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STATISTICAL ASSESSMENT OF THE DYNAMICS OF CHANGES IN THE PM_{10} AND $PM_{2,5}$ LEVEL IN THE AIR OF URBANIZED AREAS

Vira Sabadash, Oleksiy Lopushansky, Vitaliy Lysko

Lviv Polytechnic National University,
12, S. Bandery Str., Lviv, 79013, Ukraine
vira.v.sabadash@lpnu.ua

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Abstract. This article addresses the issue of atmospheric pollution caused by solid particles in urban environments. The presence of PM_{10} and $PM_{2,5}$ particles in the air of major cities and industrial areas worldwide has been examined. An evaluation of atmospheric pollution levels with PM_{10} and $PM_{2,5}$ particles in Kostopil, considering current air quality standards in Ukraine and the European Union, has been conducted. The authors employed the gravimetric method to measure the levels of suspended dust particles (PM_{10} and $PM_{2,5}$) in Kostopil from autumn 2022 to winter 2023. The study revealed an excessive amount of fine dust particles in the city's air, exceeding the maximum permissible values outlined in regulatory laws by 2.1–2.7 times. Furthermore, the monitoring of changes in suspended dust particle levels showed peak values of PM_{10} = 1.15 mg/m³ in January and $PM_{2,5}$ = 0.96 mg/m³ in December. The results of the statistical analysis of particle level distribution in Kostopil's urban areas indicated the statistical significance of certain distribution parameters, specifically SW-W and D for PM_{10} and $PM_{2,5}$ particle classes.

Keywords: solid particles, fine dust, PM_{10}, $PM_{2,5}$, air pollution, environment.

1. Introduction

Air quality has become an urgent problem in modern urbanized regions due to its adverse effects on the health of the population, the state of the environment, and the general level of comfort of life (Tian et al., 2016). Among the many factors contributing to atmospheric pollution in cities, particulate matter (PM), mainly $PM_{2.5}$ and PM_{10} is of particular concern.

Assessing the state of atmospheric air in cities is a challenging task, especially in cities with extensive technological infrastructure (Massey et al., 2012). The problem is exacerbated by thermal inversions, especially in valley regions.

The impact of human activity on the environment directly depends on such factors as the size of the city, its geographical location, population density and level of industrialization. An increase in emissions into the atmosphere affects the composition of chemical compounds in urban air, which leads to a deterioration of visibility and a decrease in the penetration of solar radiation (Jia et al., 2023).

Emissions of gases, aerosols and solid particles into the atmosphere resulting from industrial processes, traffic, energy production and condensation of water vapor significantly contribute to the pollution of the urban environment.

PM_{10}, or coarsely dispersed particles, comprises larger dust particles with an aerodynamic diameter of less than 10 micrometers. On the other hand, $PM_{2.5}$, or ultra disperse particles, consists of smaller dust particles with an aerodynamic diameter of less than 2.5 micrometers. These distinctions in particle size are important when assessing air quality and potential health impacts, as finer particles ($PM_{2.5}$) can penetrate deeper into the respiratory system, potentially causing more significant health concerns. In cities, the dust sources in the composition of gaseous air pollutants are anthropogenic emissions from the residential and

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communal sectors, industry and the transport sector. Research has substantiated that elevated levels of fine dust particles with an aerodynamic diameter less than 2.5 micrometers in the air pose a significant health risk to urban dwellers (Adamchuk, Gulay, 2015). The presence of such particles can lead to various health concerns and respiratory issues among city residents.

