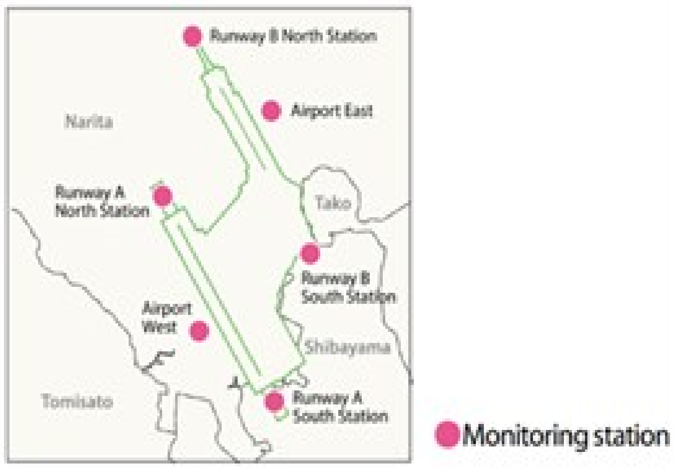


Fig.5. Scheme of monitoring sites within Tokyo Narita International Airport and the adjacent territories.

One of the most progressive airports in Asia is Tokyo Narita International Airport. To monitor the quality of the air, the six annual monitoring stations are around the airport. They constantly monitor the concentration of SO_2, NO_X, CO, photochemical oxidants, hydrocarbons, and PM.

In Europe, one of the busiest airports is Heathrow. In this connection, air quality control warrants special attention. There are 26 monitoring posts sites around the airport and in residential areas. They determine the concentration of pollutants from aircraft, handling equipment and passenger transport. They are in the city, near the road, in the suburbs and around the runway. The latter involves active and passive monitoring methods to determine pollution from aircraft, vehicle, commercial, space heating. The main traceable substances are NO_X, CO, CO_2, sulphur dioxide (SO_2), fine particles of various sizes, ozone and volatile organic compounds, hydrocarbons, etc. Despite the number of equipment, the contribution of specific emissions from aircraft engines remains unknown.

Heathrow airport implements measurements of ambient air quality at four sites according to monitoring program (BAA, 2008):

1. LHR (London Heathrow) site is located on the area of the old apron between the northern runway and the northern perimeter road to monitor air pollution arising from the airport area considering prevailing (south-west) wind direction.
2. Harlington site is established to measure air pollution concentrations in residential areas close to the airport.
3. Green Gate site is established to control of urban background.
4. Oaks Road site is in a residential area near the southwestern boundary of the airport to control urban background.

Fig.1 shows the estimated NO_X emissions that contribute to measurement at each monitoring site on and around the airport.

Over the last decade, the concentrations have fallen at most monitoring sites through the success of previous Air Quality Action Plans (BAA, 2008) and incorporating new initiatives and technological advances. The organisation of air pollution monitoring to detect and evaluate the aircraft engine emission contribution to total airport pollution should consider the influence of other emissions sources within the airport.

Zurich Airport has monitored the local air quality in the vicinity of the airport for many years. The monitoring sites have been selected following a monitoring concept that has been developed with the local authorities and last updated in 2005 (Fleuti, 2005; Zanetti et al., 2016). The monitoring stations are grouped according to their main potential contributor specified in the airport's ambient air quality monitoring concept (Fleuti, 2005; Celikel, 2005): monitoring stations most likely to be dominated by road traffic; monitoring stations most likely to be dominated by airport activities; monitoring stations most likely to dominate by other sources; background monitoring stations, Fig.7.

