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PM EMISSIONS PRODUCED BY AIRCRAFT UNDER THE OPERATIONS AT THE AIRPORT

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Abstract

Purpose*: The effects of aircraft engine emissions within the planetary boundary layer under the landing/ take-off operations contribute sufficiently to deterioration of air pollution in the vicinity of the airports and nearby residential areas. Currently the primary object of airport air quality are the nitrogen oxides and particle matter (PM_{10}, $PM_{2.5}$ and ultrafine PM) emissions from aircraft engine exhausts as initiators of photochemical smog and regional haze, which may further impact on human health. Analysis of PM emission inventory results at major European airports highlighted on sufficiently high contribution of aircraft engines and APU. The paper aims to summarize the knowledge on particle size distributions, particle effective density, morphology and internal structure of aircraft PM, these properties are critical for understanding of the fate and potential health impact of PM. It also aims to describe the basic methods for calculation of emission and dispersion of PM, produced by aircrafts under the LTO operations.* ***Methods****: analytical solution of the atmospheric diffusion equation is used to calculate the maximum PM concentration from point emission source. The PM concentration varies inversely proportional to the wind velocity u_1 and directly proportional to the vertical component of the turbulent exchange coefficient k_1/u_1. The evaluation of non-volatile PM concentration includes the size and shape of PM. PolEmiCa calculates the distributions of PM fractions for aircraft and APU exhausts (height of installation was given H=4,5m like for Tupolev-154).* ***Results:*** *The maximum concentration of PM in exhaust from APU is higher and appropriate distance is less than in case for gas. PM polydispersity leads to the separation of maximums concentration in space for individual fractions on the wind direction and therefore it contributes to the reduction of maximum total concentration.* ***Discussion****:But although the APU has contributed significantly to the emission of aircraft at airports, APU emissions are not certificated by ICAO or any other responsible for that authority.It is quite actual task for local air quality to development model and find measurement techniques to identify aircraft engine and APU contribution to total airport PM pollution.*

Keywords: air pollution; aircraft engine emission; auxiliary power unit; concentration; emission index; emission inventory; particle matter; non-volatile particle; volatile particle; particle size distribution

1. Introduction

Even through all benefits that airport brings, the surrounding communities are subjected to the deterioration of air quality. A lot of studies emphasis on extremely high concentration of toxic compounds (including nitrogen oxides (NO_x), particle matter (PM with various sizes: PM_{10}, $PM_{2.5}$ and ultrafine), unburned hydrocarbons (UHC) and carbon monoxide (CO)) due to airport-related emissions and their significant impact on the environment [1, 2] and health of the people living near the airport [3, 4].

Considered problems are intensified in connection with increasing air traffic (at a mean annual rate worldwide of about 5%) [5], rising tensions of expansion of airports and growing cities closer and closer each other (the most urgent for Ukrainian airports, such as Zhulyany, Boryspol, Lviv, Odesa and Zaporizhzhia) and accordingly growing public concern with air quality around the airport.

While engine emissions at aircraft cruise flight are the issues of air pollution at global scale, the emissions within the planetary boundary layer under the landing/take-off (LTO) operations are certainly the local air quality (LAQ) tasks and they may produce a direct effect on human health [6, 7]. Currently the primary subject of concern of airport LAQ are the NO_x and PM (PM_{10}, $PM_{2.5}$) emissions from aircraft engine exhausts, because they are the initiators of photochemical smog and regional haze, which at further steps may impact on human health directly [8]. Ultrafine particles (UFPs, diameter <100 nm) is of the most concern in recent years, as they are small enough to penetrate deep into the lungs, causing human health damage first of all. The content of UFPs is near to 90% or even more of the total particle number count in areas influenced by vehicle emissions [9].

As a consequence today the LAQ deterioration in airports at ground level due to aircraft engine emissions of non-volatile PM (nvPM) is of particular interest to the scientific community and policymakers. One of the key statements of FORUM-AE nvPM workshop was declared: "We need to work together with airports to help update their PM models, and to help them find good measurement techniques to identify different PM sources at the airport". The CAEP/9-WG3 was working to generation data to be used by MDG to calculate the inventory of nvPM emissions from aircraft engines and auxiliary power unit (APU).

2. Analysis of the research and publications

During last decade many studies are focused on the effects of aircraft emissions at ground level as they sufficiently contribute to air pollution of the airports and nearby residential areas [10-18]. A large number of studies [19-25] has highlighted, that airport emissions may lead to increased concentrations of UFPs. Particularly, Hu et al. [26], Zhu et al [27] found that the maximum of particle number concentration was observed, when aircraft engines are accelerated to the 100% thrust power for take-off (departure stage). Thus, the results of investigation at regional airport of Santa Monica [26] highlighted, that these concentrations during the take-off phase were 440 times higher than background levels for nvPM. Similar conclusions were reported by Hsu [25] for UFP: the detected UFP concentration by the monitoring stations at the end of the departure runway of Los Angeles International airport was found 50 times higher the levels at a site 250 m downwind from the runway.

3. Task

The paper was focused on emissions quantification of aircraft engine and APU to PM emission inventory at the airport and to investigate basic mechanisms and properties of PM, to identify the key characteristics (mass (EI_m) and number (EI_n) emission indices; size distribution (PSD)) of PM in aircraft exhausts.