Different fractions of solid particles differ in aerodynamic diameter, formation processes, chemical composition, and presence of microflora, behavior and half-life in the atmosphere. In urban conditions, a coarse fraction of dust is emitted directly into the atmosphere from various sources, including stationary and mobile emission sources. This category comprises dust particles, ash, soot, and similar substances. Because of substantial human-made pollution in urban areas, the degree of atmospheric pollution in the atmosphere tends to be more elevated compared to suburban or rural regions (Feng et al., 2023). Urban areas often experience heightened levels of pollutants like dust, ash, and soot due to increased industrial and human activities. The frequency and duration of periods of high atmospheric pollution depend on the mode of emissions of harmful substances and meteorological conditions that can lead to an increase in the level of pollutants in the surface layer of the atmosphere. Fine aerosols, which are composed of solid particles with a diameter smaller than 2.5 micrometers, are generated in the atmosphere during the combustion of fuels. It's crucial to emphasize that this category contains a substantial number of chemical compounds known for their carcinogenic, mutagenic, and cytotoxic properties, such as polycyclic aromatic hydrocarbons. Studies in environmental epidemiology since the latter half of the previous century have indicated a significant influence of air quality on public health (Qi et al., 2023). This influence predominantly relates to respiratory and cardiovascular ailments, leading to elevated disease rates and decreased life expectancy. The presence of these fine aerosols in the air poses a severe health risk, especially in urban areas with high levels of fuel combustion. Thus, controlling air quality and reducing pollution becomes a crucial task for preserving the health and well-being of the population. In most developed countries, there are areas where a high degree of environmental degradation was observed. This degradation is often due to the dynamic processes of urbanization and industrialization. The primary source of environmental pollution is solid fuel emissions, which account for more than 62 % of dust emissions and are associated with fuel combustion processes, especially in the communal and residential sectors (Jia et al., 2023). Silesia and the Upper Silesia agglomeration are among the most industrially developed and urbanized regions in Europe. In regions where there is a substantial release of both dust and gas pollutants into the atmosphere, ecological equilibrium has been disrupted, resulting in persistently high levels of suspended dust in the air. For instance, in 2010, the annual average levels of dust particles in these areas were some of the highest in Poland, reaching 50.5 $\mu g/m^3$ and 42.5 $\mu g/m^3$, respectively. This elevated pollution is a consequence of significant emissions of dust and gases, and it has posed environmental and health challenges in these regions. In order to control air quality and reduce pollution, it is essential to consider the impact of transport, which usually increases the level of carbon, mainly elemental carbon, in the air. This effect has already been investigated for different dust fractions in different regions of the world (Aguilera et al., 2023). The particle size composition of solid particles in urban air can be changed by meteorological conditions, emissions of pollutants, chemical processes in the atmosphere, and the quality of industrial emissions treatment. To forecast atmospheric pollutionin the city, we need to develop forecast schemes for different seasons of the year and part of the day. Meteorological conditions and predictors must be considered for each half of the day separately. Forecasts can be made in advance, including morning, afternoon, evening and night. A comparative analysis of the levels of particulate pollution of natural and anthropogenic origin allows for a better understanding of their distribution and impact on the environment and human health (Karimian et al., 2023). The purpose of the work is to assess atmospheric pollution with solid particles PM_{10} and $PM_{2.5}$, determining the composition of air dust in an area free from any industrial activity.

2. Experimental part

Research methodology Characteristics of the city of Kostopil were chosen as a typical industrial city. The industry of Kostopol is focused on the wood processing industry and food industry. These enterprises contribute to atmospheric pollutionby many substances, including solid dust particles of the ultra-dispersed fraction.

Determination of air sampling parameters. Air samples were taken at intervals of 12 hours, from 9:00 a.m. to 9:00 p.m. and from 9:00 p.m. to 9:00 a.m. The research was conducted from the autumn-winter period from October 2022 to March 2023. Information on temperature, relative humidity and wind speed was obtained from the data of the Hydro meteorological Center. The level of solid particles in the air was determined gravimetrically by the mass of dust samples collected on the filters. All parallel results were averaged, and standard error was determined.

The statistical analysis of the variables was performed using the Statistica 7.1 software. During the analysis, the leading statistical indicators were determined, such as the arithmetic mean, minimum, maximum, median and quartiles. Pearson's test was used to assess statistical dependence between variables during the study period. Only those values for which the statistical significance of the results reached $p \leq 0.05$ were taken into account to determine the statistical significance of the relationships between the variables.