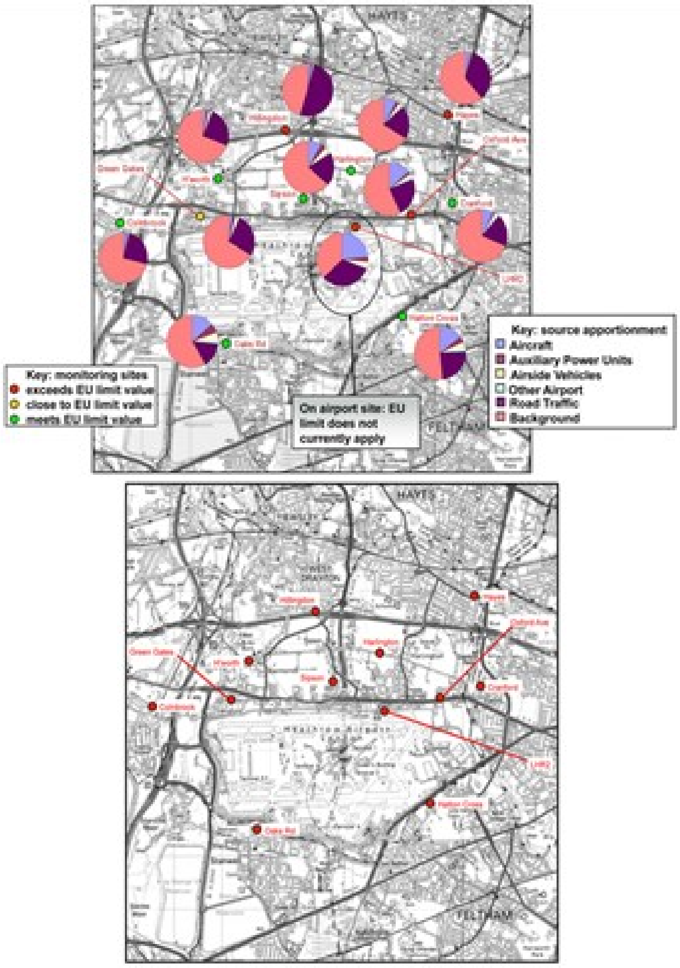


Fig. 6. Principal automatic air pollution monitoring sites near Heathrow Airport

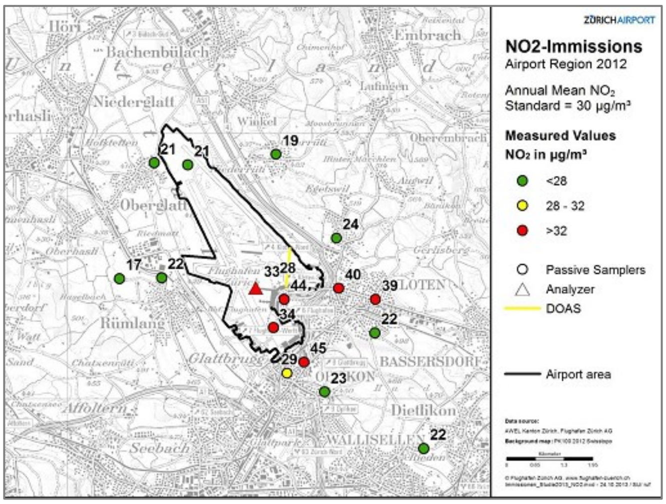


Fig.7. Measured NO_2 pollution concentration in 2012 (values are in µg NO_2/m^3)

Despite the increased attention given to aircraft emissions at the ground level and air pollution in the vicinity of airports, many research gaps remain concerning, including aircraft features as a particular source of air pollution by modelling and measurement methods.

The concentration field from aircraft operation at the airport is mainly determined by the exhaust jet distribution from aircraft engines. Hence, the maximum instantaneous concentrations observed in the exhaust gas jet's points are developed and spread. So, measurement campaigns of aircraft engine emissions must be proved by analytical models, which allow getting the understanding of contaminants transportation and dilution processes by exhaust jet from aircraft engine and meteorological conditions.

Such a combined approach of modelling and measurement methods ensures a relatively accurate and quite cost-efficient assessment of aircraft emission contribution to total air pollution in the vicinity of the airport.

2.2. Dispersion Modelling

Turning to airports, the essential document on air pollution control remains ICAO Document 9889 "Airport Air Quality Manual". It contains advice to assist the member states in implementing the instruments for air quality control. Typically, it provides a few main areas of an air quality assessment – the emission inventory and the dispersion modelling of pollution concentration.

