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MODELING OF FINE DUST DISTRIBUTION IN ATMOSPHERIC AIR WITHIN RESIDENTIAL BUILDINGS

Abstract. Sustainable development of the country includes a balance between economic growth, social welfare and environmental safety. This means managing all aspects of life so as to ensure the well-being of people and not harm the environment. This is important so that future generations can live in safety. The quality of atmospheric air is of particular importance, as it has a direct impact on people's health. Cement industry is one of the first positions on the scale of emissions of harmful substances, including carbon dioxide (CO_2). In its structure, dust emissions from cement plants are considered mainly as aerodisperse systems. In these systems, the dispersed phase consists of solid particles (dust) or fine droplets, while the dispersed phase is a gas-air mixture This gas-air mixture may contain a variety of contaminants, both organic and inorganic. Predicting and regulating air quality in areas adjacent to cement plants can be achieved by modeling the spread of cement dust. This simulation allows to determine dust concentrations in the air at different distances from the source of emissions and helps to develop effective measures to reduce the man-made load on the environment.

Cement dust is one of the priority pollutants that must be considered when organizing air quality monitoring. Effective atmospheric monitoring of dust pollution of the air environment allows you to obtain up-to-date data on dust concentration, analyze trends of change and assess the impact on human health and the environment.

Reducing the technogenic impact of aerodisperse systems formed as a result of cement production is an important task to ensure environmental safety.

We conducted a detailed analysis of the literary data of this problem and developed a mathematical model for predicting the distribution of cement dust in residential buildings. Invention proposes improvement of dust-collecting equipment in cement production that allows to reduce emissions of cement dust into atmosphere by 10-15%.

Keywords: finely dispersed cement dust, neutralization, trapping, environmental safety, air quality monitoring.

1. Introduction

Atmospheric air is an important and dynamic environment of the biosphere, and its pollution can create prerequisites for reducing environmental safety in large areas. Fine dust pollutants of cement plants are especially dangerous because of their multicomponent composition and the ability to cause synergistic effects in the interaction of various pollutants.

The spread of pollutants along with air masses can disrupt the ecological balance of biogenic substances in all components of the ecosystem. This reduces the level of environmental safety of the biosphere and contributes to the degradation of ecosystem components.

The intensity and nature of the transport of pollutants make it possible to distinguish between zones of direct (main) and indirect effects. These zones differ in the intensity and scale of impact on the environment and humans, which must be taken into account when planning environmental measures.

Aerodisperse systems of cement plants have the ability to cause synergistic effects in the interaction of various pollutants [1-3].

The spread of pollutants along with air masses can disrupt the ecological balance of biogenic substances in all components of the ecosystem. The level of environmental safety in the biosphere is decreased and ecosystem components are degraded. In addition, the migration of pollutants affects not only the atmospheric air, but also other components of the environment, which extends the negative impact on the entire environmental safety system.

The rate of distribution of dust emissions in the atmosphere in residential areas depends on several factors, including the sources of emissions, meteorological conditions, topography and the presence of natural or artificial barriers. Among the main impact factors are: sources of emissions; wind load between buildings; precipitation (rain and snow can precipitate dust particles, reducing their concentration in the air); the level of temperature and humidity of the air (high temperature and low humidity contribute to the rise of dust into the air, while high humidity can contribute to the deposition of dust); terrain topography (flat areas are usually more vulnerable to the spread of dust emissions than hilly or mountainous areas where natural barriers can trap pollutants); natural and artificial barriers (green spaces).

Cement production is one of the main sources of dust emissions, which can significantly affect air quality in areas of residential buildings located near cement plants. The intensity of the distribution of dust emissions in the production of cement depends on several key factors: the technological process (extraction and transportation, grinding of raw materials); clinker kilns (dust is formed as a result of chemical reactions at high temperatures); grinding and mixing the clinker with other components.

Given the above, the question of the process of modeling the migration of fine particulate matter in atmospheric air remains relevant. It is necessary to take into account the main stages of modeling: determining the sources of emissions; identification of point (furnace, crusher), linear (transport belts) and planar (raw material storage) sources of dust emissions; determining characteristics of each source, such as emission height, emission rate and particle size distribution; collection of meteorological data; taking into account the terrain.