3. Results and Discussion

Fig. 1 shows the distribution of daily levels of $PM_{2.5}$ and PM_{10} in the city of Kostopil in separate months of 2022–2023.

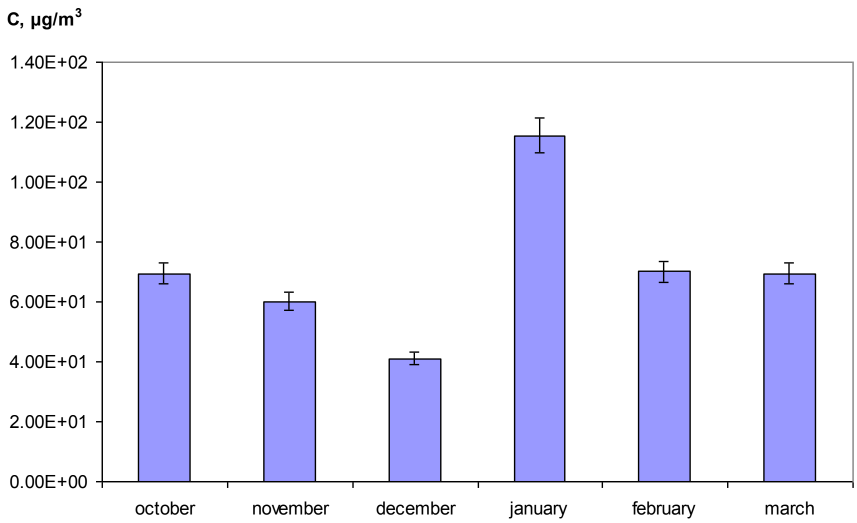

Fig. 1. The pattern of daily concentrations of solid PM_{10} particles (µg/m³) in Kostopil during the autumn-winter period of 2022–2023

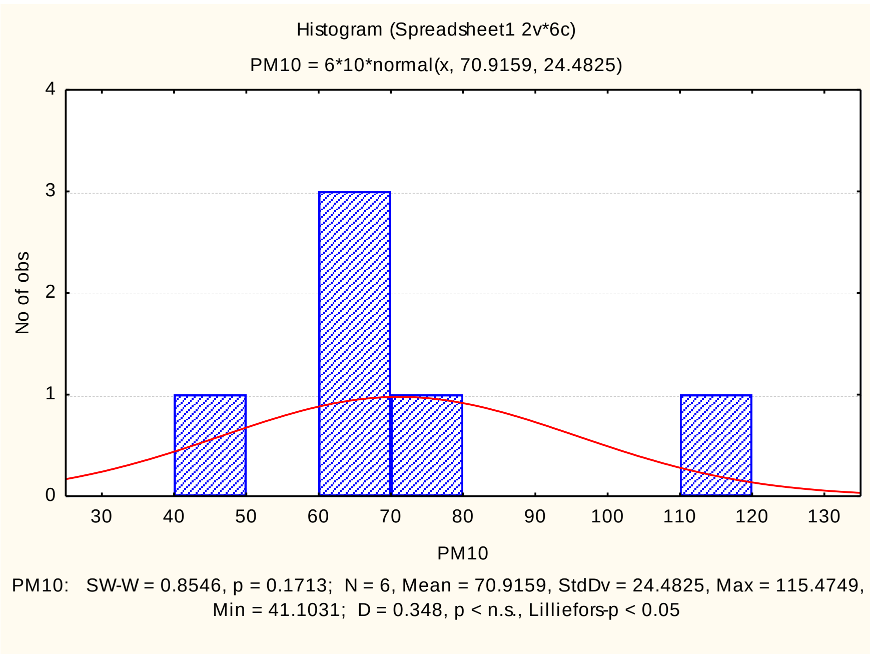

Fig. 2. Statistical assessment of the distribution of daily levels of solid particles PM_{10} (µg/m³) in the city of Kostopil

