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FORECASTING ENVIRONMENTAL POLLUTION BY ASPHALT CONCRETE PLANTS BASED ON MATHEMATICAL MODELING IN CONDITIONS OF CLIMATE INSTABILITY

ПРОГНОЗУВАННЯ ЗАБРУДНЕННЯ ДОВКІЛЛЯ АСФАЛЬТОБЕТОННИМИ ЗАВОДАМИ НА ОСНОВІ МАТЕМАТИЧНОГО МОДЕЛЮВАННЯ В УМОВАХ КЛІМАТИЧНОЇ НЕСТАБІЛЬНОСТІ

Kriukovsky Oleksandr*, postgraduate student of the Department of Transport Construction and Property Management of the National Transport University, e-mail: kriukovsky@gmail.com, tel.+380442803942,*

https://orcid.org/0009-0009-7730-0486

Liashenko Yana, *PhD in Physics and Mathematics, State University "Kyiv Aviation Institute", Associate Professor of the Department of Higher Mathematics, e-mail: Ya_Lyashnko@ukr.net, tel.+380444067323*

https://orcid.org/0000-0002-7772-7879

Abstract. The theoretical and practical aspects of predicting the dispersion of harmful impurities in atmospheric air in conditions of modern climatic instability are explored in this paper. The fundamental principles of mathematical modeling of emissions from asphalt concrete plants (ACPs) are analyzed, in particular, the features of the application of the Gaussian plume model and the OND-86 methodology. The main focus is on identifying methodological gaps in current environmental impact assessment (EIA) procedures, which are based on static meteorological parameters and do not take into account the risks caused by anomalous “heat waves”.

Based on a real industrial facility (an asphalt mixing plant in Vinnytsia region), a series of numerical experiments were performed to simulate the distribution of nitrogen dioxide (NO2) in a wide temperature range (from -10 to +40 °C). The modeling results demonstrated that extreme heat is a critical factor coursed the increase of ground-level concentrations of the pollutant and the approach of the pollution epicenter to the emission source.

The practical part of the investigation was implemented through cartographic visualization of concentration fields with reference to the topography of settlements. It has been proved that at abnormally high air temperatures (+40 °C and above), a decrease in the effective emission height is observed due to a decrease in the thermal gradient, which can lead to the coverage of residential buildings with concentrations that significantly exceed the regulatory MAC (Maximum Allowable Concentration).

A scientifically based strategy for adaptive management of asphalt concrete plants (ACP) is proposed, which involves dynamic adjustment of technological cycles and the implementation of predictive air basin monitoring systems. The conclusions of the work can be used to improve environmental regulations and justify the boundaries of sanitary protection zones of road industry enterprises.

Keywords: mathematical modeling, forecasting, Gauss's model, asphalt concrete plant, dispersion of harmful impurities, numerical experiment, climatic instability, stratification parameters, environmental risk, sanitary protection zone, adaptive environmental management.

Introduction. In the context of active development and restoration of the road and transport network, asphalt concrete plants (ACP) perform a key role in supporting the construction industry. It courses to an increase in the number and productivity of agricultural enterprises, many of which operate in close proximity to settlements or are mobile and frequently change location. Such intensive use is necessary for the economy, but creates permanent and growing environmental pressure.

According to the Law of Ukraine "On Environmental Impact Assessment", the activities of ACP belong to the category of facilities that may have a significant impact on the environment and require obligatory environmental impact assessment (EIA) procedures before the beginning of their operation or reconstruction [1]. The EIA procedure is a comprehensive analysis aimed at determining the potential impact of a factories on ecosystems and populations. A critically important element of this process is a mathematical modeling, since the calculated forecast allows us to establish a spatial illustration of the distribution of pollutants and make reasoned decisions regarding environmental safety.

Despite the obligatory EIA procedure, the modern practice of environmental regulation and environmental impact assessment of asphalt concrete plants in Ukraine faces a serious challenge due to the inconsistency of traditional calculation models with real climate change.

The main problem is that actual methods for predicting the dispersion of harmful substances are based on static meteorological parameters that do not take into account the anomalous temperature regimes that are increasingly observed in the summer period. The increase of the frequency of "heat waves" with temperatures above +35 - +40 °C radically changes the thermodynamics of the ground-level layer of the atmosphere, causing a decrease in the effective height of emissions and their intensive "pressing" to the earth's surface.

The situation is complicated by the high density of development around industrial sites. Traditional calculations of sanitary protection zones, performed based on average statistical indicators, turn out to be irrelevant during periods of extreme heat, when the zone of maximum pollution shifts closer to the source and covers residential areas with a higher concentration of impurities.

Thus, an sharp scientific and practical contradiction arises between the necessity to ensure guaranteed environmental safety of the population and the limitations of the existing forecasting tools, which requires a transition to adaptive modeling taking into account modern climatic extremes.

