Emission sources at airports and compressor stations have the potential to emit pollutants, the effects of which can degrade local air quality. In most cases, the basis of gas pumping units includes either aircraft engines that have exhausted their flight life, or their targeted modifications to fulfill the tasks of gas pumping units and compressor stations in various gas transportation systems.

The methodology for calculating the concentration of pollutants contained in the emissions of enterprises does not take into account all possible features of emission sources, in terms of passive stationary sources and cold emissions, the algorithm of the methodology requires clarification and the justifications given in the article indicate possible ways of clarification.

According to the decision of the CAEP SG-2020 Coordination Meeting "detailed documentation for the Ukrainian POLEMICA air quality model provided in CAEP/12-FESG-MDG/2-WP/09 should be considered as the final documentation for verifying this model for compliance with ICAO document 9889 requirements". The results of calculating the maximum concentration for the test scenario using Gaussian models, verified in CAEP, differ by almost 2 times. A similar result according to the PolEmiCa model ~ 1.5 μg/m^3 is almost two times less, which is due to the inclusion of the effects of the initial rise in the emission of the mixture from a stationary source into the algorithms of the OND-86 method

Keywords: pollutants, airport, compressor stations, gas turbine plants, gas pumping units, emission

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IMPROVEMENTOF THE COMPUTER MODEL OF AIR POLLUTION ESTIMATION DUE TO EMISSIONS OF STATIONARY SOURCES OF AIRPORTS AND COMPRESSOR STATIONS

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1. Introduction

Today, there is growing concern about the impact of aviation on local air quality and the corresponding implications for human well-being and health. The impact of aviation emissions on air quality at the local and regional levels should be assessed as a component of the total impact of all emission sources operating in a particular area. The urgency of the problem of local air quality is confirmed by international and national requirements. Thus, one of the decisions of the ICAO A39-1 Assembly is aimed at limiting or reducing the emissions of international aviation aircraft that affect local (local) air quality, in particular, due to the use of voluntary measures.

The International Civil Aviation Organization (ICAO) has been dealing with air emissions and air quality at airports for many years [1]. The Committee on Aviation Environmental Protection (CAEP) of ICAO began an ongoing review of emission standards for new types of aircraft engines, their modifications and new generation engines produced in the late 1970s [2]. In addition to considering technological innovations and developing certification requirements, CAEP is also handling several other promising avenues for solving the problem of aviation emissions and air pollution in and around airports, namely:

a) alternative operational mitigation measures for use at aerodromes and en-route [3, 4];

b) justification of the sanitary protection zone (SPZ) of the aerodrome based on the conditions of emission and air pollution [3];

c) it is possible to use market measures to reduce emissions [5], etc.

Part 2 of ICAO 9184 [3] provides guidance material for land-use planning in the vicinity of airports and information on the opportunities available to reduce airport emissions and improve the fuel efficiency of aircraft engines. Emission sources at airports are capable of emitting pollutants (pollutants), the impact of which can lead to a deterioration in air quality in nearby settlements [6].

The actual concentration of contaminants can be determined by measurement (eg temporary targeted sampling and/or continuous monitoring), although in this case it is impossible to exclude the influence of other sources of emissions, including sources not related to airport operations. To assess the actual, retrospective or

prospective levels of air pollution, the results of computer modeling can also be used for the given parameters of the external environment [7–9].

Compressor stations (CS) and individual gas pumping units (GPU) of gas transmission systems (GTS) are very similar to the sources of air pollution in the airport area [10]. In most cases, the GPU and the compressor station are based on either aircraft engines that have exhausted their flight life, or their targeted modifications to perform the tasks of the gas compressor unit and compressor station in different hydraulic structures [11]. Up to 90 % of the GPU park in operation does not meet the requirements of sanitary standards for emissions and noise. Noise, first of all, has a depressing effect on the operating personnel of the compressor station and residents of nearby areas, which, as a result, lose their health and efficiency. Chemical pollution of atmospheric air during the operation of gas compressor units and compressor stations is caused by the following processes:

1. Gas leaks through leaky pipe connections, through shut-off valves, as well as through microcracks and holes in the gas transmission pipe.

2. Emissions of large volumes of natural gas into the atmosphere in emergency situations accompanied by damage to the gas pipeline, or when repair and construction work is carried out on the pipeline, compressor station or a separate gas compressor unit.

3. Emissions of contaminant-products of natural gas combustion from the GPU, under normal operating conditions on the territory of the compressor station. Although the products of natural gas combustion also occur during emergency pipe ruptures with subsequent gas combustion.

The most serious source of air pollution in the area of the CS is the emission of natural gas combustion products from GPU. Individual GPUs and compressor stations are the main constant sources of pollution in the GTS. This is where the largest number of different equipment designed to ensure the technological process of gas transportation is concentrated. The composition of the CS usually includes the objects of the technological zone of the GPU and related technological installations for gas purification, liquid collection units, gas cooling, condensate collection tanks and others. There are also a number of ancillary facilities diesel power plants, boilers, repair shops, etc. According to the existing classification, the emission sources on the CS are divided into GPU, fuel storage facilities and various tanks, boiler rooms, etc. Among them are organized and unorganized, heated and cold, and mobile (means of transport) sources of contaminant emissions.

In general, the work of the CU is accompanied by the release into the atmosphere of about 20 names of the main contaminants, including 4 groups of substances, which are characterized by the effect of summation [12]. When operating normally, air emissions have the greatest impact on air quality. They account for about 98 % of all gross emissions from stationary CS sources. The fuel gas of such units accounts for up to 80 % of the total cost of the CS's own technological needs.

Receipt of contaminants into the atmosphere occurs during start-up, during operation and when stopping the GPU. The main organized sources of GHG emissions during the operation of the GPU are the exhaust pipes (mines), through which the combustion products of natural gas, which is burned in the combustion chamber of the gas turbine unit (GTU) GPU, enter the air. These include nitrogen oxides, carbon oxides, hydrocarbons, including benzo (a) pyrene, and other substances. The amount of contaminants emitted varies depending on the type of GPA (GTU) in a fairly wide range. Thus, the maximum emission power of nitrogen oxides is characterized by GT-750-6 (15.5 g/s), and the minimum – GPA-C-6.3 (3.04 g/s). In terms of carbon monoxide emissions, the maximum values are typical for GTN-25 (39.2 g/s), and the minimum values are typical for GPU-16 (0.73 g/s) [12].

In accordance with the requirements of GOST R 54404-2011 [13], the requirements for NO_x and CO emissions in exhaust gases have been established for gas turbines. For power gas turbines, according to GOST R 54403-2011 [14], the NO_x content (in terms of NO_2) in the exhaust gases of the gas turbine when operating on gaseous fuel with a load of 0.5 1.0 nominal should not exceed 50 mg/m^3 and 100 mg/m^3 on liquid fuel. For new GTUs, the NOx content in exhaust gases should not exceed 50 mg/m^3 for gaseous fuel and 100 mg/m^3 for liquid fuel; there are no requirements for CO concentration [12–14].

The storage of petroleum products at the compressor station is carried out at the storage facilities of fuels and lubricants (FL), usually distributed among the shops. The release of vapors of petroleum products into the atmosphere occurs from the breathing valves of storage tanks (small breathing), as well as from the ventilation systems of the premises of fuel and lubricants storage. The main volume of pollutant emissions into the atmosphere from the evaporation of oil products in tanks occurs due to the displacement of the gas-air mixture from the tank during its filling (big breath).