The analysis of ICAO and national methods was used to evaluate PM emission and air pollution from aircraft emission.

4. PM emission inventory at the airport

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 [14, 28, 29], fig. 1, 2.

More than 50% of total NO_x emissions inventory inside airport area is released by aircraft engines. As shown in fig.1 (b) and fig.2 (b), the contribution of aircraft emission to total airport PM emissions is sufficiently high.

As shown in fig.1, the APU contribution to PM emissions is also sufficiently high. APU of the aircraft is a small gas turbine to generate electricity while the main engines are off and to provide bleed air to start the main engines.

On the basis of measurement results at major European airports [10, 12, 30] (campaigns were realized in Frankfurt am Main, 2000; London-Heathrow, 2000; Vienna, 2001), Schafer et al. concluded, that APU emissions are comparable in magnitude to the emissions of the aircraft main engines due to sufficient APU operating time, which is much longer than for main engine operation at aircraft service area in airport [12]. Emission inventory analysis highlighted on sufficient APU contribution to PM emission elsewhere: 10.2% (PM_{10}) for Frankfurt airport [28]; 6.5% ($PM_{2.5}$) at major UK airports [31]. But although the APU has contributed significantly to the emission of aircraft at airports, APU emissions are not certificated by ICAO or any other responsible for that authority. Today the information on APU emissions is limited by security and propriety requirements of the manufactures.

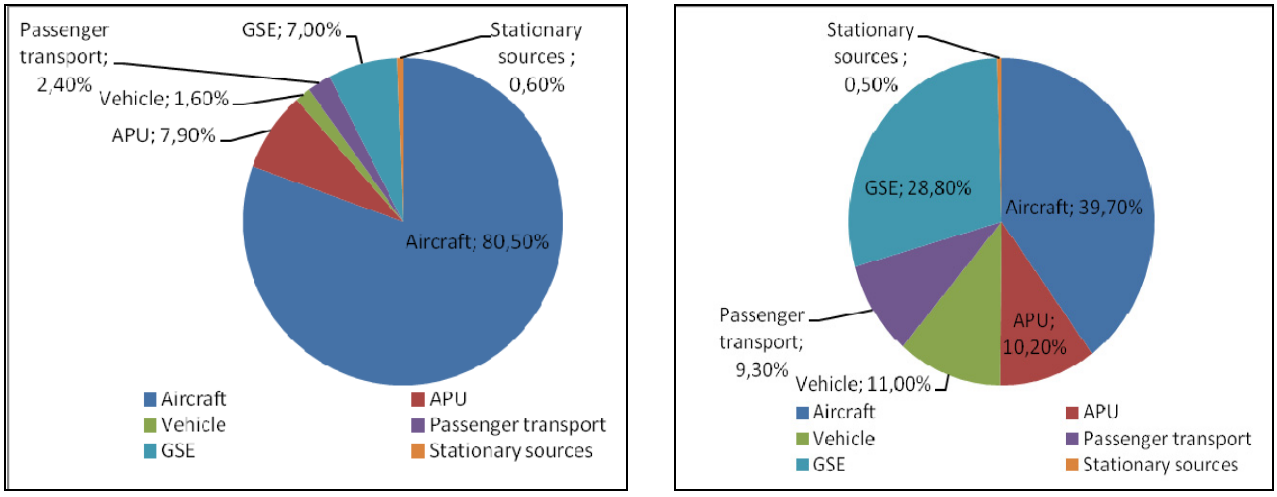


Fig. 1. The emissions inventory of NO_x (a, annual emissions – 3.284 tons/year) and PM_{10} (b, total emissions – 25 tons/year) within the International Airport Frankfurt for 2005 with an intensity of takeoffs and landings 1 300 per day

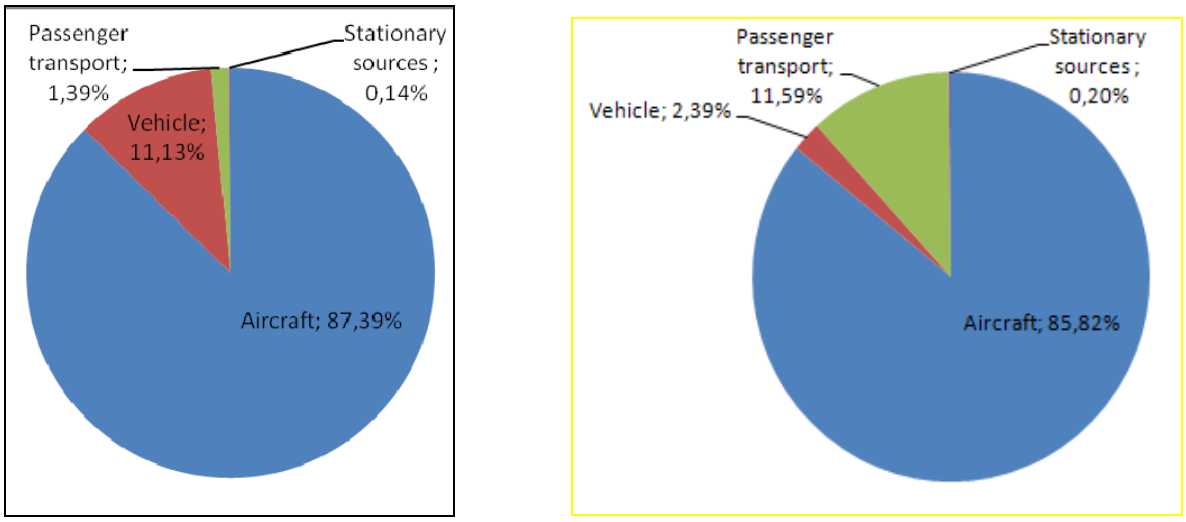


Fig. 2. The emissions inventory of nitrogen oxides (a) and PM_{10} (b) within International Boryspol airport with an intensity of takeoffs and landings 50 thousand per year