The problem of modeling atmospheric dispersion and estimation the impact of industrial facilities on the environment is a subject of active discussion in the modern scientific community. The issue of applying Gaussian models and their adaptation to complex meteorological conditions is considered in detail in the fundamental works of Zannetti P. [2] and Stockie J. M. [3], which laid the mathematical foundation for understanding the dynamics of a smoke plume and calculating ground-level concentrations. Modern foreign studies, in particular the works of Li X. та Hu X.-M. [4] and Pu X., Wang T. J., Huang X., Ding A. J., Zhou D. R. [5], indicate that global climate change, in particular anomalous "heat waves", significantly change the turbulence of the ground-level layer of the atmosphere. This makes static calculations using traditional methods, such as OND-86 [6], less accurate, as they do not fully take into account the thermal suppression of flare rise. The issue of the impact of asphalt concrete plants as specific sources of pollution was investigated by Oreto C. et al. [7], focusing on the risks from emissions of nitrogen oxides and particulate matter within the life cycle of road mix production.

In the Ukrainian scientific segment, a significant contribution to the development of methods of environmental monitoring and modeling was made by scientists Belyaev M. M. [8] (development of numerical models of impurity distribution), Vasylenko L. A. [9] (environmental safety of road construction) and Gunchenko O. M. [10]. However, despite a significant number of works, the issue of quantitative assessment of the impact of extreme temperatures (+40 °C) on the reduction of the dispersion distance (X_{max}) for road sector facilities in Ukraine remains insufficiently covered, which makes this study relevant.

The purpose of the study is to predict the levels of atmospheric air pollution by emissions from asphalt concrete plants under conditions of climate instability and to substantiate adaptive measures to minimize environmental risk for nearby territories based on mathematical modeling.

To achieve the goal, it is necessary to solve the following tasks:

1. To justify the choice of mathematical apparatus and algorithm for modeling the dispersion of emissions from industrial sources (asphalt concrete plants).
2. Perform mathematical modeling of nitrogen dioxide dispersion in a wide temperature range (from -10 °C to +40 °C) to identify regularities in changes in ground-level concentrations.
3. To investigate the spatial transformation of the impact zone and the configuration of the emission flare under the influence of extremely high air temperatures.
4. Perform cartographic modeling of the impact zones of a real ACP with a direct connection to the actual coordinates of the object and the surrounding residential area to estimate real risks for the population.
5. To substantiate a complex of adaptive environmental protection measures (technological, monitoring and planning) aimed at minimizing the negative impact of ACP on residential areas during periods of abnormal weather phenomena.

Presentation of the main research material and the obtained results.

Forecasting atmospheric pollution from asphalt concrete plants (ACP) based on mathematical modeling is an important tool for assessing environmental impact, planning environmental protection measures, and monitoring compliance with regulations. The purpose of modeling is to determine the maximum surface concentrations of pollutants at various distances from the emission source and estimate the compliance of these concentrations with maximum allowable concentrations (MAC). This modeling is a obligatory step for developing an emissions permit and determining the size of the sanitary protection zone (SPZ).

Since the ACP is a complex source of pollution, mathematical modeling should include the following key steps:

1. Collection of initial data.

1.1 Characteristics of the ACP: productivity, features of the technological process, type of fuel, availability and efficiency of dust and gas cleaning units, etc.

1.2 Emission data: identification and inventory of emission sources, actual or estimated emission capacities (M) for all main pollutants.

1.3 Meteorological data: wind speed and direction, temperature, atmospheric stability class (usually for the entire calculation period).

1.4 Geographic data: topography of the area (taking into account relief), data on buildings and structures for calculating aerodynamic flow.

2. Construction or adaptation of a mathematical model.

3. Calculation: determination of the field of pollutant concentrations at different points around the ACP.

4. Analysis of results.

4.1 Comparison of calculated maximum ground-level concentrations with maximum permissible concentrations (MAC).

4.2 Definition of the sanitary protection zone (SPZ).

4.3 Assessment of the contribution of the SPZ to overall atmospheric air pollution and development of measures to reduce the impact (for example, increasing the height of pipes, increasing the efficiency of gas purification equipment, improving the technological process, etc.).

The most widespread and simplest model for predicting the spread of impurities in the atmosphere is the Gauss's Plume Model. This model is well suited for predicting the dispersion of emissions from point sources (smokestacks) over open and flat terrain over relatively short distances (up to 10–20 km).

The Gauss's model is based on the following key assumptions:

1. **Point source:** Pollution emanates from a single point source (pipe) located at an effective height H.
2. **Permanent emission:** The emission rate (M) and meteorological conditions (wind speed u) are constant (do not change over time).

3. Gauss's distribution: The distribution of impurity concentration in the cross-section of the smoke plume (perpendicular to the wind direction) obeys the normal distribution law (Gauss's law).

4. Reflection from the ground: The earth's surface is considered to be perfectly reflective (pollutants are not absorbed, but reflected).

Within the Gauss's model, the concentration C at any point *(x,y,z)* from a point source (chimney) is defined as [2]:

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

where Q is the emission power (mass of impurity per unit time, g/s);
u is the average wind speed, m/s;
H_e is the effective emission height, m;
$\sigma_y(x)$, $\sigma_z(x)$ are dispersal parameters (standard deviations) in the horizontal and vertical directions, depending on the distance x and the atmospheric stability class.