Thus, both for airports and for compressor stations, there is a wide range of stationary sources with different parameters of the organization of emission into the atmosphere. The current normative methodology OND-86 [15] does not cover the entire range of emission parameters possible for airports and CS, or limits its application, or causes an incorrect calculation result. Therefore, the study of the conditions for the functioning of stationary sources of airports and CS is an urgent task, and as a result, the determination of restrictions on the application of the normative method for assessing concentrations in the atmospheric air and the development of proposals for its new calculation algorithms will apply to the characteristic conditions for stationary sources of airports and CS.

2. Literature review and problem statement

Calculations show [12] that nitrogen oxides NO and NO_2 are, as a rule, the main contaminants for CS, both in terms of the emission power and the volume of annual gross emissions, followed by methane emissions CH_4, and third by CO. So, first it is necessary to develop measures aimed at reducing NO_x emissions, and only then – at reducing methane and carbon monoxide emissions [14]. The transport and dispersion of impurities in a turbulent atmosphere occurs due to large-scale, two-dimensional movements of streams (wind transport) and small-scale, three-dimensional, turbulent pulsations, including from stationary and mobile sources of the airport [16, 17]. The analysis of studies on the theory

of atmospheric diffusion [18–20] was carried out to improve the normative methodology [15] for calculating the spread of pollution in the atmospheric air, taking into account the effect of stratification on the mechanisms of atmospheric diffusion. To describe atmospheric diffusion, the necessary information about the vertical profile of the wind and the statistical characteristics of the turbulent velocity field under various conditions of atmospheric stratification [17]. So, under the conditions of stable atmospheric stratification, turbulent diffusion occurs slowly, and pollution is carried by the wind, almost not dissipating. Under convection conditions (unstable stratification), on the contrary, turbulent diffusion occurs intensively and causes rapid dispersion of impurities [17]. Underlying earth's surface significantly affects the nature of atmospheric diffusion. Pollution can either be retained by the surface – "absorption" (a decrease in concentration compared to the conditions of a free environment), or "reflected" from it (correspondingly, an increase in concentration), or possible intermediate cases of a combination of "reflection" and "absorption". Accordingly, in the mathematical formulation of the boundary conditions for atmospheric diffusion near the earth's surface, it is necessary to take into account the degree of its roughness and the ability to absorb (reflect) impurities of the contaminants [17]. In all of the above cases, the decisive factor for assessing the concentration is the height of the emission into the atmospheric air – both the geometric height of the mouth of the source of the emission H and the height of the ascent of gases ΔH_{ef} more than the mouth due to the gas flow rate $w_0=V_1/(\pi D^2/4)$, so the temperature of gases T_g in the section of the mouth, where V_1 is the volume of gases, flows out of the mouth of the source per unit of time, D is the diameter of the mouth. The determining factor for the concentration is the value of the effective height $H_{ef}=H+\Delta H_{ef}$. The range of values of the velocity w_0 and the gas leak temperature T_g for stationary sources of airports and CS is wide, starting from the conditions of a neutral (or passive) plume of gas emission, when the height of the ascent of gases ΔH_{ef} is absent, that is, the effective height H_{ef} is equal to the geometric height H of the emission source, then there is a mixture of gases in the plume that is neither lighter nor heavier than the air around the source. The maximum value of the surface concentration of a harmful substance cm (mg/m^3) when a gas-air mixture is emitted from a single point source with a round mouth of the OND-86 method [15] is achieved under unfavorable meteorological conditions at a distance of X_m (m) from the source and is determined by the formula

$$c_M=\frac{A\cdot M\cdot F\cdot m\cdot n\cdot \eta}{H^2\cdot \sqrt[3]{V_1\Delta T}}, \quad (1)$$

where A – coefficient that depends on the temperature stratification of the atmosphere; M (g/s) is the mass of a harmful substance emitted into the atmosphere per unit of time; F – dimensionless coefficient that takes into account the sedimentation rate of harmful substances in the atmospheric air; m and n are coefficients. taking into account the conditions for the exit of the gas-air mixture from the mouth of the emission source; H (m) – height of the emission source above ground level; η – dimensionless coefficient taking into account the influence of the terrain, with equal or slightly rugged terrain η=1; ΔT (°C) – the difference between the temperature of the discharged gas-air mixture T_g and the temperature of the ambient atmospheric air T_a; V_1 (m^3/s) – the volume of gases flowing out of the source mouth. The values of the coefficients m and n are determined depending on the parameters f, υ_m, $\acute{\upsilon}_m$ and f_e.

$$f=1000\frac{\omega_0^2 D}{H^2\Delta T};$$

$$\upsilon_i=0{,}65\sqrt[3]{\frac{V_1\Delta T}{H}};\upsilon_i'=1{,}3\frac{\omega^2 D}{H};f_\varepsilon=800\left(\upsilon_i'\right)^3. \quad (2)$$

The coefficient m is determined depending on f by the formulas:

$$m=\frac{1}{0{,}67+0{,}1\sqrt{f}+0{,}34\sqrt[3]{f}}$$

at

$$f<100;\ m=\frac{1{,}47}{\sqrt[3]{f}}\ \text{at}\ f\geq 100. \quad (3)$$

For $f\geq 100$ (or $\Delta T\approx 0$) and $\acute{\upsilon}_m\geq 0.5$ (cold emissions), when calculating c_M, instead of formula (1), the formula is used

$$c_M=\frac{A\cdot M\cdot F\cdot n\cdot \eta}{H^{4/3}}K$$

where

$$K=\frac{D}{8V_1}=\frac{1}{7{,}1\sqrt{\omega_0 V_1}}. \quad (4)$$

Similarly, for $f<100$ and $\upsilon_m<0.5$ or $f\geq 100$ and $\acute{\upsilon}_m<0.5$ (cases of extremely low dangerous wind speeds), the calculation cm instead of (1) is performed according to the formula

$$c_M=\frac{A\cdot M\cdot F\cdot m'\cdot \eta}{H^{7/3}}, \quad (5)$$

where $m'=2.86\ m$ at $f<100$, $\upsilon_m<0.5$; $m'=0.9\ m$ at $f\geq 100$, $\acute{\upsilon}_m<0.5$.

