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ASSESSMENT OF ATMOSPHERIC AIR POLLUTION IN DNIPRO CITY AS A RESULT OF DUST ENTRAINMENT FROM THE ASH-DISPOSAL AREAS OF PRYDNIPROVSK TPP

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ОЦІНКА ЗАБРУДНЕННЯ АТМОСФЕРНОГО ПОВІТРЯ МІСТА ДНІПРО В РЕЗУЛЬТАТІ ПИЛОВИНОСУ ІЗ ЗОЛОСХОВИЩ ПРИДНІПРОВСЬКОЇ ТЕС

Purpose. The purpose of this work is to assess the pollution of atmospheric air in Dnipro city as a result of dust entrainment from the ash-disposal areas of Prydniprovsk TPP.

The methods. Assessment of atmospheric air pollution in the city of Dnipro as a result of dust entrainment from the ash-disposal areas of Prydniprovska TPP was carried out as follows: physical and chemical characteristics of the stored fly ash were determined; specific dust entrainment from the surface of dry beaches of ash-disposal areas under the most favorable conditions was determined; mathematical modeling of the spread of atmospheric air pollution of Dnipro city by suspended particles was carried out using UPCAP "ECO Center" program; a comparative assessment of dust entrainment reduction due to the gradual processing of the deposited fly ash was carried out.

Findings. Almost 100% of the total mass of ash consists of particles smaller than 80 μm, the content of particles smaller than 10 and 2.5 μm is 27.7 and 8.2%, respectively. The main chemical compounds contained in ash are silicon dioxide, aluminum oxide, iron (III) oxide and carbon. The gross entrainment of substances in the form of suspended fine-grained solid particles from the surface of the dry beaches of the Prydniprovska TPP ash-disposal facilities is 18,654 tons per year. The area of atmospheric air pollution of Dnipro city by suspended particles is about 850 km^2 and covers Samarskyi, Sobornyi, partly Industrialnyi and Shevchenkivskyi Districts. As a result of the implementation of a waste-free technology for the processing of fly ash with the utilization of the iron-containing fraction, the area of pollution can be reduced by 13.5 times up to 63 km^2, the contamination zone in this case will cover underpopulated part of Samarskyi District of the city of Dnipro.

Scientific novelty. A refined dependence of the particle size distribution of the mature Prydniprovsk TPP fly ash particles was determined for the further assessment of potential dust entrainment. For the first time, modeling of the distribution of fine-grained particles of fly ash of the Prydniprovsk TPP in the atmospheric air of the city of Dnipro was carried out, taking into account meteorological conditions, conditions of dust formation and particle size distribution.

Practical implementation. The results of the research can contribute to reducing the level of atmospheric air pollution in the city of Dnipro. This will improve the quality of life of the local population and protect the natural environment from negative impacts. Research results can also be a basis for the development and implementation of technological solutions for the waste-free processing of stored fly ash with marketable products obtaining.

Keywords: *atmospheric air, fly ash, pollution, dust entrainment, fly ash processing, impact, fuel, ash-disposal area.*

Introduction. Prydniprovsk TPP is a thermal power plant located in the east part of Dnipro city in the Samarskyi District on the left bank of the Dnipro river. The thermal power plant was designed to use anthracite as a fuel. Later, the station was switched to natural gas, but during the crisis with the supply of this type of fuel, it returned to coal consumption. In the spring of 2017, a decision was made to use gas coal as a fuel. The enterprise was designed for the production and supply of electric and thermal energy. However, during the preparation for the 2019–2020 heating season, the heating of the left-bank part of Dnipro city was reconnected from the Prydniprovsk TPP to the city's utility companies due to the temporary shutdown of the station.

Since the beginning of its operation, Prydniprovsk TPP is one of the main enterprises that pollute the environment of the city of Dnipro. The main pollutants include: metals and their compounds, substances in the form of suspended solid particles, nitrogen compounds, sulfur dioxide (SO_2), carbon monoxide (CO), methane, fluorine and its compounds. At the same time, in 2019, during the reconstruction of the gas cleaning equipment of power unit No. 10, a new modern electric filter and a system for continuous monitoring of waste gases were installed. The implementation of this project made it possible to increase the degree of flue gas purification to 99.8% and reduce dust entrainment to atmospheric air to 50 mg/m^3, which corresponds to European standards. In 2018–2019, two automatic stations for continuous monitoring of atmospheric air were installed on the territory of Prydniprovsk TPP at the border of the sanitary protection zone in order to track the concentrations of carbon monoxide, sulfur dioxide and nitrogen [1]. The analysis of the state of atmospheric air pollution in the cities of the Dnipropetrovsk Oblast is carried out according to the data of the Dnipropetrovsk regional center for hydrometeorology. The following substances are monitored: dust; sulfuric anhydride; carbon monoxide; nitrogen dioxide; nitrous oxide; phenol; ammonia; formaldehyde and hydrogen sulfide [2].