In equation (1), the first exponent $\exp\left(-\frac{y^2}{2\sigma_y^2(x)}\right)$ defines the horizontal dispersion (across the wind). The maximum concentration is always on the axis of the emission plume (*y=0*).

The second exponent $\left[\exp\left(-\frac{(z-H)^2}{2\sigma_z^2(x)}\right)+\exp\left(-\frac{(z+H)^2}{2\sigma_z^2(x)}\right)\right]$ defines the vertical dispersion.

The first term $\exp\left(-\frac{(z-H)^2}{2\sigma_z^2(x)}\right)$ is the actual Gauss's distribution around the effective height H.

The second term $\exp\left(-\frac{(z+H)^2}{2\sigma_z^2(x)}\right)$ is the imaginary source, which is used to model the total reflection of the pollutant from the earth's surface (*z=0*).

For the most of environmental assessments, the most important calculation is the ground-level concentrations along the axis of the flare.

Putting *z=0* (earth's level) and *y=0* (wind direction) into the general formula, we get:

$$C(x,0,0)=\frac{M}{\pi u\sigma_y(x)\sigma_z(x)}\exp\left(-\frac{H^2}{z\sigma_z^2(x)}\right). \tag{2}$$

The key task of environmental forecasting is to determine the maximum ground-level (at a level of 2 m from the ground) concentration C_{max} and the distance x_{max} at which it is achieved. Analysis of formula (2) allows us to make the following conclusions:

1. At short distances (*x →0*) the concentration C is zero, since the flare is located high.
2. At large distances (*x →∞*) the concentration C approaches zero, as the plume is dispersed over a large area.
3. The maximum ground-level concentrations C_{max} is reached at a certain optimal distance X_{max}, where the flare has time to descend to the earth, but has not yet completely dispersed.

The effective height (H_e) is the sum of the physical height of the pipe (H) and the additional flare lift (ΔH) caused by the kinetic energy and buoyancy (temperature) of the exhaust gases [3]:

$$H_e = H + \Delta H\ . \tag{3}$$

The larger the value H_e, then better the initial dispersal occurs and the lower the concentration in the ground-level layer will be. The flare lift ΔH is a complex parameter and is calculated using empirical formulas (e.g., Holland, Briggs formulas) that take into account the temperature of the gases, the outlet velocity, and the wind speed.

The main limitations for the application of the Gauss's model are the following:

1. Flat terrain (the model works poorly in conditions of complex buildings or mountainous terrain).
2. Non-stationarity (it cannot model changes in meteorological conditions in time).
3. Chemistry (it does not take into account chemical transformations of impurities (for example, oxidation of SO_2 NO_x)).

However, the Gauss's model is an ideal tool for:

1. Assessing the impact of ACP emissions on surrounding residential areas.
2. Designing chimneys (determining the minimum required height H).
3. Establishing sanitary protection zones (SPZ) around the plant.

Although the Gauss's model is fundamental, its direct application in engineering calculations is complicated by the necessity for permanent monitoring of the turbulent characteristics of the atmosphere σ_y and σ_z. In order to make the environmental impact assessment (EIA) process universal and accessible, Gauss's physical principles were transformed into empirical methods of the simplified calculation, such as the OND-86 method.

This approach is based on the principle of determining the worst-case scenario. Instead of calculating the concentration for each wind change, the technique immediately determines the maximum surface concentration (C_{max}) that can occur under the most adverse meteorological conditions (the so-called "dangerous wind speed").

For a single point source with a round mouth (for example, an ACP pipe), the maximum concentration formula has the form [6], mg/m^3:

$$C_{max} = \frac{AMFmn\eta}{H^2 \sqrt[3]{V_1 \Delta T}}\ , \tag{4}$$

where A is a coefficient, depending on the temperature stratification of the atmosphere at which the concentration of harmful substances in the air is maximum, sec$^{2/3}$*degree*$^{1/2}$*mg/g*;

M is the mass of harmful impurity emitted into the atmosphere, g/sec;

F is the dimensionless coefficient that takes into account the settling velocity of harmful substances in atmospheric air;

m, n are the coefficients that take into account the conditions of the gas-air mixture exiting the source;

η is the dimensionless coefficient that takes into account the influence of the terrain;

H is the height of the emission source above ground level, m;

V_1 is the gas-air mixture flow rate, *м*^{3}/sec;

ΔT is the difference between the temperature of the gas-air mixture emitted into the atmosphere and the temperature of the ambient air, $^\circ C$.

The distance from the emission source at which the ground-level concentration reaches its maximum value under adverse meteorological conditions is determined by the formula [6], m:

$$X_{max} = \frac{5-F}{4} dH\ , \tag{5}$$

where the dimensionless coefficient *d* is determined by the formulas given in [6].