There are several models that can be used to simulate the spread of cement dust, such as AERMOD, CALPUFF, ADMS, HYSPLIT and others. The choice of model depends on the specifics of the task, the available data and the requirements for the accuracy of the simulation. The AERMOD model is developed by Canadian and American scientists.

This model is designed to predict continuous emissions from ground level and dispersion of intermittent emissions has several important characteristics that ensure its accuracy and flexibility: turbulent flows are linear, while the average and vertical wind speeds are zero; taking into account meteorological conditions at different altitudes, the model allows to predict the profiles of temperature, wind, turbulence of the environment, take into account the construction aspects, simulate the dry and wet method of precipitation of impurities [4-8].

To ensure environmental safety and public health in areas adjacent to cement plants, it is crucial to develop a mathematical model of cement dust distribution.

2. Results and Discussion

Research by leading scientists suggests that dust pollution of the lower atmosphere poses a significant threat to the environment and human health. Solid dust particles, depending on their characteristics, can have a variety of negative effects [10, 11, 12].

Fine dust has the greatest fibrogenic activity, its particles penetrate the deepest and are retained by the alveoli of the lungs, which causes a number of specific diseases, which necessitates measures to reduce the flow of pollutants into the air of settlements and predict the distribution of dust particles in atmospheric air [10-12, 20].

To develop a mathematical model of the fine dust propagation process, we use the differential diffusion transport equation, this equation describes how the concentration of dust particles changes with time and three-dimensional space [20]:

$$\frac{\partial C}{\partial \tau} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} + \sigma^* C = \frac{\partial}{\partial z}y\frac{\partial C}{\partial z} + \mu^*\nabla^2 C + k, \qquad (1)$$

where u, v, w are wind speed parameters along the Cartesian coordinate system axis, m/s;
μ^* – horizontal diffusion coefficient in the plane $(x, 0, y)$, m²/s;
y – vertical diffusion coefficient in z-direction, m²/s.

The product of the Laplace operator for concentration is calculated from the following relationship:

$$\nabla^2 C = \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}, \qquad (2)$$

k – coordinate and time dependent source parameter, $k = f(x, y, z, t)$;
σ^* – value associated with substance transformation, s⁻¹.

The authors [13-15, 20] present that in order to solve this one-dimensional problem of modeling the propagation of fine dust in the atmosphere, equation 1 is considered in a simplified form, while taking into account that the transfer of solid particles in the atmosphere occurs under the condition - ∞ < x < ∞, that is, in an infinite medium.

Using the data of meteorological conditions in relation to the characteristics of the wind load, as well as taking into account the stationary process of loading on the atmosphere, equation (1) takes the form:

$$u\frac{d\mathsf{C}}{dx} + \sigma^*\mathsf{C} = \mu^*\frac{d^2\mathsf{C}}{dx^2} + Q\delta\,(x - x_0), \qquad (3)$$

where Q – power of the source emitting dust into the atmosphere, kg/s;
$\delta\,(x - x_o)$ – Dirac delta function, which takes into account the integral content of dust particles that diffuse in the volume of air in height, as well as the number of particles settling on the surface of the earth, $1/m^3$.

When solving this equation, the following boundary conditions are taken into account that the limit of dust dispersion is a stationary source is the size of the sanitary protection zone (SPZ) of the enterprise; the source is in the center of coordinates; source emission power is a constant value [15-17].

The solution of equation (3) to obtain numerical data is possible using finite difference dependencies.

To do this, it is necessary to discretize the space of distribution of contamination of solid dust particles, taking into account the distance from the source to the boundary of the SPZ of the enterprise at certain intervals.

Space sampling is an important step in the numerical solution of differential equations, such as the diffusion transfer equation. One popular method for this is the finite difference method. This method consists in replacing differential operators with difference operators, which allows you to turn a differential equation into a system of algebraic equations. Consider the space sampling for the one-dimensional diffusion equation:

$$\frac{\partial \mathsf{C}}{\partial t} = D\,\frac{\partial^2 \mathsf{C}}{\partial x^2}. \qquad (4)$$

Suppose that we sample space in increments of Δx and time in increments of Δt. Denote the concentration at point $x_i = i\Delta x$ and at time $t_n = n\Delta t$ as C_i^n.