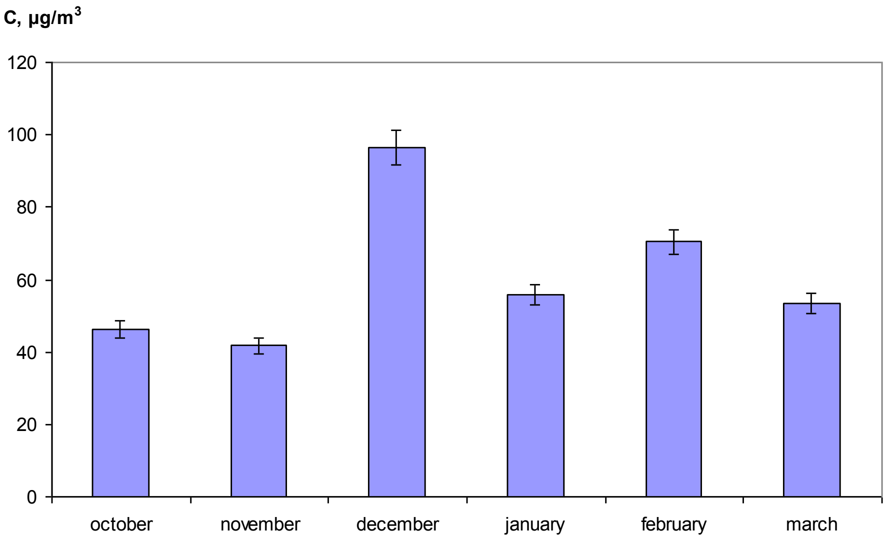

Fig. 3. The pattern of daily levels of $PM_{2.5}$ (µg/m^3) in the city of Kostopil

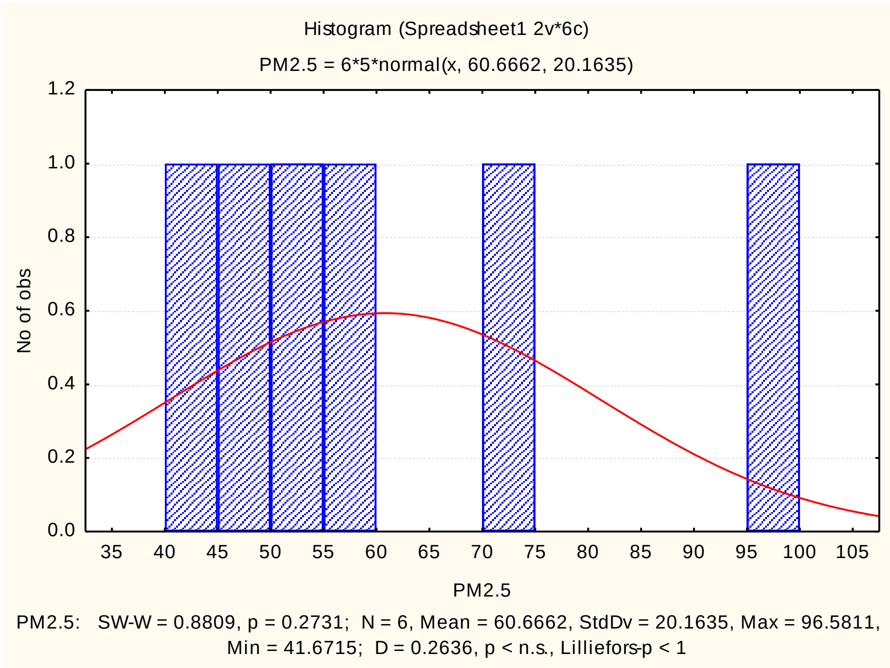

Fig. 4. The pattern of daily levels of $PM_{2.5}$ (µg/m^3) in the city of Kostopil

Table 1

Statistical assessment of the pattern of daily concentrations values of PM_{10} and $PM_{2.5}$ levels (µg/m^3)