The advantage of the application the mathematical model (4) – (5) is the possibility of scenario modeling, which allows assessing environmental risks at the design or modernization stage of production. Due to the variation of input parameters (such as discharge temperature, gas velocity or meteorological conditions), the model becomes a tool for short-term and long-term forecasting. This makes it possible to determine the boundaries of the enterprise's impact zones under different climate scenarios, in particular under anomalous temperature conditions, which are becoming increasingly frequent due to global climate change.

To verify the theoretical provisions and estimation the real impact of the asphalt concrete plant (ACP) on the state of atmospheric air, a numerical experiment was conducted based on models (1) - (3). Within the framework of the investigation, special attention was paid to the analysis of the impact of ambient air temperature on dispersion processes, since the parameter directly correlates with the lifting force of the flare and, accordingly, with the level of ground-level concentration of pollutants.

Based on the presented methodology, a series of numerical calculations were carried out for a test source of emissions from an asphalt concrete plant. The object of the study was an asphalt concrete plant chimney with the following characteristics: height H = 20m, mouth diameter d_0=1.2 m, gas outlet velocity υ_0 =5.80m/sec at a mixture temperature $T_{mixture}$ = 80 °C. Nitrogen dioxide NO_2 with an emission rate of M=3g/sec and a background pollution level C_{bg} = 0.01 mg/m³ was defined as the target impurity. Calculations were performed for flat terrain conditions η = 1 with an atmospheric stratification coefficient A=180. The control criterion was the value of the greatest one-time limited permissible concentration MPS_{se} for NO_2, which is 0.085 mg/m³.

The aim of the experiment was to establish the dependence of the maximum ground-level concentration of the pollutant and the distance to reach it on the ambient temperature T, °C.

The scenario modeling covered a wide temperature range from -10°C to +40°C, which not only reflects the typical annual temperature course in a temperate climate, but also takes into account current trends in global climate change. The study paid particular attention to a scenario with an extreme temperature of +40 °C. Including such anomalous temperature in the model allowed us to establish peak levels of anthropogenic load, which is critically important for predicting environmental risks during periods of prolonged "heat waves".

Table 1 – Results of ground-level pollutant concentration modeling under various temperature conditions

Таблиця 1 – Результати моделювання приземної концентрації забруднюючих речовин за різних температурних умов

Experiment	Air temperature, °C	Maximum ground-level concentration, mg/m³	Distance at which maximum is reached, m	Dangerous wind speed, m/sec
1	-10	0,143	256,15	2,26
2	-5	0,144	252,97	1,97
3	0	0,146	249,07	1,93
4	5	0,148	245,00	1,89
5	10	0,151	240,75	1,85
6	15	0,154	236,28	1,80
7	20	0,158	231,58	1,75
8	25	0,162	226,62	1,70
9	30	0,168	221,34	1,65
10	35	0,174	215,70	1,59
11	40	0,182	209,62	1,53

Given the increasing frequency and intensity of anomalous meteorological phenomena in Ukraine, this approach allows us to simulate the worst-case scenario of impurity dispersion, when traditional impact assessment methods may underestimate the real threat. This transforms the model from a statistical calculation tool to a means of adaptive environmental forecasting, capable of taking into account the instability of climatic parameters and ensuring the sustainability of the environmental safety of adjacent territories even under extreme conditions."

The modeling results are presented in Table 1 and Figure 2.