Near the Prydniprovsk TPP there are two ash-disposal areas. According to the state statistical report [3], 28.066 million tons of fly ash have been accumulated in these ash-disposal facilities. A feature of fly ash particles is an extremely developed specific surface, which is formed under the influence of high temperatures during combustion of coal. Due to this, ash particles intensively sorb molecules of various compounds, including toxic ones, from the flow of flue gases. When large volumes of fly ash are stored, these substances can pass the soil and groundwater, causing pollution and harming water systems. Soil pollution can affect local ecosystems and lead to loss of biodiversity, including changes in plant species composition, as well as reducing crop yields.

At the same time, fly ash is a finely dispersed material. When the beaches of ash-disposal areas desiccate, the particles easily move to a suspended state, under favorable conditions they are lifted by the wind quite high and transported to considerable distances. Taking into account the significant amount of stored fly ash and the area of ash-disposal facilities, it can be assumed that finely dispersed particles of fly ash are a significant pollutant of the atmospheric air of the city of Dnipro.

Therefore, the **purpose of this study** is to assess the pollution of atmospheric air in Dnipro city as a result of dust entrainment from the ash-disposal areas of Prydniprovsk TPP.

Main body. To achieve the purpose of the study, the following stages were performed in the process of work:

– research of physico-chemical characteristics of stored fly ash;

– study of meteorological indicators of the city of Dnipro to determine the period of the most favorable conditions for the dust entrainment to start;

– calculation of specific dust entrainment from the surface of dry beaches of ash-disposal areas depending on meteorological indicators and characteristics of the stored material;

– mathematical modeling of the spread of atmospheric air pollution in the city of Dnipro by suspended particles using the UPCAP "ECO Center" program;

– comparative assessment of reduction of dust entrainment due to gradual processing of stored ash.

Physico-chemical characteristics of stored fly ash. In the course of research, the granulometric composition of fly ash stored in the Prydniprovsk TPP ash-disposal facilities was determined. The granulometric composition was determined using a laser diffraction analyzer Malvern Mastersizer 2000 designed to determine the dispersion of particles from 20 nm to 2 mm. The method of laser light scattering, implemented in this device, is based on recording the angle of light scattering from particles. The device uses a helium-neon laser with a wavelength of 630 nm. The particle size distribution is measured by the method of dynamic scattering of laser radiation using the complete theory of Fraunhofer-Mee light scattering.

Table 1

Granulometric composition of mature fly ash of Prydniprovsk TPP

Grain-size class, mm	-0,09 +0,08	-0,08 +0,06	-0,06 +0,04	-0,04 +0,03	-0,03 +0,02	-0,02 +0,01	-0,01 +0,0025	-0,0025	Total:
Yield of the class, %	0,04	2,39	14,21	14,43	20,89	20,34	19,5	8,2	100,0

As can be seen from the research results, almost 100% of the total mass of ash is made up of particles smaller than 80 μm, the content of particles smaller than 10 μm is 27.7%, the content of particles smaller than 2.5 μm is 8.2% (Table 1, Fig. 1). The average size of ash particles is 20.86 μm. The average density of particles is 2800 kg/m^3. According to research [4], dust containing particles smaller than 5 μm is erosive and dangerous, as it has a fibrogenic effect, can negatively affect the cardiovascular system and cause allergic reactions. Under the conditions of intensive moisture evaporation and insufficient wetness, the beaches of sludge storage facilities desiccate, particles with a size of less than 0.1 mm easily become suspended and can spread to a distance of up to 20 km [5].