Then we can take advantage of spatial and temporal discrediting:

Differential equation (3) under the condition – $x = x_i,\ (i = 1,\ 2\ ,..,\ n-1)$ can be replaced by a linear equation:

$$\mu_i\,\frac{\mathsf{C}_{i+2} - 2\mathsf{C}_{i+1} + \mathsf{C}_i}{h^2} + u_i\,\frac{\mathsf{C}_{i+1} - \mathsf{C}_{i-1}}{2h} + \sigma_i\mathsf{C}_i = Q\delta(x - x_0). \qquad (5)$$

Transforming equation (5) with respect to C_i-1, u_i and $\mathsf{C}_i + 1$, we obtain a relationship for calculating the concentration of fine dust:

$$\left(\frac{\mu_i}{h^2} - \frac{u_i}{4h}\right) \cdot \mathsf{C}_{i-n} + \left(\frac{-4\mu_i}{h^2} + \frac{\delta}{(1-h)}\right) \cdot \mathsf{C}_i + \left(\frac{\mu_i}{h^2} + \frac{u_i}{4h}\right) \cdot \mathsf{C}_{i+n} =$$
$$= Q \cdot \delta(x - x_0). \qquad (6)$$

To be able to predict the concentration of fine dust at a certain distance from the source of dispersion, it is necessary to take into account the wind speed and power of the source, and it is necessary to use the dispersion equation of dust inclusions in the atmosphere. Using this equation, you can determine the distribution of dust concentrations depending on the height and distance and the source of the emission, taking into account the wind speed.

Most domestic and foreign scientists use the Gauss scattering equation [18-19] to simulate the scattering of pollutants in the atmospheric environment. This equation takes into account parameters such as wind speed, emission source power, source height, and atmospheric turbulence.

For the selected object of research, the calculation of the degree of distribution of fine particles of cement production took into account the following data: the power of the emission source 8.4×10^{-3} kg/s; the average wind speed is 1.5 m/s, the distance from the source is 1000 m, the horizontal diffusion coefficient is taken accordingly [20] as for an aerosol – 1.5 m^2/s.

The simulation results are shown in Fig. 1, indicate that the profile of change in dust concentrations from the emission source is uniform.
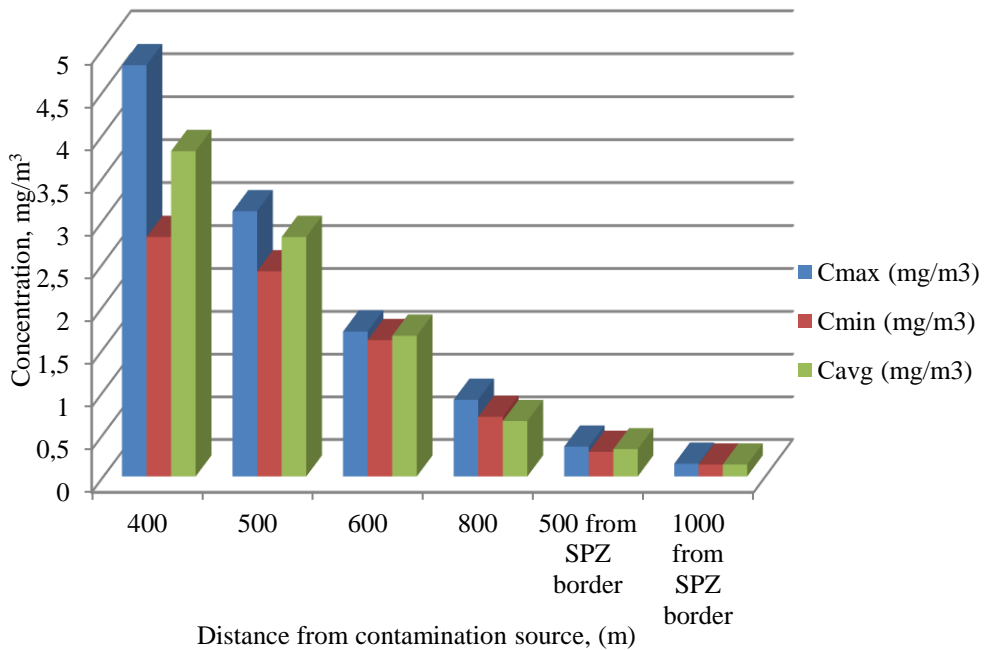