Experiment date	N	PM_{10}					$PM_{2.5}$				
		$\bar{x}$	>50	min	max	s	$\bar{x}$	>50	min	max	s
10/2022	31	71	11	11	161	11	51	19	11	119	14
11/2022	30	56	17	20	158	11	41	11	11	81	11
12/2022	31	116	14	11	118	81	115	17	11	119	57
01/2023	31	81	11	11	181	44	71	11	18	161	17
02/2023	38	81	11	18	174	16	67	16	11	151	11
03/2023	31	81	14	11	114	41	61	11	15	181	11

($\bar{x}$ – Average value, >50 – the number of results above 50 µg/m^3, s – standard deviation)

The average value of the dust level in the air of the Kostopil city during the six months of the analysed period was 83 µg/m³, which surpasses the recommended threshold by a factor of 2.1. The highest level of $PM_{2.5}$ dust pollution was observed in December (median level: 97 µg/m³, level range: 20–230 µg/m³) and in other winter months such as January (median level: 55 µg/m³, level range: 28–161 µg/m³). February (average level: 71 µg/m³, level range: 22-151 µg/m³) and March (average level: 55 µg/m³, level range: 25–182 µg/m³). For the autumn months, starting in October, there was generally less air pollution, and in July, the level was 43 µg/m³ (level range: 11–82 µg/m³). A statistical analysis of atmospheric pollution with fine particles showed that during the analysed period of time, an increase in the level of up to 90 % of all measurements was observed. The average value of the level for the six months of the studied period was 67 µg/m³, which exceeds the exceeds the suggested allowable limit by 2.7-fold. Table 2 presents the percentage ratio of $PM_{2.5}$ dust to total particulate matter compared to PM_{10} in individual months, expressed as a ratio of $PM_{2.5}$ to PM_{10}. The mean coefficient throughout the entire research duration stood at 0.81, with values ranging from 0.75 in November to 0.88 in January. More than 92 % of the total study period displayed coefficient values exceeding 0.6.

Table 2

Statistics of atmospheric pollution by aerosol particles $PM_{2.5}$ and PM_{10} in the city of Kostopil

Experiments date	PM_{10}	$PM_{2,5}$	$PM_{2,5}/PM_{10}$
10/2022	59.41	45.14	1.55
11/2022	51.19	41.57	1.59
12/2022	41.11	95.58	2.35
01/2023	115.57	55.63	1.48
02/2023	71.12	71.41	1.11
03/2023	59.41	53.48	1.77