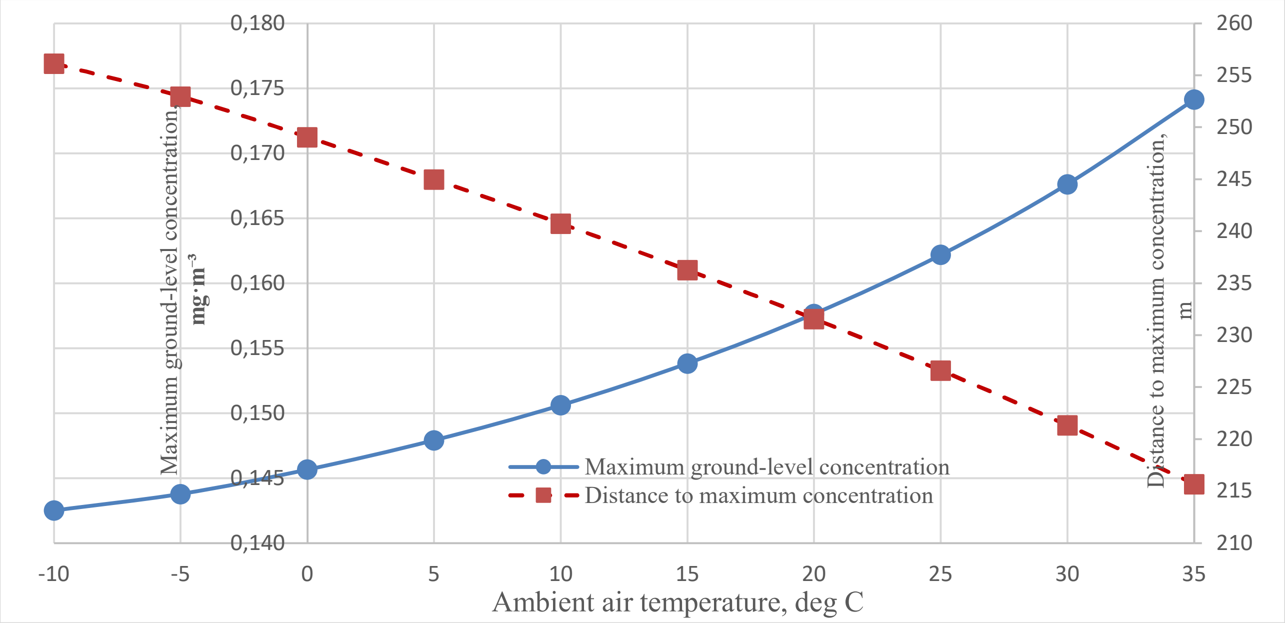

Figure 1 – Dependence of maximum ground-level pollutant concentration and its peak distance on air temperature

Рисунок 1 – Залежність максимальної приземної концентрації забруднювача та відстані її досягнення від температури повітря

As can be seen from Fig. 1, there is a direct correlation between air temperature and the level of ground-level concentration (blue line), while the distance to the maximum point (red line) has an inverse relationship - it decreases when air masses are heated.

A complex analysis of the obtained data allows us to establish the following patterns:

Dynamics of ground-level concentration. A nonlinear increasing dependence of the pollution level on the ambient temperature has been established. When the anomalous summer temperature of +40 °C is reached, the maximum ground-level concentration increases to 0.182 mg/m^3, which is 27.3% higher compared to the winter minimum (0.143 mg/m^3). Physically, this can be explained by a critical decrease in the temperature difference between exhaust gases and atmospheric air, which eliminates the effect of thermal lift of the flare and worsens the conditions for its dispersion.

Spatial shift of the risk zone. An inverse dependence between air temperature and the distance up to reach the maximum X_{max} was found. In the extreme scenario (+40 °C), the zone of maximum pollution shifts 46.53 m closer to the emission source compared to winter conditions - from 256.15 m to 209.62 m. It indicates an increase in environmental load directly near the industrial site boundary in hot weather.

Transformation of critical meteorological parameters. Calculations indicate a significant decrease in the “dangerous wind speed” from 2.26 m/sec in winter to a minimum value of 1.53 m/sec during abnormal heat. It means that in summer, conditions of extreme pollution are formed with significantly weaker air flows, which increases the risks of accumulation of harmful substances in the ground-level layer.

Thus, a comparative analysis of scenarios proves that the temperature maximum (+40 °C) is the most critical period for the operation of ACP. The combination of a 27.3% increase in concentration, an approach of the maximum zone to the source by almost 47 m, and a decrease in dangerous wind speed requires the implementation of adaptive environmental forecasting and taking into account summer indicators as estimated when establishing the boundaries of sanitary protection zones. The establishment of the boundaries of sanitary protection zones should be based not on average annual indicators, but on predicted extreme temperature scenarios.

To compare analysis of the dynamics of NO_2 dispersion, the spatial graphs of ground-level concentrations dispersal were constructed for two extreme scenarios: winter minimum (Experiment 1, -10 °C) and extreme summer maximum (Experiment 11, +40 °C).