Emissions modelling, a prerequisite to dispersion modelling, allows the change in emissions to be reviewed temporally and spatially. This requires the emissions data and explicit detail on when, where, and how the emissions occur, including airport spatial and temporal variation.

The common-used dispersion modelling methodologies are:

1. Gaussian formulation - It can be applied to plumes or individual puffs and provides needed flexibility for local air quality modelling. It has been adapted for point, line, and area sources.
2. Eddy diffusivity based on mass conservation formulation - This approach is used for widely or uniformly distributed pollutants where large individual plumes are not dominant. This occurs for such pollutants as carbon monoxide.
3. Lagrangian particle models - It relies on meteorological parameters that can be determined without dispersion experiments. The technique is routinely applied in air quality control.
4. Statistical models - Receptor modelling uses multivariate statistical methods to identify and quantify the apportionment of air pollutants to their sources.

The widely used models for the Airport air quality models are AEDT/EDMS, ADMS-Airport, ALAQS-AV, and LASPORT.

Aviation Environmental Design Tool (AEDT/EDMS) is a software system that dynamically models aircraft performance in space and time to produce fuel burn, emissions, and noise. The U.S. government currently uses the model to consider the interdependencies between aircraft-related fuel burn, noise, and emissions.

ADMS-Airport includes an allowance for all relevant emission sources at airports and utilises algorithms explicitly designed to model dispersion from aircraft engines.

Airport Local Air Quality Studies (ALAQS) - is based on delivering case study reports, guidance material, a database of default parameters for European Local Air Quality (LAQ), and the ALAQS-AV toolset.

LASPORT (LASAT - Lagrangian dispersion model for airports) – is based on experience with applying the LASAT at airports in Germany and Switzerland.

2.2.1. Complex Model PolEmiCa

A complex model PolEmiCa for assessing air pollution and emission inventory analysis, produced inside the airport, has been developed in the National Aviation University of Ukraine (Zaporozhets, 2017). It consists of the following basic components in a part of aircraft emissions:

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

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, 1987). The action of Archimedes forces causes buoyancy of a jet due to excess of temperature of jet gases above air temperature, fig.1. The Archimedes number (1) is used for the estimation of the plume rise height (2) (Zaporozhets, 2016):

$$Ar_0 = g \cdot D_0 \cdot (Q_T - 1)/U_0^2 \qquad (1)$$

$$\Delta h_A = 0.013 \cdot Ar_0 \cdot \overline{X_A^3} \cdot R_0 \qquad (2)$$

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 co-ordinate of jet axis concerning radius of the engine exhaust nozzle, $R_0 = D_0/2$.

Δh_A, X_A – height and longitudinal co-ordinate of jet axis rise due to buoyancy effect, m; h_{EN} – the height of engine installation, m; R_B – radius of jet expansion, m; X_1 – longitudinal co-ordinate of first contact point of jet with ground, m; X_2 – longitudinal co-ordinate of a point of jet lift-off from the ground due to buoyancy effect, m.

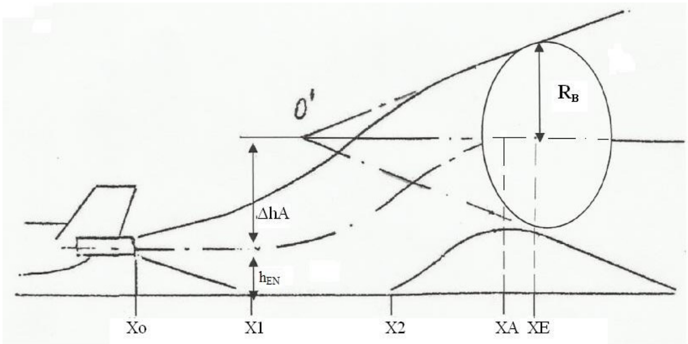


Fig. 8. Jet structure for jet transport model

The complex model PolEmiCa has been sufficiently improved in the subject of jet transport model by using computational fluid dynamics (CFD) package (FLUENT 6.3 Fluid Simulation Software) 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 fundamental equation of a complex model PolEmiCa for the definition of instantaneous concentration (dispersion model) 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 (Zaporozhets, 2017; Zaporozhets, 2016):