The main source of pollutant emissions at the mine compressor station is exhaust gas leakage from individual gas turbine units or compressor shops. In many cases, the mouths of these mines are equipped with deflectors, including for protection from atmospheric precipitation. This causes a change in the flow velocity vector at the pipe mouth to horizontal (or at a certain angle to the horizontal) from vertical, that is, the volume of gases flows out of the source mouth, $V_1>0$, and the vertical component of this flow velocity $w_0=0$. Vertical gas transport occurs only due to thermogravitational convection, which occurs in the gravitational field under the influence of the temperature difference ΔT due to the force of Archimedes. That is, in the mines of gas leakage of GPU there is always an ascending flow of gases in the air, because $T_g>T_a$. For so-called cold emissions (provided $T_g<T_a$), a downward flow, for example, from air conditioners, can be observed. The normative method for calculating concentrations from stationary emission sources [15] does not take into account such conditions, its basic formula for determining the maximum concentration when the velocity values approach zero $w_0\to 0$ and the gas leakage temperature to the ambient air temperature $T_g\to T_a$ causes an increase in the concentration in See Parameters f, υ_m, $\acute{\upsilon}_m$ and f_e (2) are calculated for the values of the vertical velocity w_0 and the excess of the gas leakage temperature ΔT, which can physically be zero. The formulas of the

normative methodology [15] provide for an assessment either for conditions of cold emissions or extremely low dangerous wind speeds, but the presence of a volume (speed) of gas flow at the pipe mouth, the use of formulas (4), (5) looks unreasonable. There is a need to expand the methodological base for assessing concentrations to take into account all of the above conditions. The work [16] presents the results of studies from numerous, analytical and statistical methods for assessing atmospheric air pollution based on the Gauss model. This model is the most common for the purpose of assessing the local air quality of airports, as shown in the ICAO guidelines [9]. The vertical and lateral (downwind) dispersion of the plume is determined from a Gaussian distribution and also includes the effect of plume reflection from the earth's surface.

The Lagrange method is quite versatile, since it allows one to study the propagation of impurities from sources of different types for different characteristics of the environment. This circumstance is quite significant for the practical application of the results of the given empirical-statistical theory to predicting the air pollution, taking into account the expected change in meteorological conditions. However, if the contaminant ingredients are reactive impurities, Lagrange's approach is completely unsuitable for investigating the diffusion of these impurities. In this case, it is correct to use Euler's method, which is more universal. The dispersion models of OR in ambient air used in the calculations of local air quality were evaluated within the framework of the activities of the Committee on Aviation and Environmental Protection (CAEP) of the International Civil Aviation Organization (ICAO), taking into account their technical capabilities and reliability. So, the ADMS-Airport 5.0, AERMOD, LASPORT 2.3, and PolEmiCa models are involved in test feasibility studies on local air quality metric for the airports organized by modelling and database group (MDG) Committee on Aviation Environmental Protection (CAEP). The above models apply various methodologies, assumptions and limitations, for example, imposed by national regulations [15, 17]. In particular, the domestic model PolEmiCa for assessing the air quality from pollutant emissions from stationary sources uses the algorithms of the OND-86 method [15]. Therefore, one can expect differences in the results of calculating the variance between the models involved in studies on local air quality metric based on concentrations derived from dispersion calculation for some set airports, despite using the same set of input data. Verification of the improved method/model PolEmiCa [21] for calculating local air pollution at airports and their surroundings for compliance with the requirements of the ICAO guidelines [9] was carried out. By the decision of the CAEP SG-2020 Coordination Meeting the Ukrainian model of air quality PolEmiCa had been considered as the final documentation for the verification of this model for compliance with ICAO requirements document [9]». However, the OND-86 methodology [15] does not take into account all possible features of stationary emission sources, in particular with regard to cold emissions and passive stationary sources. Therefore, improving models for assessing air pollution by emissions from stationary sources of airports and compressor stations is an urgent task. Thus, the work is devoted to the study of the quality of the operating parameters of the sources of pollutant emissions in the area of the airport and compressor station, and their impact on the local air quality. The main purpose of the study is to test and compare various models of stationary emission sources and assess air quality based on them.

3. The aim and objectives of research

The aim of research is to improve the models for assessing air pollution by emissions from stationary sources of airports and compressor stations by taking into account the parameters of emission sources and the peculiarities of the formation and dispersion of emissions by wind and atmospheric turbulence.

To achieve the goal, the following tasks were set:

– calculate the maximum surface concentration along the averaged axis of the plume and the maximum transversely integrated concentration for the conditions of the test scenario based on the recommended ICAO models [9] and reveal the dependences of these concentrations on the distance to a stationary high-altitude source;

– calculate the maximum surface concentration along the averaged axis of the plume and the maximum transversely integrated concentration for the same test scenario conditions using the PolEmiCa model and make recommendations for its improvement.

4. Materials and methods of research

The model of a Gaussian continuous floating plume of pollutant impurities (PO) is the basis for most of the models verified by ICAO/CAEP for compliance with the requirements and recommendations of the ICAO manual 9889 [9]. The vertical and lateral dispersion of the plume is determined from a Gaussian distribution and also includes the effect of plume reflection from the earth's surface. Analyzed the analytical and numerical solutions of the Gauss model for assessing the dispersion of pollutants from stationary high-altitude sources.

Based on the initial conditions were formed by MDG CAEP to study local air quality metric for the airports, for the purposes of test comparative studies of the PolEmiCa model, developed in Ukraine [21, 22], which, in terms of calculating stationary sources, uses the algorithms of the normative method OND-86 [15]. The test scenario is based on the results of experimental studies in a wind tunnel, that used by MDG CAEP to validate modeling results for a passive point source is considered at a height of 60 m above the earth's surface at the point x=0 m, h=0 m; mass emission rate Q=1 g/s NO_x, no chemical transformation and no contaminant deposition; wind speed at the height of the mixture ejection from the source U_w=10 m/s; Obukhov's length is *infinity* (that is, the conditions for *neutral* stratification of the atmosphere); surface roughness length z_0=0.7 m, displacement height (to determine the wind speed profile) is absent; the stationary concentration distribution at a height of 1.5 m above the earth's surface is estimated. In Fig. 1 (corresponds to Fig. 1 in MDG CAEP report of modeling results for 3 tests of stationary sources) shows the experimental results (squares) and the red line shows the calculated result using a simplified model for estimating the concentration for the emission of a light impurity of contaminants from a stationary point source [17] for a transversely integrated concentration on the earth's surface z=0 m.

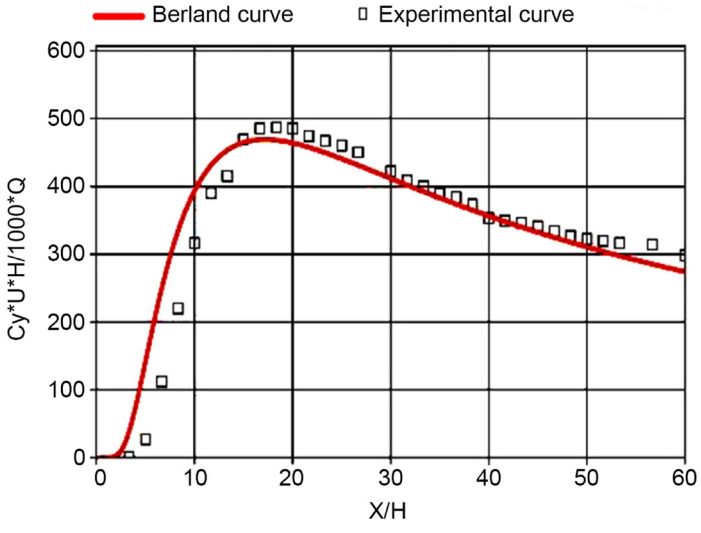

Fig. 1. Scalable, transversely integrated concentration values at ground level (z_0=0): results of experiments with a wind tunnel (squares) from MDG CAEP report for 3 simple test cases]; the red line is calculated by the formulas of the simplified analytical solution [17]

In the case when the wind speed profile is determined by a step law and the vertical diffusion coefficient is a linear function of the height:

$$u(z)=u_H(z/H)^n;\ K(z)=K'\cdot z$$

analytical solution of the atmospheric diffusion equation for the transversely integrated concentration (according to formulas (8)–(10) in [20]):

$$c_y(x)=\frac{Q}{x(1+n)K`}\exp\left(-\frac{Hu_H}{x(1+n)^2K`}\right). \quad (6)$$

The maximum of the transversely integrated C_y concentration is located in the coordinate:

$$x=(Hu_H)/(x(1+n)^2K^{(`)}), \quad (7)$$

namely, the maximum concentration value is equal to:

$$c_{y,max}=(1+n)e^{-1}\frac{Q}{Hu_H}, \quad (8)$$

where in formulas (6)–(8) to calculate the concentrations, the values of the exponent n=0.27, the wind speed at the discharge height u_H=10.0 m/s and the exchange coefficient K'= 0.36 m/s were used. The results are shown in Fig. 1 with a red line.