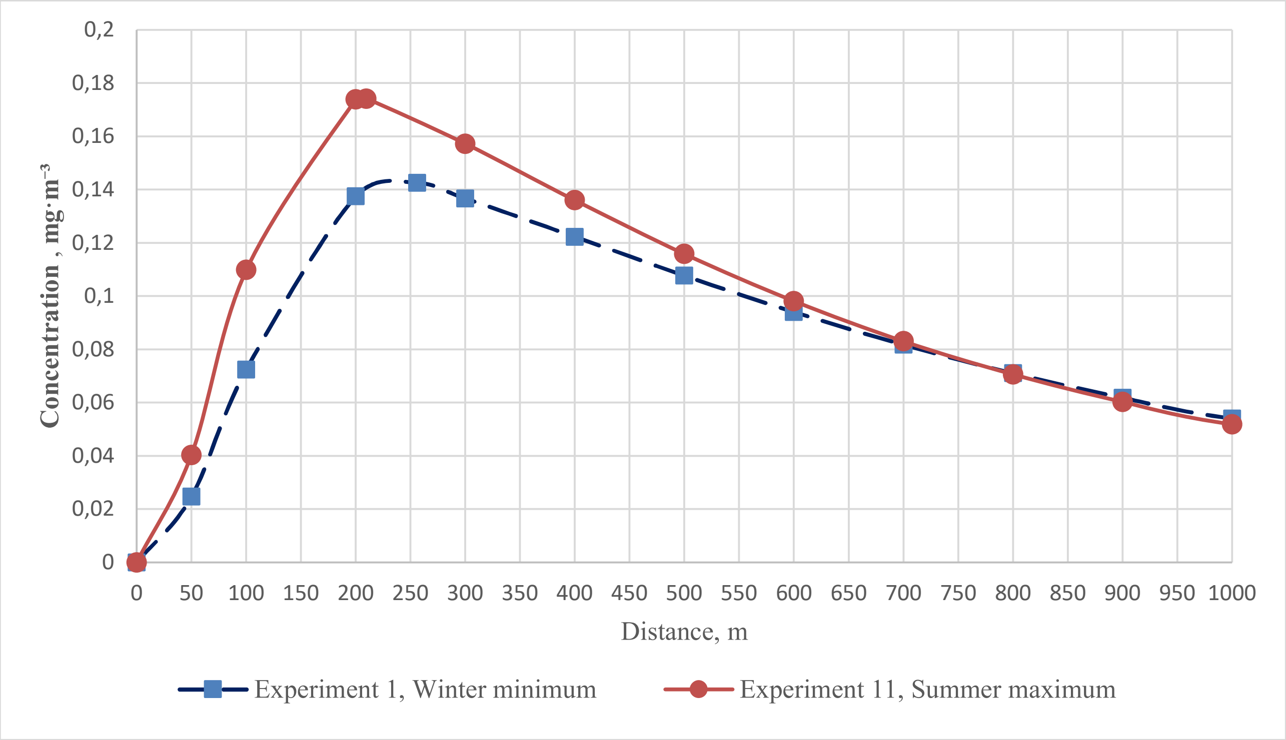

Figure 2 – Distribution of NO_2 ground-level concentration along the plume axis for extreme scenarios (winter minimum and summer maximum)

Рисунок 2 – Розподіл приземної концентрації NO_2 по осі факелу викиду для граничних сценаріїв (зимовий мінмум та літній максимум)

An analysis of Figure 2 allows us to compare two critical atmospheric states. The red line (summer maximum) demonstrates a higher pollution intensity and a shift of the zone of maximum impact closer to the source, which confirms the greater environmental hazard of emissions in the hot period of the year.

Moreover, analysis of the graphs (Fig. 2) allows us to establish the following regularities:

Transformation of the amplitude and shape of the emission flare. At an abnormally high temperature (+40 °C), the dispersion curve is characterized by a much steeper rise and higher amplitude. The maximum concentration value of 0.182 mg/m³ is reached faster and is significantly higher than the winter indicator.

Shift of the pollution epicenter. The graph confirms clearly the effect of the flare “pressing” to the ground in hot conditions. The point of maximum pollution shifts towards the source by 46.53 m (from 256.15 m to 209.62 m).

Expansion of the zone of exceeding the MAC. Analysis of the intersection of the curves with the MAC isoline equaled to 0.085 mg/m³ demonstrates a critical change in safe distances. If in winter the concentration decreases below the standard at a distance of about 680-700 m, then in extreme heat (+40 °C) the zone of exceeding the MAC expands, covering a larger area of the surrounding territory.

Long-range dynamics. Starting from a distance of 800 m, concentrations under different temperature scenarios gradually level off, but in the range of 100–700 m (which is critical for residential development), the summer scenario demonstrates consistently higher pollution levels.

The next stage of scenario modeling was the study of the spatial distribution of nitrogen dioxide concentrations, taking into account wind directions. This allows us to establish the real configuration of the enterprise’s impact zone on the surrounding buildings.

The basis for conducting a numerical experiment was the calculation of emission dispersion parameters from the chimney of the asphalt mixing plant of a real asphalt concrete plant (ACP) located in Vinnytsia region based on model (4) – (5). To ensure maximum reliability of the results, the modeling was carried out with a direct reference to the actual location of the industrial site and the surrounding topography. Taking into account the geographical coordinates of the source allowed not only to calculate theoretical concentrations, but also to visualize the directions of spread of nitrogen dioxide (NO2) pollution in the immediate vicinity of settlements (Demydivka, Mogilivka, Hnivan).

Temperature extremes typical for this region of Ukraine, in particular, abnormal heat of up to +40 °C, which corresponds to current trends in global climate change, were taken as a bases.