$$c(x,y,z,t) = \frac{Q \exp\left[-\frac{(x-x')^2}{2\sigma_{x0}^2 + 4k_x t} - \frac{(y-y')^2}{2\sigma_{y0}^2 + 4k_y t}\right]}{\{8\pi^3[\sigma_{x0}^2 + 2K_x t][\sigma_{y0}^2 + 2K_y t]\}^{1/2}} \times$$
$$\times \left\{ \frac{\exp\left[-\frac{(z-z'-H)^2}{2\sigma_{z0}^2 + 4k_z t}\right] + \exp\left[-\frac{(z+z'+H)^2}{2\sigma_{z0}^2 + 4k_z t}\right]}{[\sigma_{z0}^2 + 2k_z t]^{1/2}} \right\} \qquad (3)$$

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:

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

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

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

where (x_0, y_0, z_0) – initial co-ordinates 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.

The model calculates the co-ordinates (x_{wmax}; y_{wmax}) and period of maximum concentration formation (t_{wmax}) on the runway from the moment of aircraft engine run:

$$t_{w\max} = (x_{w\max} - x_{1w}) / u_{PL} \tag{7}$$

Also, the model predicts maximum concentration distribution due to dilution by jet and diffusion by atmospheric turbulence and its detection by monitoring station (Fig.9).

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

$$t_{\max} = \frac{x_{wind}}{u_w} - \sqrt{x_{wind} \frac{dK_x}{u_w^3}} \tag{8}$$

where x_{wind} – the distance of the contaminants transport by the wind to monitoring station; u_w – wind velocity.

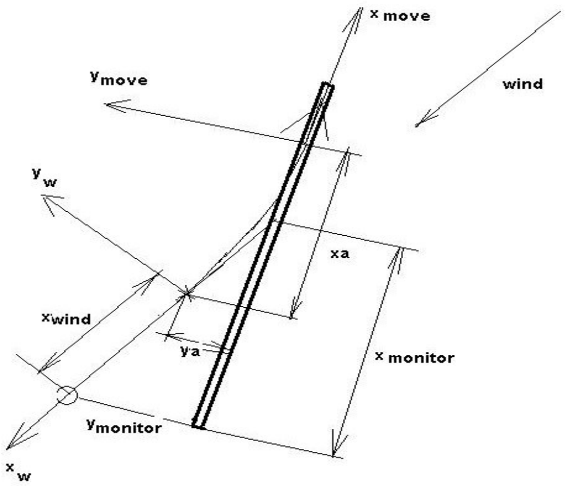


Fig.9. Modelling scheme of transport and dilution of air contaminants by exhaust gases jet from aircraft engine and atmospheric diffusion: (x_{move}; y_{move};) – initial co-ordinate system: axis X is directed toward an aircraft take-off; (x_{wind}; y_{wind};) – secondary co-ordinate system: axis X is directed toward a wind velocity vector u_w; ($x_{monitor}$; $y_{monitor}$) – co-ordinates of monitoring station B at initial co-ordinate system.

PolEmiCa calculates the emission inventory and concentration filed inside the airport area, considering the intensity of flights of airplanes, the loading factor of different taxiways and runways, and other operational circumstances.

Also, PolEmiCa provides the co-ordinated point at which maximum instantaneous concentrations will be fixed due to the development and spread of exhaust gas jet from aircraft engines. Thus, the models, for instance, PolEmiCa, provide grounding for scheme and height of sample systems installation, time-integration of measured values to detect aircraft engine emission and pollution with considering basic fluid mechanisms of the exhaust (buoyancy and Coanda effect) and ground impact on its structure and behaviour. Such a proposed approach of modelling and measurement methods were realised at Boryspol and Zulyany airports.