5. Results of the study of models for assessing air pollution by emissions from stationary sources of airports and compressor stations

5. 1. Analysis of analytical and numerical solutions of the Gauss model

A simplified formula for the concentration distribution c (x, y, z) of a Gaussian plume, which provides a description of the plume from a stationary source, both high-altitude and located on the earth's surface, is recommended for use in (9):

$$c(x,y,z)=$$
$$=\frac{Q}{2\pi u}\exp\left[\frac{y^2}{2\sigma_y^2}\right]\left\{\exp\left[-\frac{(z-H)^2}{2\sigma_y^2}\right]+\exp\left[-\frac{(z+H)^2}{2\sigma_z^2}\right]\right\}, \quad (9)$$

and between the parameters of the Gaussian plume σ_y, σ_z and the coefficients of turbulent exchange (turbulent diffusion) in the atmospheric air, the usual relationships are applied:

$$\sigma_y(x)=\sqrt{2K_yx/\bar{u}},\sigma_z(x)=\sqrt{2K_zx/\bar{u}}, \quad (10)$$

where Q is the value of the magnitude of the release of the contaminant impurity into the air from the source, H is the height of the emission source, ū is the averaged wind speed, and K_y and K_z are some duly determined horizontal and vertical coefficients of turbulent atmospheric diffusion.

Maximum concentration (1) along the OX axis (y=0) at the ground level (z=0):

$$C_x=\frac{Q\,2}{2\pi\bar{u}\sigma_y\sigma_z}\exp\left[-\frac{H^2}{2\cdot\sigma_z^2}\right]=$$
$$=\frac{Q}{2\pi x\sqrt{K_yK_z}}\exp\left[-\frac{H^2\bar{u}}{4\cdot K_zx}\right]. \quad (11)$$

If in (11) to take as constants:

$$a=\left(\frac{H^2\bar{u}}{4/K_z}\right);\ b=\frac{Q}{2/\pi}(K_yK_z)^{1/2},$$

then the maximum for the transversely integrated concentration C_y will be at the point that is the solution to the equation describing the first derivative of the function $bexp(-a/x)/x$ equated to zero. The solution to this equation is: x=a, that is

$x_{max}=H^2$ ū $/4/K_z$,

$$C_{x\max}=\frac{Q}{2\pi x_{\max}\sqrt{K_yK_z}}\exp\left[-\frac{H^2\bar{u}}{4\cdot K_z x_{\max}}\right]=$$
$$=\frac{2Q}{\pi H^2\bar{u}}\sqrt{\frac{K_z}{K_y}}=\frac{2Q}{\pi H^2\bar{u}}\frac{\sigma_z}{\sigma_y}. \quad (12)$$

The results of calculating the maximum concentration and its coordinates using formulas (12) for the parameters of the test scenario are summarized in Table 1 for options:

1) the wind speed at a height of 10 m is the same along the height and is equal to 10 m/s;

2) the wind speed at a height of 10 m is 10 m/s, the averaged value along the height in accordance with the step law and the exponent 0.27 is 2.42 m/s.

The solution for the transversely integrated concentration along the mean axis of the plume, which does not depend on the horizontal width of the concentration distribution on the earth's surface:

$$c_y(x)=\int_{-\infty}^{\infty}c(x,y,0)\mathrm{d}y, \quad (13)$$

is the following formula (14) for the maximum value of the transversely integrated concentration according to approach which is used by MDG CAEP in studies on local air quality metric for the simple test cases:

$$c_{y,\max}=\sqrt{\frac{2}{\pi e}}\frac{Q}{H}, \quad (14)$$

generated in the coordinate:

$$x_{max}=\frac{H^2\hat{u}}{2K_z}. \quad (15)$$

For the Gaussian stationary plume model (1) and for the maximum transversely integrated concentration (14), after substituting the values of the emission and source height proposed in the test scenario, let's obtain the results of calculation option 2 in Table 1 for the averaged value of the wind speed and the diffusion coefficient along the height of the emission source H for the exponent n=0.27 in the power-law formula for the wind profile, as suggested in MDG CAEP report for 3 simple test cases.

Then, the dimensionless scaled value of the transversely integrated concentration C_y of the distribution in the stationary loop is approach, which is used by MDG CAEP in studies on local air quality metric for the simple test cases:

$$C_y(x)=C_y(x)\frac{HU}{Q}, \quad (16)$$

and the dimensionless coordinate of the formation of the concentration maximum x/H, where the velocity in the scaling procedure U is set as the wind speed at the source height H.

In [17], a solution to the atmospheric diffusion equation was obtained for the emission of a light admixture of contaminant from a stationary point source of the form:

$$q(x,y,0)=\frac{M}{2(1+n)k_1}e^{\frac{u_1H^1+n}{(1+n)^2k_1x}\frac{y^2}{4k_0x}}, \quad (17)$$

where the wind speed u_1 and the turbulent diffusion coefficients k_1 and k_0 correspond to the height z_1=1 m, and the value $M=Q$ and n=0.27, as suggested in [20]. The results of their calculation by the PreMeteo meteorological preprocessor of the PolEmiCa program: u_1=0,8 m/s; k_1=0,06 m/s; k_0=0,36 m/s. It can be seen that the maximum of the transversely integrated concentration C_y, max (14) and its coordinate (15) were obtained for this dependence of the ground concentration, if to set the height z_1 equal to the unit of length. The values of the maximum concentration q for dependence (17) q_m and x_m are found from the condition:

$$\frac{dq}{dx}=\frac{dq}{dy}=0:$$

$$q_m=\frac{0.116(1+n)^2M}{u_1H^{1.5(1+n)}}\sqrt{\frac{k_1}{k_0u_1}}, \quad (18)$$

$$x_m=\frac{2}{3}\frac{u_1H^{1+n}}{k_1(1+n)^2} \quad (19)$$

Their numerical values are entered in the row of calculation variant 4 in Table 1.

The numerical solution for the transversely integrated concentration C_y for the solution (16) for a light impurity in the atmospheric air is emitted by a point source at a height of H=60 m, shown in Fig. 2. The difference in the results of calculating the transversely integrated values of the C_y concentration in Fig. 1 and 2 can be explained by using values for wind speed u1 and turbulent diffusion coefficients k1 i k_0 at height z_1=1 m in formula (17) and at height H=60 m in formulas (8), (9). Including the position of the $S_{y\max}$ maximum differs x_{max}/H=16.65 for formula (19) from the measured value in Fig. 2 – 24.8. When scaling, the wind speed was taken as 10 m/s, as in MDG CAEP report.