In order to compare the black carbon (BC) emissions from the APU to those of the main propulsion engines, fig.3 plots the Aerodyne BC EIs versus EGT for both the APU and the two main engines tested during alternative aviation fuel experiment (AAFEX) by Kinsey [32]. As can be seen from this fig.3, the APU EIs are substantially higher. Also, if the BC emission rate (mg/min) of the APU operating at maximum output is compared to the four main engines of the DC-8 operating at 7% idle, such as might occur prior to take-off, the APU emissions would be a factor of 1.2 (FT-2) to 1.9 (JP-8) times higher [32]. Therefore, APU operation at airports can be a significant contributor to the total PM emissions also and depending on their fuel usage.

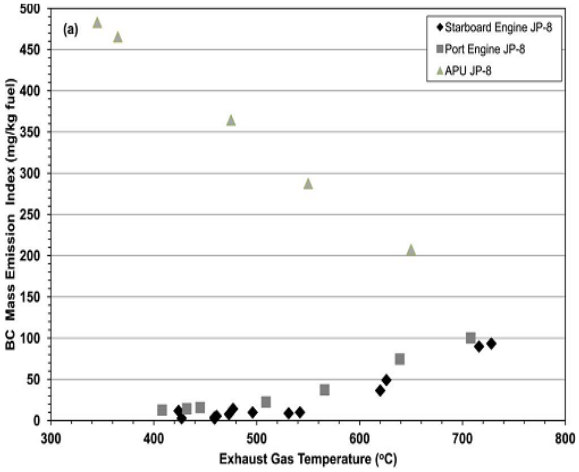


Fig. 3. Aerodyne BC emissions indices versus EGT for the APU compared to the two CFM56-2C1 main propulsion engines tested during the AAFEX campaign [32]

5. PM characteristics

PM is a complex mixture of extra small particles and liquid droplets in ambient air. Non-volatile PM is mainly composed by soot, BC, elemental carbon (EC) and traces of the metal [23]. Permanent monitoring at a small regional airport in Warwick, Phode Island is indicated, that aircraft contribution obtains 24-28% of the total BC concentrations [22]

Volatile PM is mainly composed by the gas- and particulate-phases due to nucleation and conversion process of sulphur and various organic gases in plume downstream of aircraft engine [23, 33]. The composition and the quantity of volatile PM are changed in plume sufficiently in time and space and depends on environmental conditions (temperature, humidity, sunlight, wind), plume age and fuel sulfur content [34]. Due to nucleation of sulphate and organic materials in cooling exhaust plume, the volatile PM are only detected at 15-20 m downwind, while nvPM (soot) are detected at aircraft engine exit plane elsewhere [35].

PM is identified by the following characteristics:

- mass emission index (EI_m);
- number emission index (EI_n);
- particle size distribution (PSD) – PM_{10} (aerodynamic diameter <10 microns), $PM_{2.5}$ (aerodynamic diameter <2.5 microns) and ultrafine (UFP or $PM_{0.1}$).

Sufficient numbers of experiments were implemented by Kinsey [23, 24] to assess particle emissions from commercial aircraft engines. It was found, that EI_m changed from 10 to 550 mg/kg fuel. The similar order of EI_m range (100-700 mg/kg fuel) was defined during the measurement campaign by Lobo [36] at the Oakland International airport for idle/taxi and take-off conditions for various aircraft/engine combinations. In most part of references [22-24, 33-35] PM emissions are obtained of quite high level at low engine thrust, are decreasing to minimum at midrange power and then increasing again at high engine thrust.

During the experiments by Kinsey [23, 24] the EI_n were determined in range $1 \cdot 10^{15}$ – $1 \cdot 10^{17}$ particles/kg fuel. Timko [35] found that EI_n increases in order 1-2 magnitude downwind in comparison with value at aircraft engine exit due to nucleation of volatile particles in exhaust gases. Also measurement campaign at airports [36, 37] indicated that EI_n are higher during taxi phases than during take-offs.