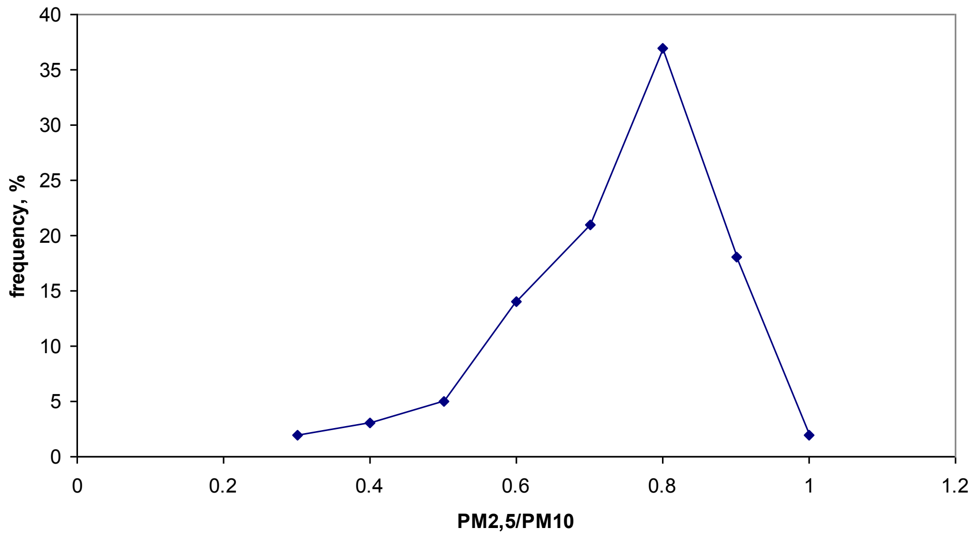

Fig. 5. Ratio of $PM_{2.5}$ and PM_{10} particles in the city of Kostopil

Mathematical model of the dispersion of solid particles in the atmosphere within urban regions. The main direction of studying the spread of impurities is modelling the dispersion of pollutants in the environment according to the theory of atmospheric diffusion using the equation of turbulent diffusion. It makes it possible to study the distribution of impurities from sources of different types under different characteristics of the environment,

In general, the problem of forecasting atmospheric pollution can be mathematically described by a differential equation under certain initial and boundary conditions:

$$\frac{\partial C}{\partial t} + w_x \frac{\partial C}{\partial x} + w_e \frac{\partial C}{\partial y} + w_z \frac{\partial C}{\partial z} = = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - kC, \quad (1)$$

where t is time; x, y, z is the coordinates; w_x, w_y, w_z is the components of the average speed of movement of the impurity D_x, D_y, D_z is the components of the exchange coefficient; k is the coefficient that determines the change in level due to the transformation of the impurity (reaction rate constant, provided that the destruction of the impurity occurs - a first-order reaction; if there will be a complex chemical reaction in which the impurity participates, the last term will be a different entry).

When solving practical problems, the form of the equation is simplified, If the x-axis is oriented towards the average wind speed, then the value of the speed in the projection on the y-axis is zero $w_y = 0$.

We take $w_z = 0$ for light impurities, and for heavy w_z the sedimentation rate, which is included in the equation, is taken with a minus sign.

Changes in levels in the atmosphere subsequently usually have a quasi-stationary character, and therefore it can be assumed:

$$\frac{\partial C}{\partial t} = 0. \quad (2)$$

Therefore, the equation in the case of a light admixture can be reduced to the form:

$$D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - w_x \frac{\partial C}{\partial x} - kC = 0. \quad (3)$$

For a heavy admixture:

$$D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - w_x \frac{\partial C}{\partial x} - w_z \frac{\partial C}{\partial z} - kC = 0. \quad (4)$$

When considering an inert admixture (for a substance that does not undergo transformation $k = 0$), we obtain:

$$D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - w_x \frac{\partial C}{\partial x} = 0. \quad (5)$$

When forecasting air pollution, the main aspect is the determination of expected levels of pollutants in the lower layer of the atmosphere at a height from the ground surface, which is equal to h = 1.5–2 meters. Studies have shown that in this lower layer of the atmosphere at the height $z = h$, the coefficient of turbulent diffusion increases in proportion to the height itself, and its dependence is represented as D_z. The velocity also varies with height, and its dependence can be described by a logarithmic function, namely $w_x \sim \ln(z)$.

If we consider the height $z = 0$ (which corresponds to the flat surface of the earth), then we can take D_z as a limiting value that corresponds to the molecular diffusion coefficient for air.

For the case when w_x and D are static functions of z (w_x = w0x · zn; $D = D_{zzl}$) for a light conservative admixture (where $w_z = w_y = 0$, $k = 0$), analytical calculations of the convective diffusion equations can be used,

At the terrestrial level (at z = 0):

$$C = \frac{M}{2(n-1)D_z\sqrt{\pi D x^3}} \exp\left(\frac{w_x H^{1+n}}{(1+n)^3 D_z x} - \frac{y^2}{4Dx}\right), \quad (6)$$

where M is the volume of dust emission, mg/c; H is the height, m.

A characteristic feature of the distribution of the ground level C along the x-axis is the presence of its maximum C_{max} at a distance x_{max} from the source.

In order to spread the distribution of the level of solid particles in the air depending on the diameter, let us represent the mass of the particles $M = \frac{\pi d^3}{6}\rho$.