Table 1

The results of calculating the maximum concentration and its coordinates

Calculation options	u, m/s	K, m^2/s	$X_{\max}$, m	$X_{\max}$/H	$C_{x\max}$, mg/m^3	$C_{y\max}$, mg/m^3	$C_{y\max}$Hu/Q
1	2.42	1.90	1146.30	19.1	0.0093	–	–
2	1.90	3.60	1033.34	17.22	–	0.779	467.4
3	1.90	3.60	–	–	–	4.24	2543.4
4	–	–	998.88/1490.00	16.65/24.8	0.044	3.22	1933.0
5	0.80	0.06	1498.25	24.97	–	2.5372510	1522.35
6	10.00	0.36	3121.35	52.02	–	0.2029801	121.79
7	2.42	0.36	593.92	9.90	–	1.0667590	640.06

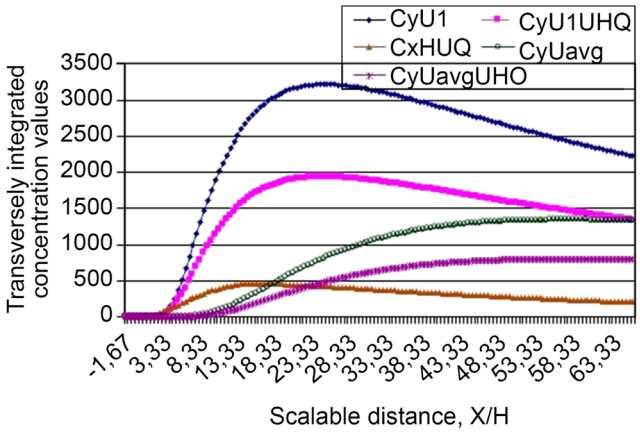

Fig. 2. The transversely integrated concentration valuesat the ground level (z_0=0) and their scalable value for the analytical solution [17] are determined by the computational method (C_y is presented in terms of g/m^3, the magnitude increased by 10^6 times): *a* – for the speed at level 1 m – blue rhombus; *b* – for the average velocity along the height of the emission source – blue circle; *c* – scalable analytical solution (8) – brown triangle; *d* – scalable computed solution (12) for speed at the level of 1 m – pink square; *e* – scalable computed solution (12) for the averaged velocity along the height of the ejection source – purple cross

From the x axis in the transverse direction to the axis, the concentration decreases exponentially symmetrically, and this decrease slows down with increasing x. The main part of the OP impurity in the atmospheric air is thus concentrated in a relatively narrow gas plume from the ejection of the source, the axis of which is directed along the x axis (y=0). From the calculations performed [17] for the maximum concentration and its coordinates it follows approximately:

$$q_m = C_1 \frac{M}{u_1}\sqrt{\frac{k_1}{u_1 k_0}}\frac{1}{H^{(3_1)}}, x_m = C_2 \frac{u_1}{k_1} H^{1+3_1}, \quad (20)$$

where C_i, β_i (i=l, 2) are constants, which, as studies have shown, depend relatively little on H and z_o. At H=100 m and z_o=0.01 m, the value β_1=1.9 and β_2=0.2, a C_1=0.15 and C_2=0.5 [17]. The values of these quantities are close to the values of the corresponding quantities in (18) and (19) at n=0.15–0.2. The step function describing the wind speed profile with such a value of the exponent is close to the logarithmic dependence for the wind speed profile (at z_o=0.01 m), the exponent at H in (18) in this case is 1.7–1. 8.

To determine the ground concentration q at other values of the coordinate of the second, not equal to xm, the ratio between q/q_m and x/x_m can be used:

$$\frac{q_y = 0}{q_m} = f\left(\frac{x}{x_m}\right) e^{2/3\left(1-\frac{x_m}{x}\right)} \left(\frac{x_m}{x}\right)^{3/2}, \quad (21)$$

Thus, analytical solutions (18)–(21) can be used as the basis for the model for calculating the concentrations of pollutants in the atmospheric air, which are formed as a result of emission from a stationary source in the absence of data on temperature and emission volumes.

Nevertheless, the question of the influence of the duration of the observation time, to which the concentrations obtained as a result of the solution of the diffusion equation, belong, is of significant importance. This influence is associated with the need to study the relationship between calculated and measured concentrations. When determining the content of the contaminant impurity in the air experimentally, the concentration values depend on the sampling time. The results of the impact of air pollution on the environment (on living organisms, vegetation, various coatings, etc.) are determined not only by the concentration of contaminant impurities, but also by the duration (i. e., exposure) of exposure. Depending on the properties of impurities and the duration of their action, the corresponding maximum permissible concentrations (MPC) are set, including the maximum one-time MPC is set for a time interval of 20 minutes.

In particular, for a light impurity (w=0), when the exchange coefficient k_z increases linearly with height, and the wind speed u changes according to a stepwise law, using solution (17), in [17] a formula was obtained for calculating the concentration taking into account the duration of the observation time :

$$\overline{q} = \frac{M}{(1+n)k_1\varphi_0 x^2\sqrt{2\pi}}\, e^{-\frac{u_1 H^{1+n}}{k_1(1+n)^2 x} - \frac{y^2}{2\varphi_0^2 x^2}}. \quad (22)$$

It should be noted that in this formula the coefficient k_o in comparison with (17) turned out to be excluded and instead of it the value ϕ_0 – the dispersion of the wind direction for the observation period (determination of concentration) T.

Accordingly, the expression for the maximum concentration q_m and the distance x_m, at which it is attained changes.

$$\overline{q}_m = \frac{0.216 k_1 (1+n)^3 M}{\varphi_0 u_1^2 H^{2(1+n)}}; \overline{x}_m = \frac{u_1 H^{1+n}}{2k_1(1+n)^2 x}. \quad (23)$$

Expressions (22) are similar to formulas (18) and (19) for concentration q_m and distance x_m. However, taking into account the effect of observation time - concentration

averaging — the values of the maximum concentration and the distance where it is reached decrease, and the degree of dependence of the maximum concentration on H turns out to be much higher.

It is necessary to calculate the transversely integrated concentration C_y to express the 2030 minute concentration (22), similarly to the instantaneous concentration (17). The transversely integrated concentration C_y was obtained in the form of formula (13) and, similarly, the value of the concentration C_y depends on the solution of the integral of the form

$$\int_{-\infty}^{\infty} \exp\left[-\frac{y^2}{2\cdot\phi_0^2\cdot x^2}\right]dy = \int_{-\infty}^{\infty} \exp\left(-\frac{y^2}{a}\right)dy,$$

where $a=2x^2\phi_0^2$.

Then the maximum of the transversely integrated concentration C_y will be in the coordinate:

$$x_{\max} = \frac{H^{1+n}\,u_1}{(1+n)^2 K_1} \qquad (24)$$

that is similar to formula (14), but not equal to it, and the maximum value of the transversely integrated concentration for the Gaussian tail (12) after substitution of the solution for the coordinate $\boldsymbol{x_{max}}$ will be

$$C_{y\max} = \frac{Q(1+n)}{eu_1\cdot H^{1+n}}, \qquad (25)$$

which is similar to formula (15), but not equal to it.