3. Results

3.1. Measurement of Aircraft Engine Emissions at Boryspol Airport

Based on measurement campaign analysis at main airports of the world (London-Heathrow, Frankfurt/Main, Vienna, Zurich, Munich, Budapest and Athens) and modelling results by complex model PolEmiCa, it was suggested the method and technical characteristics for a measurement system to detect the aircraft engine emissions:

- High time resolution of detected concentrations - 1 second: to measure the maximum concentration values in jets from each engine the aircraft and therefore to implement objective estimation of aircraft engine emissions contribution in total airport air pollution. Recommended equipment also provides measurements of averaged concentration for any period, which is an essential characteristic for air quality control according to the established sanitary-hygienic standards as - maximum permissible concentration MPC - with an averaging period of 20 minutes.
- The high detection limit (± 2ppbV): to guarantee the safe distance to the aircraft, identify peak concentrations of air contaminant in emissions from aircraft engine and their separation from other sources of airport air pollution (background pollution).
- The different heights to collect the gases samples considered the buoyancy effect of exhaust gases jet under different operational and meteorological conditions.

The combined approach of modelling and measurement methods was realised at International Boryspol Airport (IBA) within bilateral cooperation between Germany and Ukraine. Monitoring of air pollution produced by aircraft engine emissions at IBA was conducted by two stations (stationary station A and movable station B) under operation conditions: idle (aircraft is taxing) and maximum (aircraft is accelerating on the runway or takes-off). Scheme for disposition of the monitoring stations in the airport was developed with considering modelling results (model PolEmiCa) of transportation and dilution contaminants by jet (stationary station A) from aircraft engine and its transfer by wind and atmospheric turbulence (movable station B) for differential operational and meteorological conditions, fig.10. Station B (movable van) is oriented to dominant wind direction (south-east) and displayed at a distance of 120m from runway axis in west direction and opposite guide path near 36R end of the runway, fig.3. The position of the stations guaranteed that the most important sector of the aircraft exhaust for taxing, landing and take-off conditions was scanned by the measurement systems. Analysis results of measurement data at station "B" clearly demonstrated a correlation between the peak concentrations of NO_x and CO_2 are correlated with aircraft plumes correspondingly at take-off and taxing conditions, fig.11 (Zaporozhets, 2016).

As shown from Table 1 and Figure 12, the modelling results for each engine are in good agreement with the results of measurements by the AC32M system due to considering the jet- and plume-regime during an experimental investigation at Boryspol airport. Also, using CFD-code (Fluent 6.3) improves results by 30% (coefficient of correlation, r=0.76) by considering lateral wind and ground impact on jet parameters.

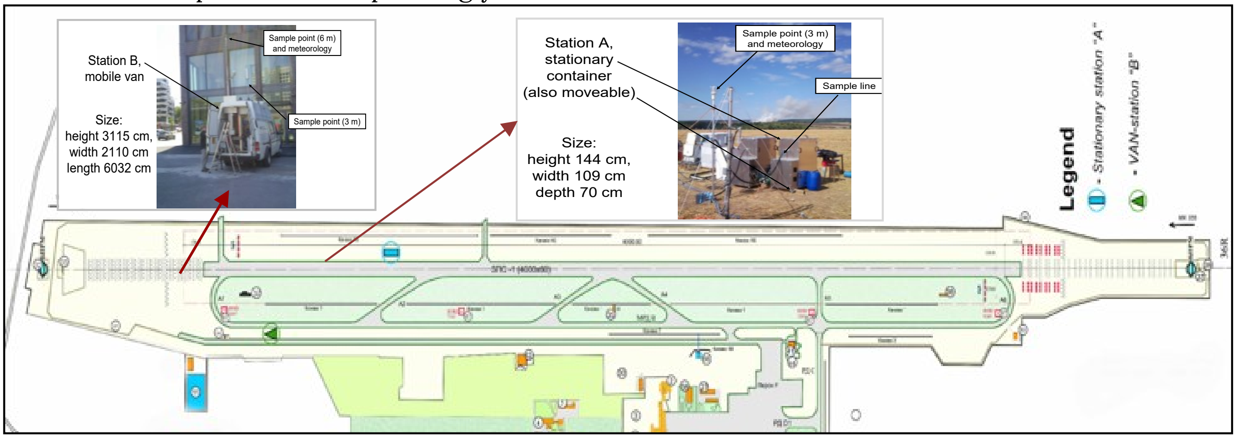


Fig.10. Location of stationary station A and movable station B at International Boryspol Airport