Then (5) will take the form:

$$C = \frac{\pi d^3 \rho}{12(n-1)D_z\sqrt{\pi D x^3}} \exp\left(\frac{w_x H^{1+n}}{(1+n)^3 D_z x} - \frac{y^2}{4Dx}\right). \quad (7)$$

PM_{10} impurities and $PM_{2.5}$ from a single point source can be illustrated graphically (Fig. 6).

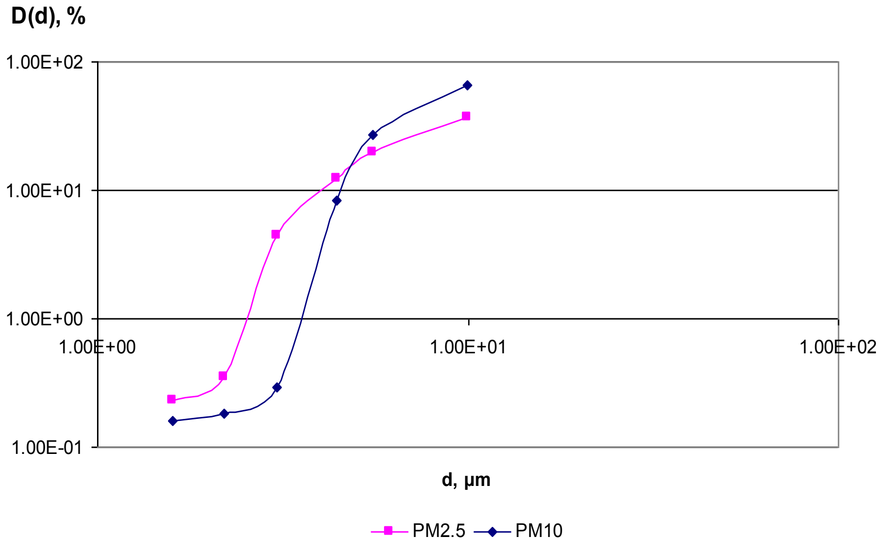

Fig. 6. Integral curves of $PM_{2.5}$ and PM_{10} particles in the air of urban areas

Fig. 6 represents the dependence of the percentage content of dust particles D (%) classes $PM_{2,5}$ and PM_{10} in atmospheric air from the diameter of the particles, The following statistical parameters were calculated for the presented data: Pearson test $\chi^2 = 1 \cdot 10^{-5}$, root mean square deviation 0.2–0.001 and the statistical significance of the results p<0,005.

Atmospheric pollution due to anthropogenic emissions associated with the functioning of housing, industrial and transport, Moreover, the area is subject to an advection of dust from nearby industrial centers. As a result, this leads to the deterioration of air quality in the industrial areas of the city, aggravated by the increase in the consumption of solid fuel during the heating season in local thermal power plants and in-home furnace heating.

4, Conclusions

The article presents the study results of the dynamics of changes in the level of size-fractionated solid phase particles in the air of urbanized areas. It was established that the level levels of different fractions of the solid phase can fluctuate significantly due to various factors, such as technological processes, traffic and climatic conditions. It has been investigated that effective measures to regulate emissions and improve air quality in urban areas should be aimed not only at the total level of the solid phase but also at its dispersion. The paper presents the dependences between the percentage content of dust particles D(%) of different $PM_{2.5}$ and PM_{10} classes in the air in urban areas, as well as different particle diameters. Based on the presented data, statistical parameters were calculated, which emphasize the significance of the obtained results. In particular, the Pearson criterion χ^2, equal to $1 \cdot 10^{-5}$, indicates a statistical relationship between the content of dust particles of different classes and their diameter. At the same time, the root mean square deviation varies in the range from 0.2 to 0.001, which indicates the diversity of the content of particles and their sizes. The most important is the statistical significance of the results, where $p < 0.005$, which confirms that the established relationships are statistically justified. The results of this study can be the basis for the development and implementation of effective strategies to control atmospheric pollution and improve the quality of life in urban environments.

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