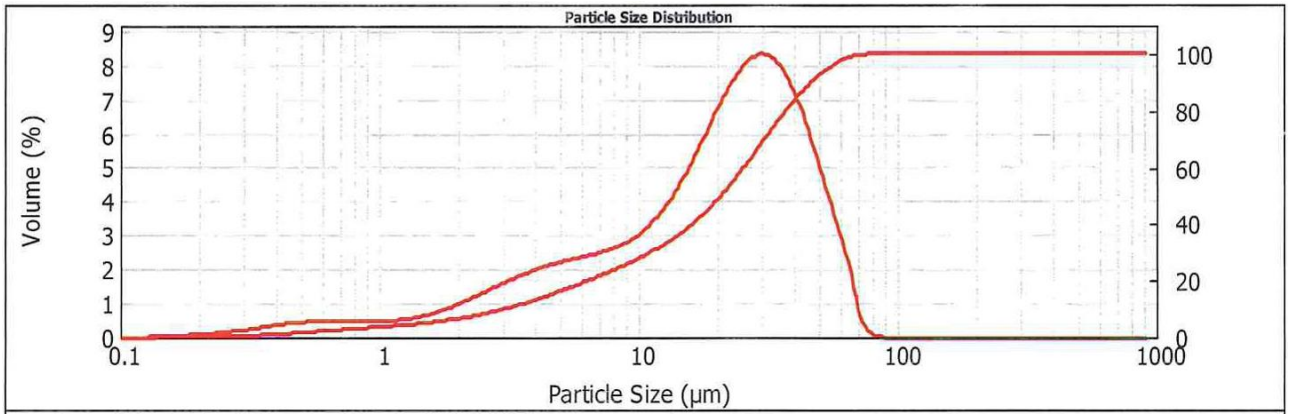


Fig. 1. Distribution of fly ash particles of Prydniprovsk TPP by size

The moisture content of fly ash was determined by drying the sample at a temperature of 120°C to a constant mass, based on the ratio of the mass of water to the mass of wet material. In the course of research, it was found that the moisture content of ash is from 7.1 to 9.8%.

The chemical composition of fly ash was determined in the laboratory of the Center for processing mineral and man-made raw materials of Dnipro University of Technology. As can be seen from the results of the analysis (Table 2, Fig. 2), the main chemical compounds contained in the ash are silicon dioxide, aluminum oxide, iron (III) oxide and carbon. All of these components are individually commercial products and can be used in industry. Therefore, the development of waste-free ash processing technology is an urgent task. It allows not only to solve the environmental problems of ash storages, but also to make a profit due to the sale of final products.

Table 2

Chemical composition of mature fly ash of Prydniprovsk TPP

Ash component	SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3	TiO_2	Na_2O	K_2O	S_{tot}	C
Content, %	49.25	2.39	1.58	19.47	9.43	0.85	0.66	3.67	0.12	12.56

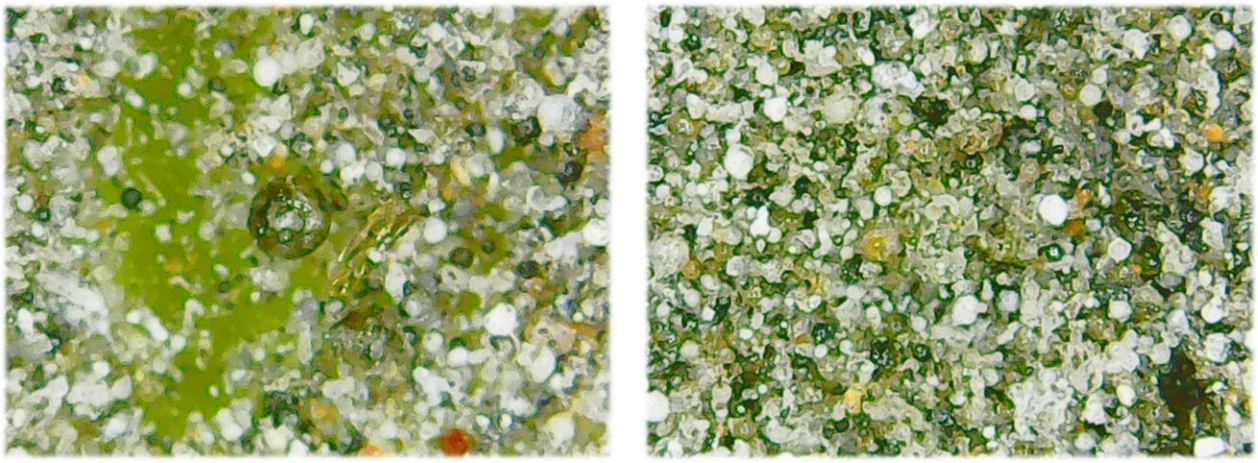


Fig. 2. Micro-photographs of fly ash from Prydniprovsk TPP (x 200)