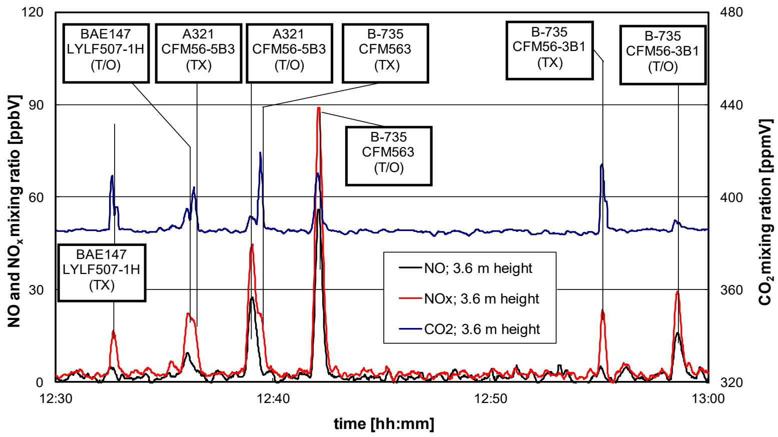


Fig.11. Background and plume concentration for NO, NO_x and CO_2 at mobile station B for different aircraft at take-off (T/O) and ground taxi (TX) conditions

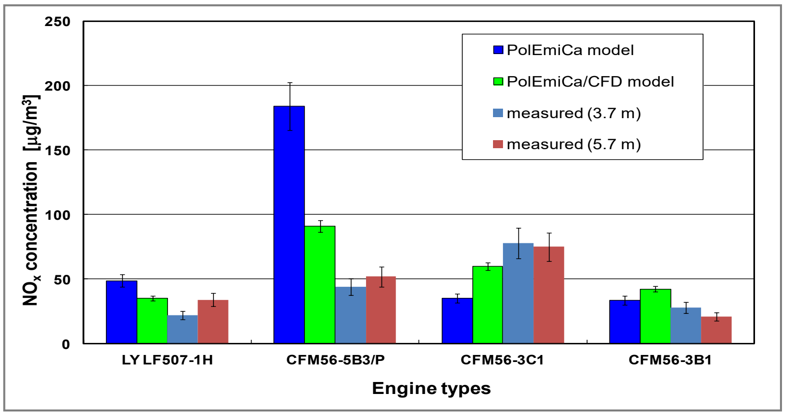


Figure 12. Comparison of the PolEmiCa and PolEmiCa/CFD model results with the measured NOx concentration at different height for selected aircraft engines under maximum operation mode

Therefore, the location of the monitoring station should consider the transport and dilution mechanisms of air contaminants by exhaust jet from aircraft engine and dispersion process by wind and atmospheric turbulence.

3.2. Measurement Of Aircraft Engine Emissions At Zuliany Airport

The residents around the airdrome can feel an acute problem of atmospheric air pollution. In this regard, in the summer of 2018, one more study was conducted at another airport - Kyiv International Airport (Zhuliany). This airport is an interesting object for studying atmospheric air pollution as it finds within the city and surrounding residential areas.

Air quality monitoring installed on the territory of the aerodrome. The location of the monitoring station determined according to the scenario of the aircraft moving (landing, running along the runway and take-off) and the dominant wind direction. The scheme for a disposition of the monitoring station was developed by considering the processes of transportation and dilution of air contaminants by exhaust gas jet from aircraft engine and its transfer by wind and atmospheric turbulence for differential operational and meteorological conditions Fig.13.