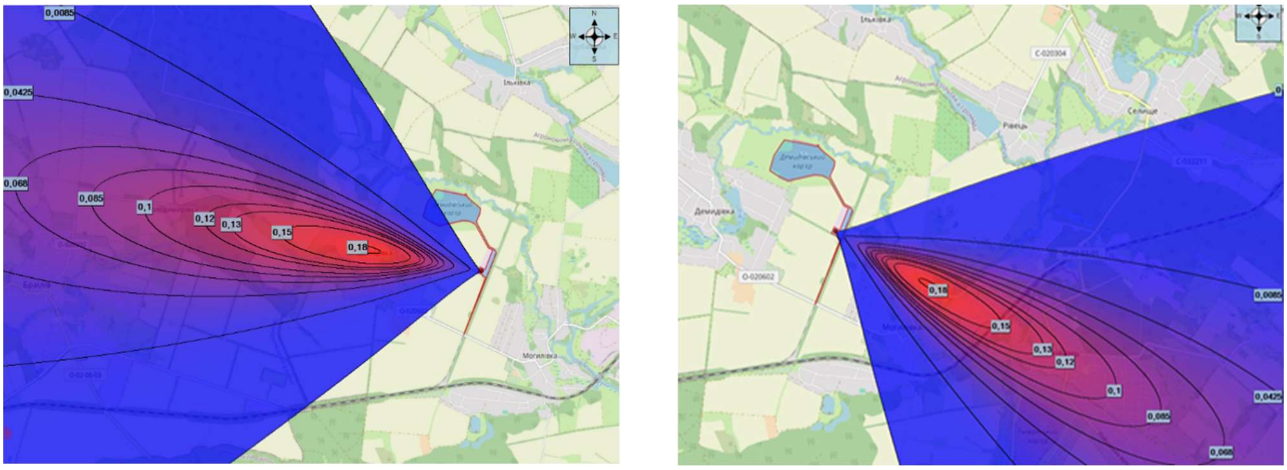

Figure 3 **–** Modeling of the asphalt plant’s impact zone on the residential areas of settlements (Demydivka, Mohylivka, Hnivan) under various wind directions and extreme conditions (temperature +40 °C, dangerous wind speed)

Рисунок 3 – Моделювання зони впливу АБЗ на селітебні забудови населених пунктів (Демидівка, Могилівка, Гнівань) при різних напрямках вітру за найбільш екстремальних умов (температура +40 °C, небезпечна швидкість вутру)

As can be seen in Fig. 3, the zone of maximum pollution directly covers the residential areas of the settlements of Demydivka, Mohylivka and Hnivan.

Integration of numerical modeling with terrain maps confirms that modern climate changes in Ukraine (increased periods of abnormal heat) make the existing boundaries of the SPZ insufficient to fully protect the residents of Demydivka and Hnivan.

It clearly demonstrates the summer period is the time of maximum risk, when the pollution flare "presses" on the ground and covers a larger area of settlements with higher NO_2 concentrations.

Geometry of pollution fields. The constructed isolines of concentrations C(x, y) demonstrate that during abnormal heat the emission flare becomes more intense and localized. The pollution core with concentrations of 0.15–0.18 mg/m³ (which is 1.8–2.1 times higher than the MAC) is concentrated directly in the ground-level layer along the axis of wind spread.

Impact on residential development in the settlement of Demydivka. With a westerly wind direction, a plume of pollution with a concentration of more than 0.12 mg/m³ directly covers the eastern part of the settlement. In particular, it has been established that the MAC (0.085 mg/m³) under such conditions shifts deep into the residential area, creating an excessive load on residential development.

Environmental risks for the settlements of Hnivan and Mogilevka. Modeling with a north-westerly wind represented that the emissions of the ACP form a zone of persistent pollution in the direction of Hnivan and Mogilevka. Taking into account the previously identified regularity of expanding the distance of influence in the summer (see Fig. 2), it was found that the isolines of concentrations 0.085–0.1 mg/m³ can reach the borders of these settlements, which requires special attention to the plant's operating schedules on hot days.

Based on the obtained modeling results, which confirmed the increase of ground-level concentrations by 27.3% and the approach of the maximum zone to the residential areas of Demydivka and Hnivan during "heat waves", the following set of adaptation measures for the ACP can be proposed during the most dangerous temperature maxima:

1. Adjustment of the operating mode of the enterprise:

Temperature regulation. During periods of extreme heat (at air temperatures above +30 - +35 °C), it is recommended to transfer the most intensive production cycles to night or early morning, when the temperature gradient contributes to better dispersion of impurities.

Capacity management. If the reaching the critical mark of +40 °C and the fixing of a weak wind (about 1.53 m/s), it is necessary to consider the possibility of temporarily reducing production volumes to prevent the formation of zones with a NO2 concentration above 0.182 mg/m³ in residential areas.

2. Implementation of an adaptive monitoring system:

Predictive modeling. It is recommended to implement an early warning system that, based on weather forecasts, will determine the risks of flare direction in settlements (in this specific example, Demydivka or Hnivan).

Location of monitoring posts. Installation of automated air quality sensors should be carried out in the sectors of greatest risk identified during modeling (in this case, at a distance of about 210 m from the source in the direction of the prevailing summer winds).

3. Urban planning and engineering solutions:

Adaptation of SPZ. When establishing the boundaries of sanitary protection zones for new or reconstructed sanitary protection zones, it is necessary to use the maximum air temperature as a calculation scenario, but not the average annual indicators, since exactly during abnormal heat the pollution flare is "pressed" to the ground most intensively.

Phytofiltration barriers. Creation of multi-tiered forest belts on the border of the industrial site (in this example, towards the settlements of Demydivka and Hnivan) for additional air turbulence and mechanical sedimentation of particles.

The implementation of the proposed recommendations will allow to transform the environmental management system of the enterprise into an adaptive management format capable of effectively responding to the challenges associated with climate change in Ukraine.

Conclusions and recommendations. Based on the calculations and modeling, it is possible to make a general conclusion that climate changes in Ukraine, which are manifested as an extreme summer temperatures, directly worsen the state of atmospheric air in the zone of influence of the ACP. It requires the calculation of sanitary protection zones not according to average, but according to the extremum meteorological parameters to ensure guaranteed environmental safety of the population.