A comprehensive review of the studies [23, 38, 39] indicated the dependence of particles size distribution on nucleation, coagulation and dispersion mechanisms in plume. The most part of campaigns [23, 38, 39] express on diameter range between 3 and 100 nm and correspondingly a geometric mean diameter varies between 10-35 nm depending on engine power setting, fuel type and environmental conditions. The studies [23, 38-41] also found bimodal distribution of particles: first (non-volatile) mode is characterized by nearly 20 nm and second (volatile) mode is caused by the secondary aerosol generation at 7 nm. Also Kinsey [32] determined particle size in the range of 30-60 nm for APU (GTCP85-98CK) under different engine power setting, as it is shown in fig.4

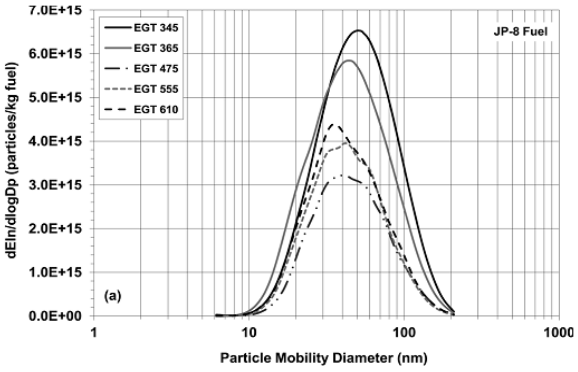


Fig. 4. PSD for the APU burning: JP-8 fuel [32]

Particle size distribution can be changed after the plume development. Some experimental investigations [42] observed that UFP concentrations, which were measured at residential area (2-3 km downwind of the airport), reached the level between airport runway and the background reference site concentrations.

6. Estimation of PM pollution from aircraft emissions by ICAO and the national methods

ICAO Doc 9889 [43] recommends first order approximation method (FOA 3.0) for estimating the particulate emissions, both non-volatile (soot) and volatile, in the form of emission indices (EI) as mass emitted per kilogram of fuel.

The calculation of nvPM is based on the engine's smoke number (SN), air fuel ratio (AFR) and, if applicable, its bypass ratio (BPR). The essence of the technique is to convert the SN via an experimental correlation into a carbon index (CI). The CI is the mass of nvPM per unit volume of exhaust. Thus, under certification conditions (standard temperature is 273.15 degrees Kelvin and pressure is 1 atmosphere) for SN≤30, the CI (mg/m^3

based on 1 kg of fuel burn) is determined in following way [43]:

$$CI = 0.06949 \times (SN)^{1.234} \text{ for SN} \leq 30$$
$$CI = 0.0297 \times (SN)^2 - 1.803 \times (SN) + 31.94 \text{ for SN} > 30 \quad (1)$$

The volume of the exhaust (Q) per kilogram of fuel is calculated by using the engine AFR and BPR values:

$$Q = 0.7769 \times (AFR) \times (1 + BPR) + 0.877 \quad (2)$$

On the basis of the estimated values of CI and Q, the EI of nvPM (mass per kilogram of fuel burn) is computed by following formula:

$$EI_{PMnvol} = CI \times Q \quad (3)$$

The EI_{PMnvol} must be computed for the various engine power settings used in the vicinity of airports.

Volatile sulphate PM is formed from the fuel sulphur via oxidation of SO_2 (S^{IV}) to SO_3 (S^{VI}) and subsequent hydration, in the exhaust plume, of SO_3 to H_2SO_4. Fuel sulphur contents (FSC) can vary widely between different batches of aviation fuel and are not included in the ICAO databank. For application to the FOA airport, this input has been left as a variable to allow the most applicable value, such as the national and/or international mean sulphur contents, to be used. As a guide, typical FSC values range from 0.005 to 0.068 weight percent [44] with a global average of 0.03 weight percent [45]. Using a conservative value of 0.068 weight per cent is currently recommended in the absence of more specific FSC data.

The EI (mg/kg) of volatile sulphate PM is calculated by using the FSC and the conversion rate of S^{IV} to S^{VI} (ε) [43]:

$$EI_{PM_{vol-FSC}} = 10^6 \times \left[\frac{FSC \times \varepsilon \times MW_{out}}{MW_{sulphur}} \right] \quad (4)$$

where MW_{out}=96 (SO_4^{-2}) and $MW_{sulphur}$=32.

The values of FSC and ε are user-defined with default values as previously mentioned.

In Ukraine today, the air pollution must be calculated, first of all, for the stationary sources in accordance with the national standard OND-86 method [46], which is used for administration purpose of air quality control, including the definition of the boundaries of sanitary protection zones around the sources of air pollution, airport is among them. The OND-86 method provides 20-30 minutes averaged concentrations, which are used, as concentration limits for domestic normative regulations.

Estimation and prediction methods of air pollution are based on atmospheric diffusion by using the turbulent diffusion equation. In formulating the initial equations describing the distribution of pollutants in the atmosphere and their concentrations change over time, used the possibility of separating fluctuations from the average impurity concentration. This allows using averaging techniques known to move from the diffusion equation for the instantaneous concentrations of the equation to the averaged values. In general, the problem of air pollution forecast mathematically can be defined as a decision under certain initial and boundary conditions of the following equation [47]:

$$\frac{\partial q}{\partial t} + \sum_{i=1}^{3} u_i \frac{\partial q}{\partial x_i} = \sum_{i=1}^{3} \frac{\partial}{\partial x_i} k_i \frac{\partial q}{\partial x_i} - \alpha \times q \quad (5)$$

where t — time; x_i — coordinates; u_i – velocity vector components; k_i — the turbulent diffusion coefficients (i=1, 2, 3); α — coefficient, which takes into account the air pollutant transformation.