Compared to the maximum for the instantaneous transversely integrated concentration (14), (15), the solutions for 20—30-minute concentration (24), (25) result in lower values of the maximum located at a greater distance from the emission source (u_1=0.8 m/s; k_1=0.06 m/s; n=0.27) – calculation option 5 in Table 1 and with the data as in MDG CAEP report with modelled concentration values for simple test case (U_n=10 m/s; k_0=0.36 m/s; n=0.27) – calculation option 6 in Table 1:

$$C_{y\max} = \frac{Q}{eu_H\cdot H^{1+n}}\ x_{\max} = \frac{H^{1+n}\,u_H}{(1+n)^2 K'}$$

and averaged data along the height of the emission source (U_n=1.907 m/s; k_0=0.36 m/s; n=0.27)) – calculation option 7 in Table 1.

That is, for the input data from [20], let's obtain the following values for the maximum $C_{\max}$, located closer to the emission source $x_{\max}$, and which are more similar to the values calculated by the formulas for the maximum transversely integrated concentration (14) $C_{\max}$=0.779 mg/m^3 and its coordinates (15) $x_{\max}$=1033.34 m for the Gaussian stub model, or in dimensionless (scalable) values $C_{y\max}$UH/Q= =467.4; $x_{\max}$/H= 17.22.

5. 2. Study of the calculated dependences of the OND-86 method

Under conditions of a dangerous wind speed Um, the surface concentration of harmful substances c (mg/m^3) in the atmosphere along the axis of the emission plume at various distances x (m) from the emission source is determined by the formula

$$c=s_1\cdot c_m,$$

where Cm is determined by formulas (1)–(5), and the dimensionless coefficient s_1, which is determined depending on the ratio x/x_M and the coefficient F according to the formulas of the method [15], depending on $x/x_м$ and F. The value of the surface concentration of harmful substances in the atmosphere c_y (mg/m^3) at a distance y (m) perpendicular to the axis of the emission plume is determined by the formula

$$c=s_2\,c.$$

where s_2 – dimensionless coefficient determined depending on the wind speed and (m/s) and the ratio y/x according to the value of the argument t_y also according to the formulas of the method [15].

The maximum of the transversely integrated concentration (similar to the) approach in MDG CAEP report can be determined by formula (13) for a dependence of the form вид $c(x,y,0) = s_1\cdot s_2\cdot c_m$. Taking into account the results obtained in Table 1 for all calculation options, it can be assumed that its maximum is located on the segment, determined by the formula of the method [18]:

$$s_1 = \frac{1.13}{0{,}13\left(x/x_m\right)^2+1}\ at\ 1< x/x_m \le 8.$$

The function s_1 can be represented as $a/(bx^2+1)$, its derivative is equal to $2abx/(bx^2+1)^2 2$ and only for x=0 this derivative is equal to 0, which does not correspond to the conditions of this test study.

If integral (13) is considered for $c=s_1\cdot s_2\cdot c_m$, that is,

$$\tilde{n}_y = \int_{-\infty}^{\infty}\tilde{n}_{max}s_1s_2dy = \int_{-\infty}^{\infty}\tilde{n}_{max}\frac{1.13}{0.13/x_{max}^2x^2+1}s_2dy,$$

where s_2 is determined by the method of [18], then such an integral has no analytical solution.

As shown above, namely, that the highest value of the concentration c_y along the b-axis at a distance x is determined in accordance with:

$$\bar{q} = \frac{q'(X,z)}{2\sqrt{\pi X}}e^{-\frac{y^2}{4X}},$$

taking into account the dependence of ϕ_o on u, it is possible to write

$$c_y = cs_2\left(\frac{|y|}{x}\right); s_2\left(\frac{|y|}{x}\right) = \left[1+8.4u\left(\frac{y}{x}\right)^2\right]\left[1+28.2u^2\left(\frac{y}{x}\right)^4\right].$$

Then formula (36) approximates s_2, which is defined as an exponent of the coordinate at in formula (12):

$$\bar{q} = \frac{M}{(1+n)k_1\varphi_0x^2\sqrt{2\pi}}e^{\frac{u_1H^{1+n}}{k_1(1+n)^2x}-\frac{y^2}{2\varphi_0^2x^2}}.$$

the integral of which is found above and is equal to

$$\int_{-\infty}^{\infty}\exp\left(-\frac{y^2}{a}\right)dy=\sqrt{\pi a}=\sqrt{2\pi}x\phi_0.$$

$$c_y=1=\frac{1.13}{0.13\left(\frac{x}{x_M}\right)^2+1}\cdot(2\pi)^{(1/2)}x\varphi 0\rightarrow$$

$$\rightarrow ax\div\left(bx^2+1\right),b=0.13/x_m^2.$$

Then the transverse integral concentration

$$C_y=C_{\max}\frac{1.13\sqrt{2\pi\phi_0 x}}{0.13\div x_{\max}^2x^2+1},$$

reaches a maximum at x=2,7735x_{max}, that is, almost three times farther than $x_{\max}$ on the torch axis of a 20-minute averaged concentration according to the OND-86 formulas, and the $S_{y\max}$ maximum is

$$C_{y\max}=C_{\max}\frac{1.13\sqrt{2\pi\phi_0 x}}{0.13\div x_{\max}^2x^2+1}=$$

$$=C_{\max}\frac{1.13\sqrt{2\pi\phi_0 x_{\max}}}{\sqrt{2\cdot 0.360555}}=3.928\phi_0 x_{\max}C_{\max},$$

Thus, the performed numerical analysis indicates that the direct use of the algorithms of the normative methodology OND-86 [15] results in 2–3 times lower values of the maximum transverse-integral concentration (option 7 in Table 1), which is formed at a distance of 2–3 times more than the experimental results obtained.

Fig. 3 shows for comparison the results of test exams for the leading models for assessing air quality at airports along the torch axis, and Fig. 4 – their comparison for the concentration field [21].

From Fig. 3 it can be seen that analytical solutions [17] and algorithms of the OND-86 methodology [15] determine 2–3 times less than the value of the maximum concentration on the flame axis. And from Fig. 4, it is obvious that the concentration field (averaging 20 min.) According to the method of [16] is narrower than according to the results of calculating Gaussian models (averaging 1 h).