Fig. 1. Fine dust concentration distribution from emission source

Calculations and model (Fig. 1) together characterize the circular wind direction. The greatest amount of impurities falls at some distance from the emission source due to the transfer of air masses. This is due to the high inertia of fine dust, the particles of which are picked up and transported with the flow of wind. For a visual expression of the results of the obtained mathematical model, we built scattering maps of pollutants depending on the distance from the source which are shown in Figures 2 and 3.
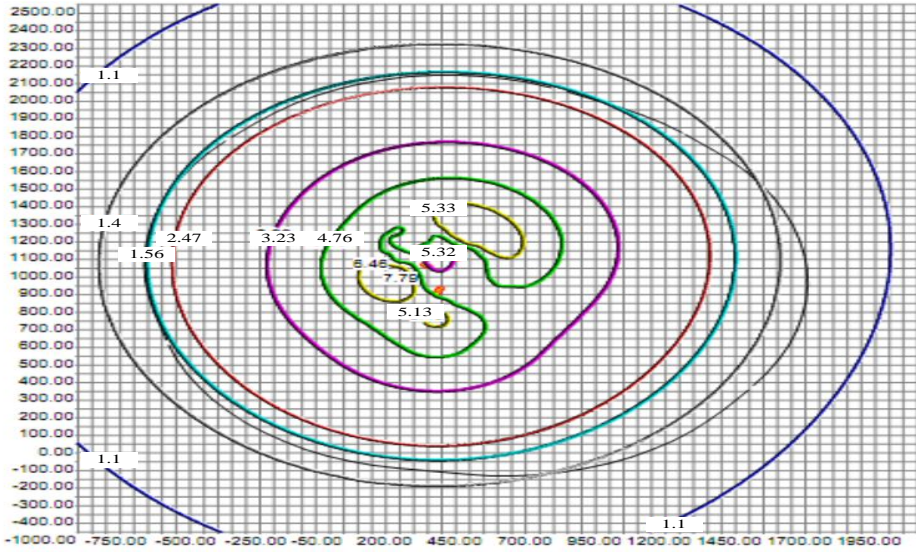
Fig. 2. Map of dispersion of cement dust in the atmosphere with the existing cleaning scheme
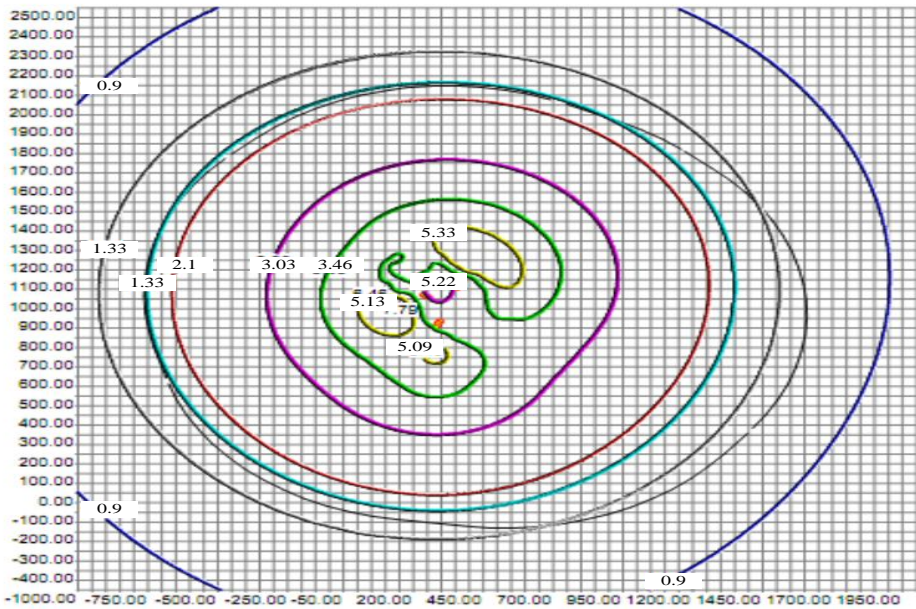

Fig. 3. Map of dispersion of cement dust in the atmosphere under the proposed scheme of air cleaning from cement dust

Experimental data on the degree of concentration of pollutants in the dispersion of cement dust according to the existing technological process are 10-15% higher according to the technological scheme proposed by us.