The main calculation expressions of the OND-86 [46] method are based on the analytical solution of the semi-empirical equation for turbulent diffusion in the atmosphere with a vertical wind profile of the form $u_{w0}(y/y_0)^c$. Wind velocities u_w and coefficients of atmosphere turbulence k_x, k_y, k_z describe the state of the atmosphere (depending on stratification or stability class). The significant material was assembled according to parameters of wind velocities and turbulent diffusion factors depending on atmospheric stability class (meteorological parameters), time of the day, season, and geographical arrangement of the location under the research. It means that the coefficients of atmospheric diffusion (k_x, k_y, k_z) are predefined as initial data for the dispersion calculation in dependence to these meteorological parameters.

The **maximum value** of surface concentration (mg/m^3) produced by emission of point source (round nozzle) under **unfavorable meteorological conditions** at distance x_M (m) from the source is determined by OND-86 method [46] in following way:

$$q_{mu} = \frac{A \cdot M \cdot F \cdot m \cdot n \cdot \eta}{H^2 \sqrt[3]{V_1 \cdot \Delta T}} \quad (6)$$

where: A - coefficient depending on the temperature stratification of the atmosphere; M – emission rate, g/s; F – dimensionless coefficient that takes into account the rate of PM sedimentation in the ambient air; m, n – coefficients depending on output conditions of the exhaust mixture from the

emission source; H – the height of the emission source above ground level, m; η – dimensionless coefficient that takes into account the effect of the terrain, in the case of flat terrain η = 1; ΔT – temperature difference between exhaust mixture and ambient air, °C; V_1 – exhaust mixture rate, m^3/s .

Dimensionless coefficient F is determined by deposition rate of particles. If data on the distribution of PM size are collected, in this case diameter d_g and appropriate deposition rate ω_g will be determined in a way that the mass of PM with a diameter greater d_g is 5% of the total PM mass [46]:

– F=1, if $\omega_g/U_m \leq 0.015$;

– F=1.5, if $0.015 \leq \omega_g/U_m \leq 0.030$;

– F=2.0 – 3.0, if $\omega_g/U_m > 0.03$,

where U_m–unfavorable wind velocity with taking into the emission purification factor (EPF): if EPF is at least 90%, F = 2; if EPF is in the range 75-90%, F=2.5; F = 2; if EPF is less than 75%, F=3.

The deposition rate of particles is calculated according to Stocks law [47]:

$$\omega_g = \frac{10^{-8} \cdot d_g^2 \cdot \rho \cdot g}{18 \cdot \mu} \qquad (7)$$

where: μ-dynamic viscosity of the air, g/cm·s.

So in dependence on deposition rate and wind velocity the coefficient F may be determined in wider range of their values (fig.5).

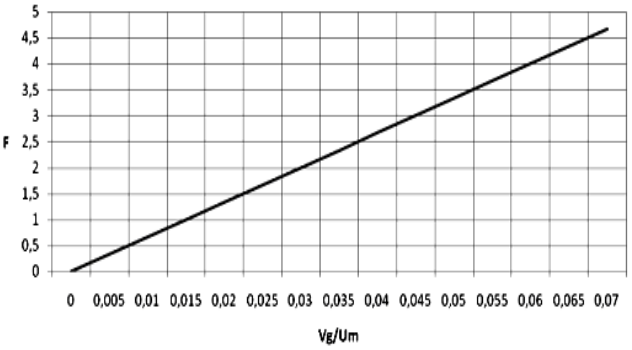


Fig. 5. Dependence of dimensionless coefficient F coefficient on v_g/u_m

It is important to note, that according to the equation of atmospheric diffusion (5), the concentration distribution of the passive pollutant (gas or PM) in atmosphere is determined by a coefficient of the turbulent exchange k_i and wind speed u_i. As established by numerous studies [47-49], one of the main characteristics of the surface layer is keeping the vertical fluxes of heat and momentum with height. However, the wind speed, temperature and turbulence are significantly changed with height. There is very clearly manifested the impact of atmospheric stability is directly related to the temperature stratification.

Overview of the boundary layer studies [50, 51] indicated a large number of models to determine the coefficient of turbulent exchange k_z and wind velocity u_w inside the surface and boundary layers.

Thus, for the calculation the pollutant concentration, it is almost enough to adopt, that [47, 50, 51]:

$$u = u_1 \frac{\ln z/z_0}{\ln z_1/z_0}$$

$$k_z = \nu + k_1 z/z_1 \quad \text{for } z \leq h, \qquad k_z = \nu + k_1 h/z_1 \quad \text{for } z > h \qquad (8)$$

where z_0 — the roughness of the underlying surface. So, k_z increases linearly with height z in the surface layer $z<h$ and remains constant for $z>h$.

Berlyand [47] found analytical solution of the equation (5) to calculate the maximum PM concentration from point emission source for the case, that the wind speed varies with power law and the coefficient of turbulent diffusion linearly increases (9).

$$u = u_1 \times z^n, \qquad k_z = k_1 \times z \qquad (9)$$

So, maximum concentration is calculated in following way for volatile (10) and non-volatile (11) PM [47]:

$$q_m = \frac{0.116 \times (1+n)^2 \times M}{u_1 \times H^{1.5\times(1+n)}} \sqrt{\frac{k_1}{k_o u_1}} \qquad (10)$$

$$q_{\omega m} = \frac{0.063 \times (1+n)^2 \times M}{u_1 \times H^{1.5\times(1+n)}} \sqrt{\frac{k_1}{k_0 u_1}} \frac{(1.5+\omega)^{1.5+\omega}}{\Gamma(1+\omega) e^{\omega}} \qquad (11)$$

where u_1 – wind velocity and k_1 – coefficient of turbulent diffusion at height z_1 both; n – temperature stratification of the atmosphere; M – emission rate; ω – deposition rate; H – height of the emission source.