Instrumental air pollution studies within the aerodrome were performed in Zhuliany through the gas analysers Elan NO, Elan NO_2, Elan CO. The measured parameter is air pollutant concentration in the ambient air (mg/m3).

The method is electrochemical. It is pretty versatile and does not require the use of complicated equipment. Compactness, speed of operation and low cost are typical for these devices with an electrochemical sensor. The relative measurement error for the Elan gas analysers is 25%.

The gas analyser "Elan" is used to measure the instantaneous concentration of NO, NO_2, CO in the plume from the aircraft engine and ambient air (background level). Uncertainly -, time resolution – 0.5 s.

Fig.13- Scheme for the monitoring station disposition on the aerodrome.

Argued location of the monitoring station (fig.13) allows catching the instantaneous maximum concentration in the plume from the aircraft engine at the stages of taxing, clearing of take-off, acceleration on the runway and further take-off.

Analysis of measured instantaneous concentration (NO, NO_X, CO) demonstrates the following correlation (fig.15):

- Taxing of aircraft along the main taxiway causes the high concentration of NO, which can be explained short distance to aircraft (nearly 10 m) and most of NO_X is represented by NO in the exhaust.
- An extremely high concentration of CO characterises the stage of cleared for take-off before accelerating of aircraft.
- Accelerating of aircraft along the runway and Take-off leads to the detection of a high concentration of NO_X.

Table 1: Comparison measured (AC32M, ELAN) and calculated concentration (averaged for 3 seconds) of NOx produced by aircraft engine emissions at accelerating stage on the runway

Aircraft	Aircraft engine	ELAN		AC32M			PolEmiCa CFD (Fluent 6.3)		PolEmiCa	
		Peak 1	Peak 1	Back ground	3 м	6 м	1 engine	All engines	1 engine	All engines
		NO_X	NO_X	NO_X	NO_X	NO_X	NO_X	NO_X	NO_X	NO_X
BAE147	LY LF507-1H	38	35	1.70	22.07	33.90	35.10	70.46	48.90	202.30
A321	CFM56-5B3/P	39	39	0.72	44.00	54.20	90.85	182.90	184.20	371.20
B735	CFM-563C1	40	45	0.77	94.09	76.57	60.03	120.91	35.30	71.10
B735	CFM56-3B1	45	41	1.74	29,20	23.40	42.34	85.30	33.70	67.76

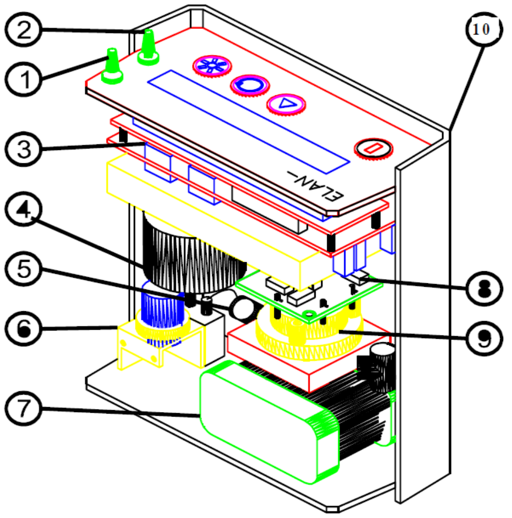


Fig. 14- The general form of the gas analyser includes 1. Fitting "Gas inlet". 2. The union "Gas outlet". 3. Processor module. 4. Filter. 5. Tee. 6. Pump. 7. Rechargeable battery. 8. Potentiostat. 9. Electrochemical cell. 10. Cover.