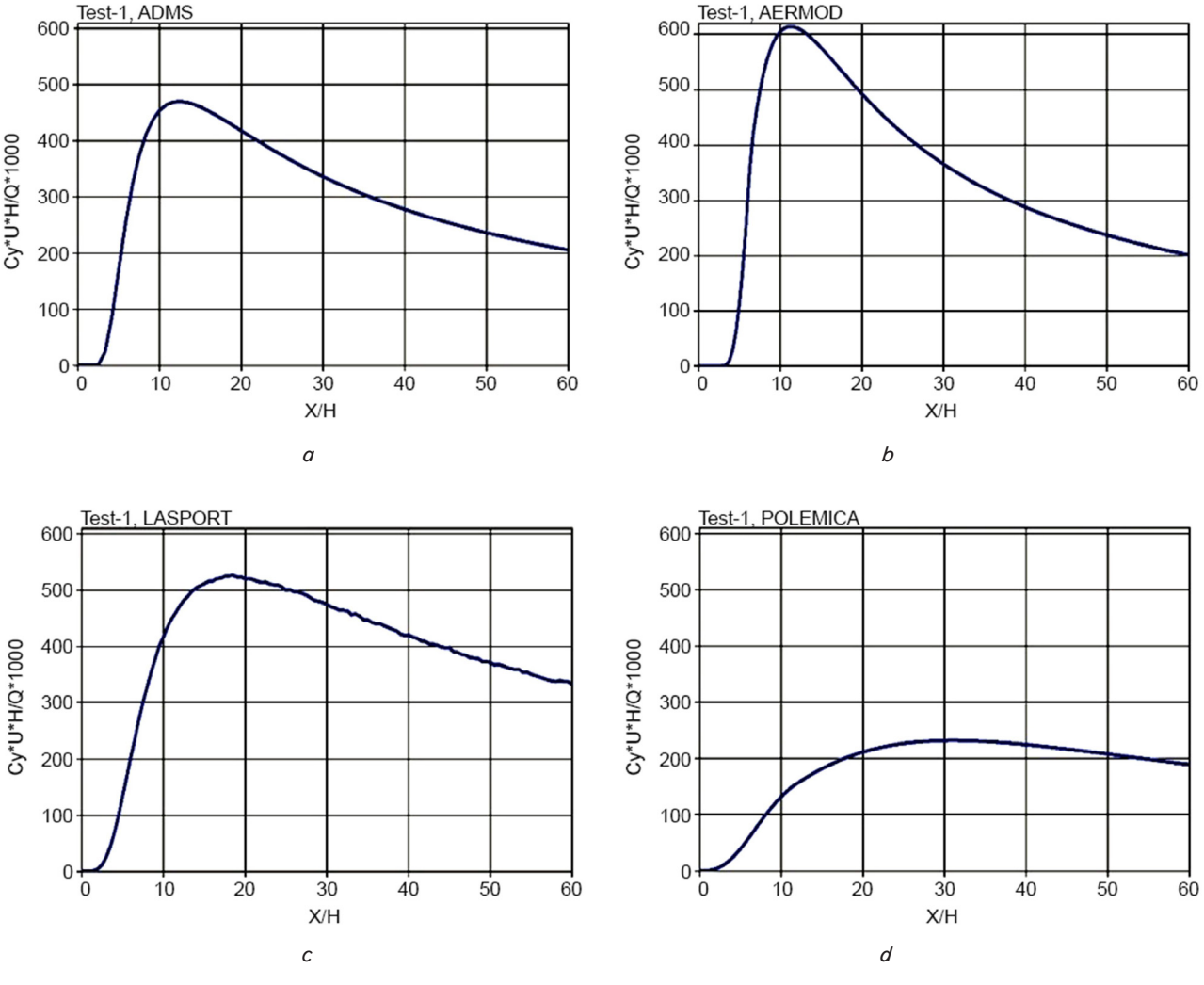

Fig. 3. Comparison of the results of calculating the maximum integrated concentrations along the flare axis for test 1 [16] by leading models for assessing air quality at airports: *a* – English ADMS model; *b* – American model AERMOD; *c* – German model LASPORT; *d* – Ukrainian model POLEMICA

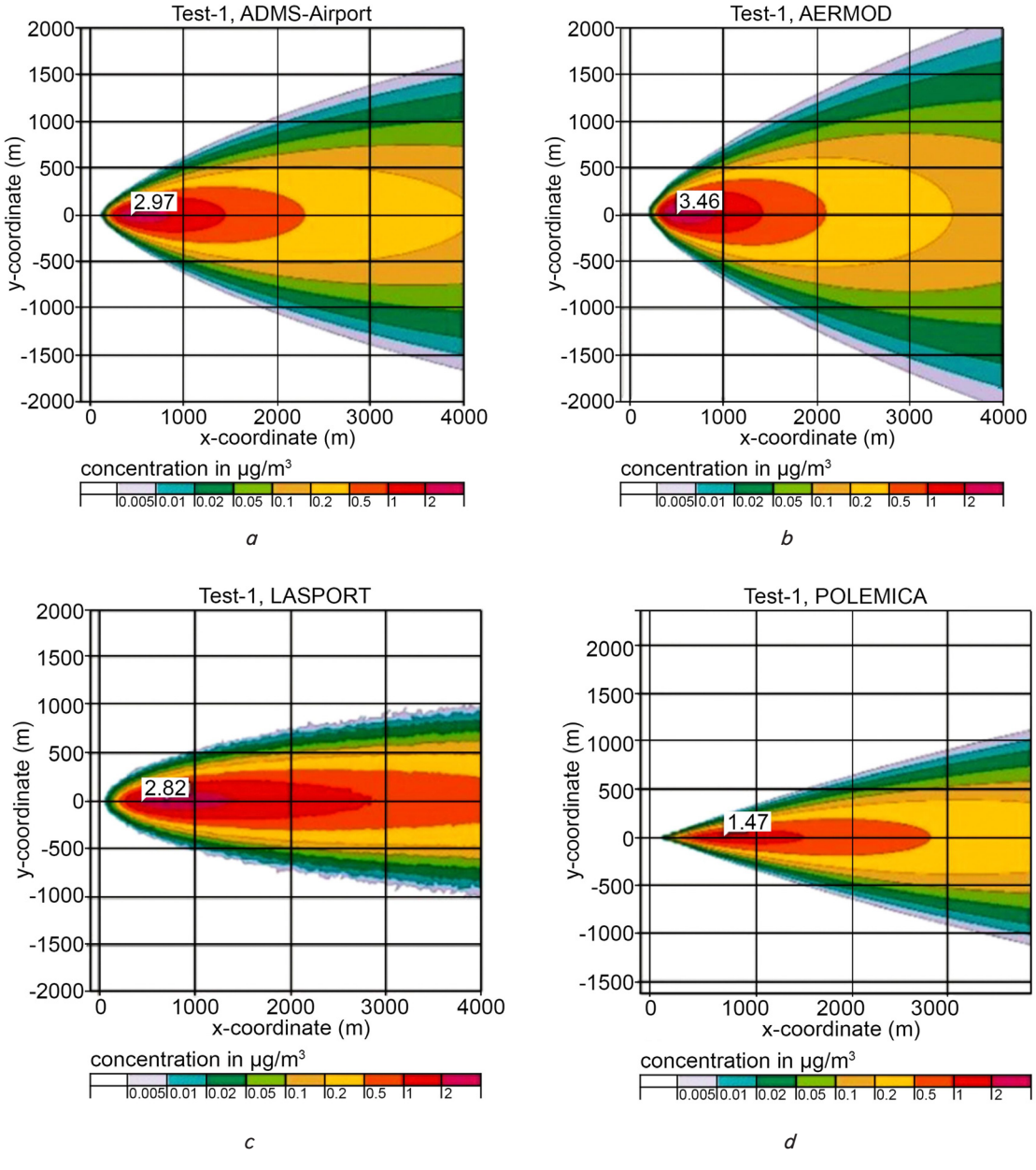

Fig. 4. Comparison of the results of calculating the concentration field from a stationary passive source along the torch axis for the test scenario considered within the studies on local air quality metrics by MDG CAEP including the leading models for assessing air quality at airports: *a* – English ADMS model; *b* – German model LASPORT; *c* – American model AERMOD; *d* – Ukrainian model POLEMICA

6. Discussion of the results of the study of methods for assessing air pollution by emissions from stationary sources of airports and compressor stations

The obtained results of analytical solutions of the Gauss model (13)–(15) and the model for calculating the concentration taking into account the duration of the observation time (22)–(25) are in good agreement with each other.