Calculation of specific dust entrainment. At the power plant, there is a system of removal of fly ash via hydraulic transport. Ash is transported by means of a system of sludge pipelines to two sludge accumulators, namely: the passage of the Shiyanka River and balka Zakhidna. The total area of ash-disposal facilities is about 250 hectares [6]. Using the Google Earth service, the area of the dry beaches of the Prydniprovsk TPP ash-disposal facilities was determined on aerial photographs. They amount, respectively, to 128.8 hectares for the passage of the Shiyanka River and 66.3 hectares for balka Zachidna. The total area of dry beaches is 1,951,456 m^2 or 195.1 hectares.

At a constant intensity of the dust entrainment source, the level of local atmospheric pollution is a function of the air speed at the location of the source, the direction of the air flow, the degree of its turbulence, and the distance from the dust entrainment source. The process of dust entrainment is very complex, its intensity depends on a number of factors, namely: dispersed composition of dust and shape of particles, its specific gravity, physical and chemical properties, magnitude of adhesion forces, air flow speed, dust content, etc. Dust entrainment occurs only when the action of aerodynamic forces on the particle exceeds the action of all other forces. According to the methodology for calculating the content of pollutants in emissions from unorganized sources of atmospheric pollution [7], dust entrainment is defined as emissions during static storage of material by the expression:

$$q = k_3 \cdot k_4 \cdot k_5 \cdot k_6 \cdot k_7 \cdot q' \cdot F, \quad (1)$$

where q – dust entrainment from the surface of dry beaches of ash-disposal areas, g/s; k_3 – coefficient that takes into account local meteorological conditions, namely the average surface wind speed (for calculations, we accept values from 1.2 to 1.4); k_4 – coefficient that takes into account the degree of protection of the dump from external influences, conditions of dust entrainment (for a dump open on 4 sides is equal to 1.0); k_5 – coefficient that takes into account the moisture content of the stored material (for calculations, we accept values from 0.1 to 0.4); k_6 – coefficient that takes into account the profile of the surface of the stored material and is defined as a ratio F_{act}/F, for ash storage facility is equal to 1.0; k_7 – coefficient that takes into account the coarseness of the material (for particles less than 1 mm is equal to 1.0); q' – dust entrainment from 1 m^2 of actual surface, g/s (for materials of clay size, we accept 0.004 g/s·m^2); F – dusting surface of the material, m^2.

The gross emission of a pollutant M (tons per year) is determined by the expression:

$$M = q \cdot T_{\max} \cdot 3600 \cdot 10^{-6}, \quad (2)$$

where q – dust entrainment from the surface of dry beaches of ash-disposal areas, g/s; T_{max} – the period most favorable for dust entrainment, based on the analysis of meteorological observations, h.

It is obvious that the entrainment of dust from the surface of the ash-disposal areas will occur only under favorable meteorological conditions. According to research results [4, 5], air humidity has a significant impact on the process of dust entrainment from the surface of the sludge storage. Thus, with air humidity above 70 %, the adhesion of fine-grained particles increases significantly. Accordingly, at high air

temperatures and low humidity, the desiccated surface of the sludge storage becomes a potential source of dust entrainment. The results of climate observations in the city of Dnipro for 2023 indicate that relative humidity below 70 % is observed for 8 months (from March to October) [8–10]. According to the results of the analysis of the meteorological indicators of the city of Dnipro for 2023, namely: the amount of precipitation, the number of clear, cloudy and overcast days, cloud cover, the average monthly air temperature and the absolute maximum air temperature, the period most favorable for dust entrainment (T_{max}) was calculated for each month.

According to expressions (1), (2) for each month, the calculation of annual dust entrainment from the surface of dry beaches of ash-disposal areas and gross pollutant emission was performed. The results of the calculations are given in Table 3.