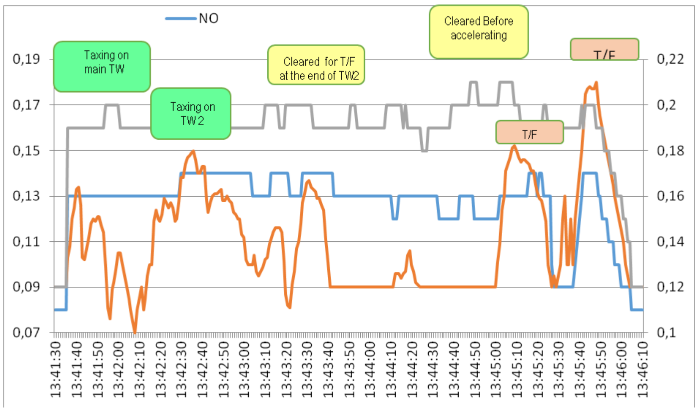


Fig.15. Background and plume concentration for NO, NO_x, CO_2 at monitoring station under taxing and take-off conditions of A320

The obtained results of the experiment within Kyiv International Airport (Zhuliany) confirm the necessity of organising continuous instrumental monitoring to define the field of pollutant concentrations as a result of emissions of aircraft engines within the airport.

4. Conclusions

Consequently, the monitoring of aircraft engine emissions should aim to detect the maximum instantaneous concentration of air contaminants in plume under real operational conditions to obtain objective information concerning aircraft engines emissions contribution to total air pollution within the airport area. The concentration field is mainly determined by the exhaust jet distribution from aircraft engines. Hence, the maximum instantaneous concentrations observed in the exhaust gas jet's points are developed and spread. Therefore, the location of the monitoring station should take into account the transport and dilution mechanisms of air contaminants by exhaust jet from aircraft engine and dispersion process by wind and atmospheric turbulence.

Based on measurement campaign analysis at main airports of the world (London-Heathrow, Frankfurt/Main, Vienna, Zurich, Munich, Budapest and Athens) and modelling results by complex model PolEmiCa it was suggested the method and technical characteristics for a measurement system to detect the aircraft engine emissions. The developed practical recommendations were realised at Ukrainian airports and used for validation of model PolEmiCa. To assess the concentration at the Ukrainian airports, there were applied the complex model PolEmiCa, and the short-term ambient air monitoring through gas analysers. Thus, the modelling results for each engine are in good agreement with the results of measurements by the AC32M system due to considering the jet- and plume-regime during an experimental investigation at Boryspol airport. Also, using CFD-code (Fluent 6.3) improves results by 30% (coefficient of correlation, r=0.76) by considering lateral wind and ground impact on jet parameters. Furthermore, the measured instantaneous concentration (NO, NOx, CO) analysis demonstrates a high correlation with the accelerating stage of aircraft along the runway and take-off at Zhulyany airport. The obtained results of the experimental investigations within Ukrainian airports confirm the necessity of organising continuous instrumental monitoring to define pollutant concentrations because of emissions of aircraft engines within the airport.

Abbreviations

ACARE	:	Advisory Council for Aeronautics Research in Europe
AEDT	:	Aviation Environmental Design Tool
ALAQS	:	Airport Local Air Quality Studies
CFD		Computational fluid dynamics
CO	:	Carbon Monoxide
CO_2	:	Carbon Dioxide
EASA	:	European Aviation Safety Agency
EDMS	:	Aviation Environmental Design Tool
FAA	:	Federal Aviation Authority
FLUENT	:	Fluid Simulation Software
GHG	:	Greenhouse gasses
ICAO	:	International Civil Aviation Organisation
LAQ	:	Local Air Quality
LASAT	:	Lagrangian Dispersion Method
LASPORT	:	LASAT for Aiportts
LHR	:	London Heathrow
LICOR	:	Non-dispersive infrared absorption method
LIDAR	:	Light Detection and Ranging
NO	:	Nitrogen Monoxide
NO_X	:	Nitrogen Oxides
PM	:	Particulate matter
PolEmiCa	:	Pollution and Emission Calculation)
SO_2	:	Sulphur Dioxide
TILDAS	:	Tuneable Diode Laser Differential Absorption Spectroscopy
UHC	:	Unburned hydrocarbons
VOC	:	Volatile organic compound

CRediT Author Statement

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