The results of calculating the transversely integrated values of the C_y concentration by analytical solutions (18)–(21) for the instantaneous concentration and averaged over 20 min. (22)–(25) differ from those in Fig. 1. This can be explained by using the values for the wind speed u_1 and the coefficients of turbulent diffusion k_1 and k_0 at the height z_1=1 m in formulas (18), (19), and not the corresponding values for the height H=60 m.

Taking into account the above arguments, it is quite easy to explain the difference in the test scenario results for different models involved in the studies on local air quality metrics by MDG CAEP. Similar to the dependencies in Fig. 2, the results for the PolEmiCa model are 2–3 times lower than those for other models, primarily due to the influence of the effect of concentration averaging, substantiated in this work. The same averaging effect (for the US AERMOD and UK ADMS models for one hour) explains the wider distribution of the concentration field for the AERMOD and ADMS models, compared to the LASPORT and PolEmiCa models. The latest models are designed to calculate instantaneous or

averaged concentrations (2—30 min., as per the normative methodology [15]).

7. Conclusions

1. The parameters of sources of pollutant emissions in the area of the airport and compressor stations and their impact on local air quality have been analyzed. The normative methodology OND-86 [18] for calculating the maximum concentrations of pollutants as a result of emissions from stationary sources does not take into account all possible features of the emission, in particular in terms of passive stationary sources and cold emissions.

2. Test scenario for calculating the maximum concene trations and the field of concentrations of pollutants in the atmospheric air determined for a simple type of stationary source – the emission temperature is equal to the ambient air temperature and the volume of the mixture emission is close to zero. In this case, only the height of the emission source and meteorological parameters are decisive for the concentration of air pollution. The results of calculating the maximum concentration for the test scenario using Gaussian models, verified in CAEP, diverge by almost 2 times. The minimum value was obtained for the ADMS model — 2 μg/m^3, the maximum — for the AERMOD model — 3.5 μg/m^3. A similar result according to the PolEmiCa model — 1.5 μg/m^3 is almost twice less, which is due to the inclusion of the effects of the initial rise in the emission of the mixture from a stationary source into the algorithms of the OND-86 method. Thus, to improve the PolEmiCa model, which should take into account the passive conditions of emission from stationary sources ($V_1 \approx 0$ and $\Delta T \approx 0$), it is proposed to take into account analytical solutions of the atmospheric diffusion equations [17], including the effects of the initial rise in the emission of a mixture from a stationary source. In particular, the variant of calculating 7 averaged data along the height of the emission source (Un=1.907 m/s; k_0=0.36 m/s; n=0.27) indicates the closest possible results to the experimental ones, and it is this model that is proposed in addition to algorithms of the OND-86 method to take into account the passive conditions of emission by stationary sources.

References

1. Global Aviation and Our Sustainable Future. International Civil Aviation Organization Briefing for RIO+20. ICAO.
2. Ohrana okruzhayuschey sredy. Aviatsionniy shum. Prilozhenie 16 k Konventsii Mezhdunarodnoy grazhdanskoy aviatsii. Vol. 2 (2014). Monreal': IKAO, 258.
3. ICAO Doc. 9184–AN/902/3. Rukovodstvo po proektirovaniyu aeroportov. Ch. 2: Ispol'zovanie zemel'nyh uchastkov i kontrol' nad okruzhayuschey sredoy (2005). Monreal': IKAO, 35.
4. Operational Opportunities to Reduce Fuel Burn and Emissions (Doc 10013). ICAO.
5. ICAO Doc 9948. Scoping study on the application of emissions trading and offsets for local air quality in aviation (2011). ICAO.
6. Kurtenbach, R., Wiesen, P., Synylo, K. V. (2015). Measurement of aircraft engine emissions inside the airport area. 4th International Conference on Transport, Atmosphere and Climate (TAC-4) 2015. Bad Kohlgrub, Germany.
7. Zaporozhets, O., Levchenko, L., Synylo, K. (2019). Risk and exposure control of aviation impact on environment. Advanced Information Systems, 3 (3), 17–24. doi: https://doi.org/10.20998/2522-9052.2019.3.02
8. Zaporozhets, O. Synylo, K. (2016). New and Improved LAQ Models for Assessment of Aircraft Engine Emissions and Air Pollution in and Around Airports. ICAO Environmental Report, 82–84.
9. ICAO Doc 9889. Airport Air Quality (2011).
10. Borodavkin, P. P. (1981). Ohrana okruzhayuschey sredy pri stroitel'stve i ekspluatatsii magistral'nyh gazoprovodov. Moscow: Nedra, 160.
11. Kozachenko, A. N. (1999). Ekspluatatsiya kompressornyh stantsiy magistral'nyh gazoprovodov. Moscow: Neft' i gaz, 463.
12. Ostrovskaya, A. V. (2017). Ekologicheskaya bezopasnost' gazokompressornyh stantsiy. Chast' 2. Vozdeystvie sistemy transporta gaza na okruzhayuschuyu sredu. Ekaterinburg, 151.
13. GOST R 54404-2011. Gas pumping units driven with gas turbine. General specifications. Available at: https://docs.cntd.ru/document/1200087119
14. GOST R 54403-2011. Stationary gas turbines for drive of turbogenerators. General specifications. Available at: https://docs.cntd.ru/document/1200087117
15. OND-86. Metodika rascheta kontsentratsii v atmosfernom vozduhe vrednyh veschestv, soderzhaschihsya v vybrosah predpriyatiy (1986). Leningrad: Gidrometeoizdat, 97.
16. Berlyand, M. E. (1985). Prognoz i regulirovanie zagryazneniya atmosfery. Leningrad: Gidrometeoizdat, 272.
17. Berlyand, M. E. (1975). Sovremennye problemy atmosfernoy diffuzii i zagryaznenie atmosfery. Leningrad: Gidrometeoizdat, 448.
18. Byzova, N. L. (1974). Rasseivanie primesey v pogranichnom sloe atmosfery. Moscow: Gidrometeoizdat, 190.
19. Byzova, N. L., Ivanov, V. N., Garger, E. K. (1989). Turbulentnost' v pogranichnom sloe atmosfery. Leningrad: Gidrometeoizdat, 263.
20. Byzova, N. L., Garger, E. K., Ivanov, V. N. (1991). Eksperimental'nye issledovaniya atmosfernoy diffuzii i raschety rasseivaniya primesi. Leningrad: Gidrometeoizdat, 278.
21. Zaporozhets, O. I., Synylo, K. V. (2019). The main concepts of the PolEmiCA technique for stationary sources of emission in airporst. Visnyk Natsionalnoho transportnoho universytetu, 3, 179–191.
22. Zaporozhets, O., Synylo, K. (2017). Improvements on aircraft engine emission and emission inventory asesessment inside the airport area. Energy, 140, 1350–1357. doi: https://doi.org/10.1016/j.energy.2017.07.178