Thus, if we know the expected values of wind speed, stability of the atmosphere and the value of emission rate, it is possible to predict the PM concentration. The dependence of the concentration on mentioned input data is characterized by the same trend for volatile and non-volatile PM.

Analysis of the expressions (6, 7) indicates that the concentration varies inversely proportional to the wind velocity u_1 and directly proportional to the vertical component of the turbulent exchange coefficient k_1/u_1. The impact of the horizontal component of the turbulent exchange coefficient is determined by $k_0=k_y/u$.

The distance x_m from emission point source, at which PM concentration will obtain the maximum value, is calculated according to formulas (8, 9) correspondingly for volatile and non-volatile PM [47]:

$$x_m = \frac{2}{3}\frac{u_1 H^{1+n}}{k_1(1+n)^2} \quad (12)$$

$$x_m = \frac{u_1 H^{1+n}}{k_1(1+n)^2(1.5+\omega)} \quad (13)$$

It was found, that the maximum concentration of nvPM ($q_{\omega m}$) is higher than volatile one (q_m), while the distance x_m is less. The difference in q_m and x_m values increases for volatile and non-volatile PM with increasing of particle deposition rate.

Concentration of non-volatile PM (q_w, q_{wm}) is related with concentration of volatile PM (q, q_m) by following way at the distance x from emission source with height H [47, 52]:

$$q_\omega = q\chi\left(\frac{\omega}{k_1}, \frac{k_1 x}{u_1}, H\right) \quad (14)$$

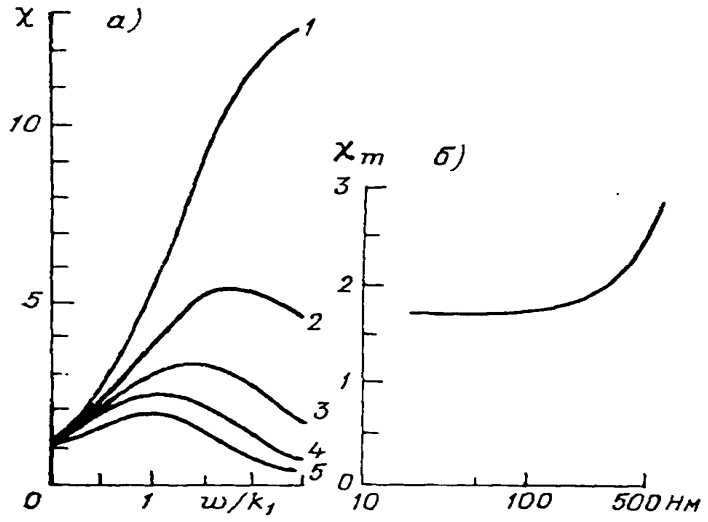
$$q_{\omega m} = q_m \chi_m\left(\frac{\omega}{k_1}, H\right) \quad (15)$$

Differences in concentrations of volatile and non-volatile PM are caused mainly by the dimensionless parameter w/k_1. At same value of ω the sedimentation rate of PM will be different depending on the atmospheric turbulence intensity. In strong turbulence, for example, in the case of well-developed convection, the differences in the sedimentation velocity ω are manifested mainly for large x.

The mentioned features for nvPM distribution are included by functions (χ, χ_m), which are determined by formula (16) on the basis of numerical solution of the equation (5):

$$\chi = \frac{\left[\frac{u_1}{(1+n)^2 k_1}\right]^{\omega} H^{\omega(1+n)}}{\Gamma(1+\omega)\times x^{\omega}} \quad (16)$$

Berlyand and Onikul [53] found the following dependences for χ and χ_m on ω/k_1 and height H (fig.).



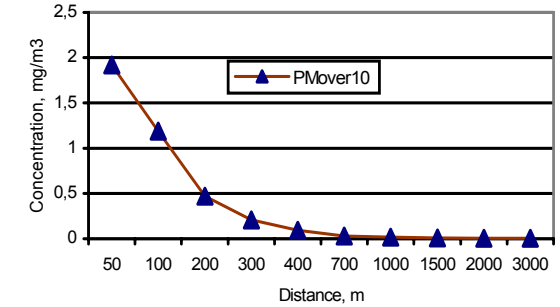
Curve	1	2	3	4	5
k_1x/u_1	300	400	500	600	700

Fig. 6. Dependence coefficients χ and χ_m on ω/k_1 and height H

Analysis of analytical and numerical investigations highlighted that the maximum concentration of nvPM is always higher and appropriate distance to the emission source is less than for volatile PM. Additionally, the dependence was obtained for χ_m on height H for $\omega/k_1 = const$. As it is shown in fig. 6, the χ_m is practically independent of the height of emission source, which are displayed in surface layer. However, for higher emission sources, the value of χ_m increases relatively quickly with height H.