Table 3

Calculation of the gross annual entrainment of pollutants in the form of suspended fine-grained particles of fly ash from the surface of the ash-disposal areas of Prydniprovsk TPP

	Wind speed, m/s	Moisture content, %	q, g/s	T_{max}, h	M, tons
March	6,2	9.5	1093	72	283
April	6,3	9.8	1093	144	567
May	4,8	8.6	1873	216	1456
June	4,9	7.4	3747	288	3885
July	6,8	7.1	4371	360	5665
August	6,7	7.2	4371	288	4532
September	6,7	8.2	2186	216	1700
October	6,5	9.7	1093	144	567
Total:		8.5	2478	1332	18654

According to the performed calculations, the gross emission of substances in the form of suspended fine-grained solid particles from the surface of the dry beaches of the Prydniprovsk TPP ash-disposal areas amounts 18,654 tons per year.

Modeling of the distribution of pollutants in atmospheric air. The main purpose of modeling the spread of pollutants in atmospheric air is to estimate the spatial distribution of concentrations and predict the change in concentrations of pollutants as the distance from the source of pollution.

Typically, scattering models are described by turbulent diffusion processes in the atmosphere. Conservation of mass for a given pollutant at an arbitrary point in space is described by the Euler equation:

$$C(x,y,z)=\frac{Q}{4\pi Dr}\exp\left[-\frac{u}{2D}(r-x)\right], \qquad (3)$$

where C – pollutant concentration, g/m^3; Q – pollution source capacity, g/s; D – coefficient of turbulent diffusion, m^2/s; r – distance from the source of pollution, m; u – average wind speed, m/s.

According to this model, the dependence of the concentration on the distance to the pollution source is hyperbolic. A feature of the model based on the Euler equation is the use of a fixed grid (vertical and horizontal). The solution of equation (3) occurs simultaneously at all intersection points of this grid, while taking into account the process of pollutant exchange between the intersection points.

Modeling of atmospheric air pollution by suspended particles as a result of dust entrainment was carried out with the help of the Unified Program for the Calculation of Atmospheric Pollution – UPCAP "ECO Center". Aerial photographs of the surface of the ash-disposal areas were obtained using the SAS.Planet software, which enables viewing and analysis of maps and satellite photographs of the earth's surface. The scale of the image was chosen in such a way as to maximally display the calculated area of atmospheric air pollution. The satellite image covers an area of 28.35 km in width and 31.65 km in height, or 897 km^2 of the total area of the city of Dnipro.

The following initial data were used for the calculation: the amount of dust entrained from the surface of the Prydniprovsk TPP ash-disposal areas, the average surface wind speed for the year, the average air temperature in the winter and summer seasons, the area of dry beaches of the ash-disposal areas, the recurrence of winds from different directions in the city of Dnipro for the year 2023. Meteorological indicators were taken in accordance with the ecological passport of the city of Dnipro, developed by the Department of Transport and Environmental Protection of the Dnipro City Council, and archival data of climate observations were also used [3, 4]. The size of the sanitary protection zone for the ash-disposal areas was set at 300 m, in accordance with the State Sanitary Rules for the Planning and Development of Settlements [11].