The obtained results allow us to make the following conclusions:

1. The methodological limitation of traditional approaches to environmental impact assessment (EIA), which are based on average meteorological indicators, has been proved. Ignoring temperature extremes is established to lead to a significant underestimation of real environmental risks for nearby residential areas.

2. A direct correlation was found between the temperature of the atmospheric air and the level of ground-level pollution. According to the results of mathematical modeling, it was established that with an increase in temperature from -10 °C to +40 °C, the maximum ground-level concentration of nitrogen dioxide (NO_2) increases by 27.3% (from 0.143 mg/m³ to 0.182 mg/m³), which is due to a decrease in the effect of the thermal underground flare.

3. In conditions of "heat waves" (+40 °C), the point of maximum pollution (X_{max}) shifts closer to the industrial site compared to the winter period. This causes the effect of "pressing" the emission plume to the ground, which increases the toxic load directly at the border of the sanitary protection zone.

4. Based on cartographic modeling with reference to the area (Demydivka, Mohylivka, Hnivan), zones of potential exceedance of the MAC were visualized. It was proved that under unfavorable wind directions and temperature above +35 °C, the pollution flare directly covers residential buildings, creating an excessive load on the population.

5. The necessity to transition to adaptive environmental management of ACPZ is substantiated. The introduction of temperature regulations (power limitation at $T > +35$ °C), predictive monitoring systems, and the creation of multi-tiered phytofiltration barriers to protect residential areas have been proposed.

6. It is recommended to review approaches to establishing the boundaries of sanitary protection zones (SPZ) for new road sector facilities, using as a calculation scenario not average annual, but predicted extreme summer air temperatures, which corresponds to current trends in climate change in Ukraine.

Thus, the developed and tested mathematical modeling methodology confirms its ability to provide high reliability in predicting the environmental impact of ACP, which is a necessary condition for the resistant development of road infrastructure and ensuring environmental safety.

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ПРОГНОЗУВАННЯ ЗАБРУДНЕННЯ ДОВКІЛЛЯ АСФАЛЬТОБЕТОННИМИ ЗАВОДАМИ НА ОСНОВІ МАТЕМАТИЧНОГО МОДЕЛЮВАННЯ В УМОВАХ КЛІМАТИЧНОЇ НЕСТАБІЛЬНОСТІ

Крюковський Олександр Миколайович, аспірант кафедри транспортного будівництва та управління майном Національного транспортного університету, e-mail: kriukovsky@gmail.com, тел.+380442803942, https://orcid.org/0009-0009-7730-0486

Ляшенко Яна Григорівна, кандидат фізико-математичних наук, доцент, доцент кафедри вищої математики, Державний університет «Київський авіаційний інститут», Київ, Україна, e-mail: Ya_Lyashnko@ukr.net, тел.+380444067323, https://orcid.org/0000-0002-7772-7879

Анотація. У статті досліджено теоретичні та практичні аспекти прогнозування розсіювання шкідливих домішок в атмосферному повітрі в умовах сучасної кліматичної нестабільності. Проаналізовано фундаментальні принципи математичного моделювання викидів асфальтобетонних заводів (АБЗ), зокрема особливості застосування Гауссової моделі факела та методики ОНД-86. Основну увагу приділено виявленню методологічних прогалин у чинних процедурах оцінки впливу на довкілля (ОВД), які базуються на статичних метеорологічних параметрах і не враховують ризики, спричинені аномальними «хвилями тепла».

На базі реального промислового об’єкта (асфальтозмішувальної установки у Вінницькій області) виконано серію чисельних експериментів, що моделюють розповсюдження діоксиду азоту (NO_2) у широкому температурному діапазоні (від -10 до +40 °C). Результати моделювання продемонстрували, що екстремальна спека є критичним фактором, який зумовлює зростання приземних концентрацій забруднювача та наближення епіцентру забруднення до джерела викиду.

Практична частина дослідження реалізована через картографічну візуалізацію полів концентрацій з прив’язкою до топографії населених пунктів. Доведено, що за аномально високих температур повітря (+40 °C і вище) спостерігається зниження ефективної висоти викиду внаслідок зменшення термічного градієнта, що може призводити до накриття житлової забудови концентраціями, які значно перевищують нормативні показники ГДК.

Запропоновано науково обґрунтовану стратегію адаптивного менеджменту АБЗ, яка передбачає динамічне коригування технологічних циклів та впровадження систем прогностичного моніторингу повітряного басейну. Висновки роботи можуть бути використані для вдосконалення екологічних регламентів та обґрунтування меж санітарно-захисних зон підприємств дорожньої галузі.

Ключові слова: математичне моделювання, прогнозування, Гауссова модель, асфальтобетонний завод, розсіювання шкідливих домішок, чисельний експеримент, кліматична нестабільність, параметри стратифікації, екологічний ризик, санітарно-захисна зона, адаптивний екологічний менеджмент.

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