In the National Aviation University (Kyiv, Ukraine) a complex model PolEmiCa has been developed [54], which is based on the Eulerian

approach to describe dispersion processes for the matter in atmosphere. Reason for choice of the Eulerian approach (principle difference of PolEmiCa dispersion model from Doc 9889 recommendation to use the Gauss model – Lagrangian approach) was defined by existing and widely used in USSR previously and in most of the FSU countries currently the national standard OND-86. The complex model PolEmiCa allow to calculate the inventory and dispersion parameters of the aircraft engine emission during the landing-takeoff cycle of the aircraft in airport area [55, 56]. In particular PolEmiCa was used to calculate the distributions of PM fractions for aircraft APU exhausts (height of installation was given H=4,5m like for Tupolev-154), the results are shown in comparison to gas emission (fig. 7, 8) and between themselves (fig. 9, 10). From fig. 7 and 8 there is evident higher concentration for PM close to the source of emission than for gas. Also, it may be concluded that PM polydispersity leads to the separation of maximums concentration in space for individual fractions on the wind direction and therefore it contributes to the reduction of maximum total concentration (fig. 9, 10 in comparison with fig. 7a, 8a correspondingly). The coefficient χ_m for the maximum of surface concentration is substantially *less dependent* on the source height H than in the case of monodisperse PM, but it is still somewhat increases with H, especially when h> 300m [47].



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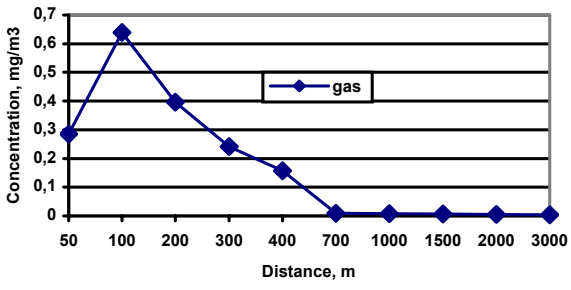
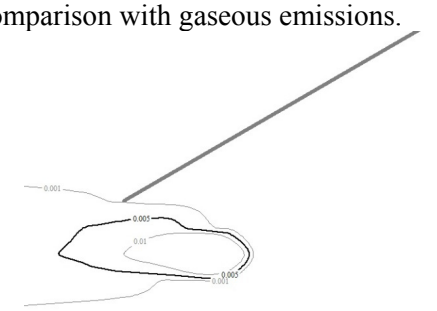


b)

Fig. 7. Longitudinal distribution of PM_{10} (a) and gas (b) emitted by APU of Tupolev-154 along wind axis

The PolEmiCa model is under the improvement of the modeling PM dispersion in the atmosphere with taking in mind the investigated mechanisms and properties of PM, which are quite different in comparison with gaseous emissions.



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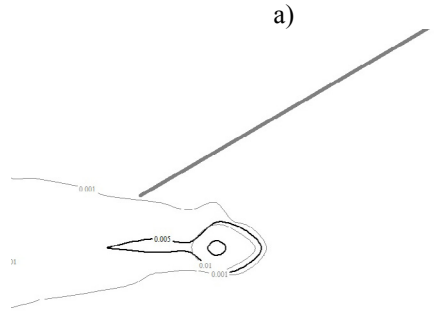

b)

Fig. 8. Area distribution of PM_{10} (a) and gas (b) emitted by APU of Tupolev-154 at stand close to runway (shown as direct line) in wind direction

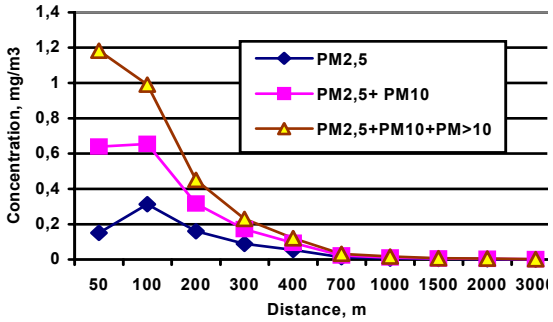

Fig. 9. Longitudinal distribution of polydispersed PM ($PM_{2,5}$, PM_{10} and $PM_{>10}$) emitted by APU of Tupolev-154 along wind axis

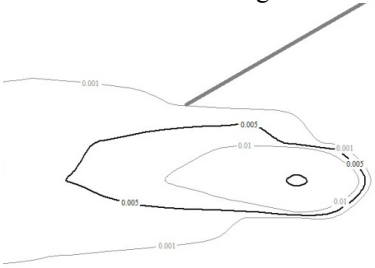

Fig. 10. Area distribution of polydispersed PM ($PM_{2,5}$, PM_{10} and $PM_{>10}$) emitted by APU of Tupolev-154 at stand close to runway (shown as direct line) in wind direction

7. **Conclusion**

Analysis of PM emission inventory results at major European and Ukrainian airports highlighted on sufficiently high contribution of aircraft engines and APU. Although the APU has contributed significantly to the emission of aircraft at airports, APU emissions are still not certificated by ICAO or any other responsible for that national or international authority. Information on APU emissions is quite limited by security and propriety requirements of the manufactures.

Analysis of numarous studies and experimental investigations allowed to evaluate mass, number and size of PM in exhausts from aircraft engines and APUs during the aircraft LTO operations.

The PolEmiCa model is under the improvement, including the modeling of PM dispersion in the atmosphere with taking in mind the investigated production mechanisms and properties of the PM, which are quite different in comparison with gaseous emissions.