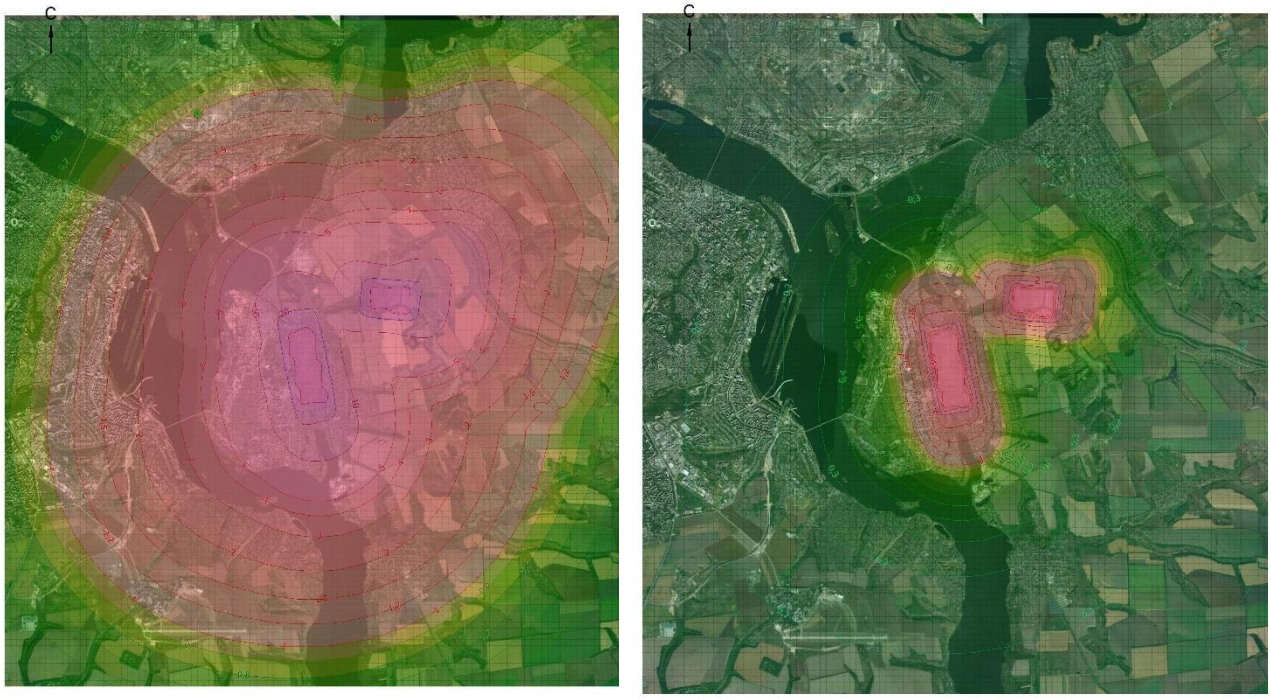
As a result of modeling the distribution of pollutants in the form of suspended fine particles of fly ash from the dry beaches of the Prydniprovsk TPP ash-disposal areas in the atmospheric air of the city of Dipro, it was found that the area of atmospheric air pollution is about 850 km^2 and covers Samarskyi, Sobornyi, partly Industrialnyi and Shevchenkivskyi Districts (Fig.3, *a*).

At the same time, surface concentrations of dust at the border of the sanitary protection zone exceed the maximum allowable concentration by 20 times, which indicates significant dustiness of the air and a high risk of non-carcinogenic danger for the population living in the zone of influence of this pollutant.

The next step of the modeling included an assessment of the degree of reduction in dust entrainment as a result of the gradual processing of ash-disposal areas and the release of land occupied by these facilities for further reclamation. As a result of ash-disposal areas processing, dust entrainment from the surface of dry beaches will obviously decrease, however it does not seem possible to predict its exact indicators.

The existing processing technology includes the classification of the initial fly ash by size and further enrichment in a flotation machine with a high degree of pulp aeration of the "Jameson Cell" type [12, 13]. This technology makes it possible to extract

the carbon fraction from ash with high efficiency. It is suitable for further use as a fuel or sorbent, since it has a developed specific surface.



a *b*

Fig. 3. Results of modeling the distribution of fine-grained fly ash particles of Prydniprovsk TPP in the atmospheric air of the city of Dnipro:
a – the current situation; *b* – projected situation in case of gradual fly ash processing

However, this technology does not provide a solution for the utilization of the iron-containing fraction. Taking into account the fact that fly ash can contain up to 30% of the iron-containing fraction [14], the development of processing technology which allows its utilization is an urgent task. This will make it possible to create an actually waste-free technology for the complete processing of the accumulated volumes of fly ash.

As a result of previous studies, the possibility of using the iron-containing fraction of fly ash as a weighting agent in dense medium separation of coal was substantiated. The use of high-frequency demagnetization in the regeneration scheme of the weighting agent particles makes it possible to completely restore the rheological properties of the suspension. At the same time, the sedimentation rate of demagnetized magnetite suspension decreases by 3 times, which allows to increase the efficiency of dense medium separation [15].

For the calculation, the conditions were determined that the stored fly ash in the amount of 28.066 million tons can be processed within eight years at a facility productivity of 500 t/h. As a result of the modeling, it was found that the implementation of the proposed technological solutions for the complete processing of mature fly ash will significantly reduce dust entrainment from the surface of the ash-disposal areas of Prydniprovsk TPP. At the same time, surface concentrations of dust will exceed the maximum allowable concentration by two times at the border of the sanitary protection

zone. The area of atmospheric air pollution by suspended particles will cover an underpopulated part of Samarskyi District and will amount approximately 63 km^2, which is 13.5 times less than the area of existing pollution (Fig. 3, *b*).