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Викиди зважених часток від повітряних суден під час експлуатації в межах аеропорту

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Мета: Викиди авіадвигунів в межах приземного граничного шару під час етапів зльоту та посадки призводять до значного погіршення якості повітря в межах аеропорту та на прилеглих житлових територіях. На сьогодні, основними об'єктами забруднення повітря в аеропортах є оксиди азоту і зважені частки (ЗЧ10, ЗЧ2.5 і ультрадісперсні ЗЧ), які спричиняють виникнення відповідно фотохімічного смогу та туману з наступними несприятливими наслідками для здоров'я населення. Аналіз результатів інвентаризації викидів ЗЧ у головних аеропортах Європи вказує на домінантність викидів авіадвигунів та допоміжної силової установки. Стаття спрямована на аналіз теоретичних та експериментальних досліджень із розподілу часток за розміром у викидах авіадвигунів, а також особливостей їх морфології та внутрішньої структури, оскільки зазначені властивості мають важливе значення для розуміння потенційного впливу ЗЧ на здоров'я населення. Стаття також надає детальний опис основних методів розрахунку викидів та дисперсії ЗЧ від авіадвигуна протягом злітно-посадкового циклу повітряного судна. **Методи:** аналітичне розв'язання рівняння атмосферної дифузії використовується для розрахунку максимальної концентрації ЗЧ від точкового джерела емісії. Концентрація ЗЧ змінюється обернено пропорційно швидкості вітру u1 і прямо пропорційно вертикальній складовій коефіцієнту турбулентного обміну k1/u1. Оцінка концентрації нелетучої ЗЧ враховує розмір і форму ЗЧ. Модель PolEmiCa обчислює розподіл фракцій ЗЧ у викидах від авіадвигунів та ДСУ (висота установки H = 4,5 м для Ту-154). **Результати:** Максимальна концентрація ЗЧ у викидах ДСУ вища, а відповідна відстань менша, у порівнянні з випадком для газу. Полідисперсність призводить до розподілу максимумів концентрацій в просторі для окремих фракцій за напрямком вітру, що призводить до зменшення загальної максимальної концентрації. **Обговорення:** Хоча емісія ДСУ сягає рівня авіадвигунів, викиди ДСУ не сертифіковані ІСАО. Отже, зазначена проблема є актуальною для місцевої якості повітря, зокрема для розробки моделі та визначення методів виявлення складової викидів авіадвигунів і ДСУ у загальне забруднення повітря аеропорту ЗЧ.

Ключові слова: допоміжна силова установка; зважена частка; інвентаризації авіаційних двигунів; індекс емісії; забруднення повітря; моделювання забруднення атмосферного повітря; емісія авіаційних двигунів.

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Выбросы взвешенных частиц от воздушных суден при експлуатации в зоне аеропорта
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Цель: Выбросы авиадвигателей в пределах приземного пограничного слоя во время этапов взлета и посадки обуславливают существенное ухудшение качества воздуха в зоне аэропорта и близлежащих жилых районов. На сегодня, основными объектами загрязнения воздуха в аэропортах являются оксиды азота и взвешенные частицы (ВЧ10, ВЧ2.5 и ультрадисперсные ВЧ), которые обуславливают возникновение соответственно фотохимического смога и тумана с последующими неблагоприятными последствиями для здоровья населения. Анализ результатов инвентаризации выбросов ВЧ в главных аэропортах Европы указывает на доминантность выбросов авиадвигателей и вспомогательной силовой установки. Статья направлена на анализ теоретических и экспериментальных исследований относительно распределения частиц по размеру в выбросах авиадвигателей, а также особенностей их морфологии и внутренней структуры, поскольку указанные свойства имеют важное значение для понимания потенциального влияния ВЧ на здоровья населения. Статья также предоставляет детальное описание основных методов расчета выбросов и дисперсии ВЧ от авиадвигателя в течении взлетно-посадочного цикла воздушного судна. **Методы:** аналитическое решение уравнения атмосферной диффузии используется для расчета максимальной концентрации ВЧ от точечного источника эмиссии. Концентрация ВЧ изменяется обратно пропорционально скорости ветра u1 и прямо пропорциональна вертикальной составляющей турбулентного обмена коэффициента k1/u1. Оценка концентрации нелетучих ВЧ учитывает размер и форму частиц. Модель PolEmiCa вычисляет распределение фракций ЗЧ в выбросах от авиадвигателей и ВСУ (высота установки H=4.5 м для Ту-154). **Результаты:** Максимальная концентрация ВЧ в выбросах ВСУ выше, а соответствующее расстояние меньше, чем в случае для газа. Полидисперсность приводит к разнесению положений максимумов концентраций в пространстве для отдельных фракций по направлению ветра, что приводит к уменьшению общей максимальной концентрации. **Обсуждение:** Хотя эмиссия ВСУ достигает уровня авиадвигателей, выбросы ВСУ не сертифицированы ИСАО. Таким образом, эта проблема актуальна для местного качества воздуха, в частности для разработки модели и определения методов выявления составляющей выбросов авиадвигателей и ВСУ в общее загрязнение воздуха аэропорта ВЧ.

Ключевые слова: вспомогательная силовая установка; инвентаризация выбросов авиационных двигателей; индекс эмиссии; загрязнения воздуха; моделирование загрязнения атмосферного воздуха; эмиссия авиационных двигателей.

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