Conclusions. Almost 100% of the total mass of ash consists of particles smaller than 80 μm, the content of particles smaller than 10 and 2.5 μm is 27.7 and 8.2%, respectively. The average size of ash particles is 20.86 μm. The average density of particles is 2800 kg/m^3. Finely dispersed ash particles easily move into a suspended state. Taking into account the significant amount of stored fly ash and the area of ash-disposal facilities, finely dispersed particles of fly ash can cause a significant pollution of the atmospheric air of the city of Dnipro.

The main chemical compounds contained in the ash are silicon dioxide, aluminum oxide, iron (III) oxide and carbon. All of these components are individually commercial products and can be used in industry. Therefore, the development of waste-free ash processing technology is an urgent task. It allows not only to solve the environmental problems of ash storages, but also to make a profit due to the sale of final products.

The gross emission of substances in the form of suspended fine-grained solid particles from the surface of the dry beaches of the Prydniprovsk TPP ash-disposal areas amounts 18,654 tons per year.

As a result of modeling the distribution of pollutants in the form of suspended fine particles of fly ash from the dry beaches of the Prydniprovsk TPP ash-disposal areas in the atmospheric air of the city of Dipro, it was found that the area of atmospheric air pollution is about 850 km^2 and covers Samarskyi, Sobornyi, partly Industrialnyi and Shevchenkivskyi Districts. At the same time, surface concentrations of dust at the border of the sanitary protection zone exceed the maximum allowable concentration by 20 times, which indicates significant dustiness of the air and a high risk of non-carcinogenic danger for the population living in the zone of influence of this pollutant.

As a result of the implementation of a waste-free technology for the processing of fly ash with the utilization of the iron-containing fraction, the area of atmospheric air pollution can be reduced by 13.5 times up to 63 km^2. The contamination zone in this case will cover underpopulated part of Samarskyi District of the city of Dnipro.

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АНОТАЦІЯ

Мета. Метою роботи є оцінка забруднення атмосферного повітря міста Дніпро в результаті пиловиносу із золосховищ Придніпровської ТЕС.

Методика. Оцінку забруднення атмосферного повітря міста Дніпро в результаті пиловиносу із золосховищ Придніпровської ТЕС проводили наступним чином: визначено фізико-хімічні характеристики заскладованої золи; визначено питомий пиловинос з поверхні сухих пляжів золосховищ за максимально сприятливих умов; проведено математичне моделювання розповсюдження зони забруднення атмосферного повітря міста Дніпро зваженими частинками за

допомогою програми УПРЗА «ЕКО Центр»; проведено порівняльну оцінку зниження пиловиносу за рахунок поступової переробки заскладованої золи.

Результати. Майже 100% від загальної маси золи становлять частинки розміром менше 80 мкм, вміст частинок менше 10 та 2,5 мкм становить 27,7 та 8,2% відповідно. Основними хімічними сполуками, що містяться у золі, є діоксид кремнію, оксид алюмінію, оксид заліза (III) та вуглець. Валовий викид речовин у вигляді суспендованих тонкозернистих твердих частинок з поверхні сухих пляжів золосховищ Придніпровської ТЕС становить 18,654 тонн на рік. Площа забруднення атмосферного повітря міста Дніпро зваженими частинками складає близько 850 км^2 та охоплює Самарський, Соборний, частину Індустріального та Шевченківського районів міста Дніпро. В результаті впровадження безвідходної технології переробки золи виносу з утилізацією залізовмісної фракції площу забруднення можливо зменшити у 13,5 разів до 63 км^2, зона забруднення при цьому охоплюватиме малонаселену частину Самарського району міста Дніпро.

Наукова новизна. Визначено уточнену залежність розподілу частинок лежалої золи Придніпровської ТЕС за крупністю задля подальшої оцінки потенційного пиловиносу. Вперше проведено моделювання поширення тонкозернистих частинок лежалої золи виносу Придніпровської ТЕС в атмосферному повітрі міста Дніпро з урахуванням метеорологічних умов, умов пилоутворення та крупності частинок.

Практична значимість. Результати досліджень можуть сприяти зменшенню рівня забруднення атмосферного повітря міста Дніпро. Це дозволить покращити якість життя місцевого населення та вберегти природне середовище від негативного впливу. Результати досліджень також можуть слугувати основою для розробки та впровадження технологічних рішень з безвідходної переробки заскладованої золи виносу з отриманням товарних продуктів.

Ключові слова: *атмосферне повітря, зола виносу, забруднення, пиловинос, переробка золи, вплив, паливо, золосховище.*