Based on the results of verification of the adequacy of the mathematical model of fine dust dispersion and experimental data, it was established that the deviation of the calculated values of the mathematical model from the experimental results does not exceed 20% over the entire studied range of distances (Fig. 4).
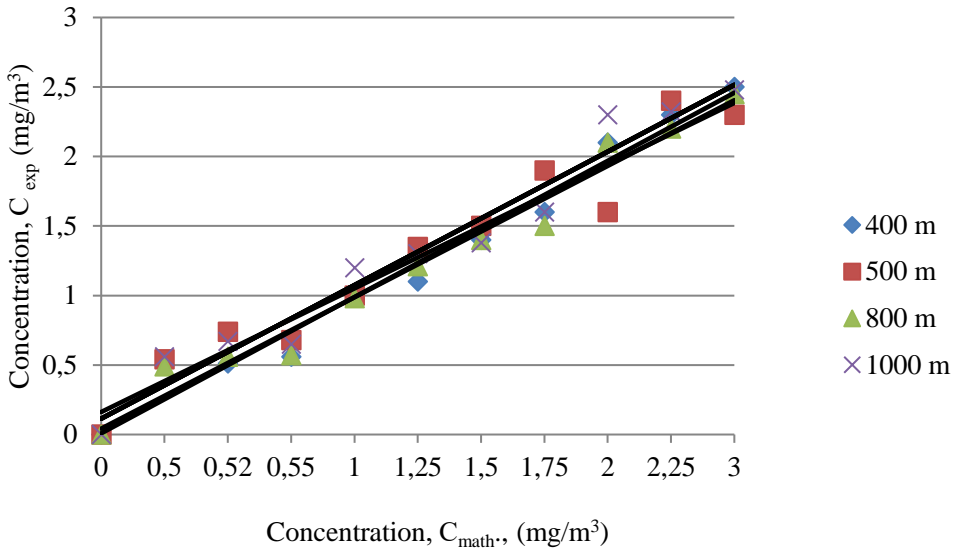
Fig. 4. Comparison of calculation results on dependence (6) and experimental data on concentration of cement dust in atmosphere

The Pearson correlation coefficient that characterizes a measure of covariance, one whose result is always within −1 and 1. It is a statistical measure that estimates the strength and path of the linear coupling of an equation with two variables. In relation to the obtained experimental and trend lines, the Pearson correlation coefficient (R_2) is in the range of 0.85-0.95.

The calculation of the proposed model, taking into account the boundary conditions, allows us to compare the 3D graphic distribution of cement dust in real conditions, depending on the distance from the source of pollution, provided that the proposed device is implemented to effectively clean the air from cement dust [18]. The solutions of criterial equations and the construction of graphical dependencies are obtained using the Wolfram Alpha program in Figures 5-6 in the following sequence.

$$\text{Interpreting as: } maximize\ (Y \times 158{,}24 \ \times 17{,}2 \times X) \times \frac{(X^{0,754} \times Y^{0,15})}{(2{,}24 \times X^{0,94})} \tag{7}$$
$$\text{in } 12 \le X \le 20;\ 23 \le Y \le 58.$$

Input interpretation:

$$maximize \quad \text{function} \quad (Y \times 158{,}24 \ \times 17{,}2 \times X) \times \frac{(X^{0,754} \times Y^{0,15})}{(2{,}24 \times X^{0,94})} \tag{8}$$

$$\text{domain} \quad 12 \le X \le 20;\ 23 \le Y \le 58.$$

Global maximum:

$$max\left\{ \frac{(Y\ 158{,}24 \ \times 17{,}2\ X)\left(X^{0,754} \times Y^{0,15}\right)}{2{,}24 \times X^{0,94}} \ \middle|\ 12 \le X \le 20 \ \wedge 23 \le Y \le 58 \right\} =$$
$$\frac{6737932912839621 \times 2^{389/500} \times 5^{407/500} \times 29^{3/20}}{47804853377} \text{at } (X,Y) = (20,\ 58). \tag{9}$$
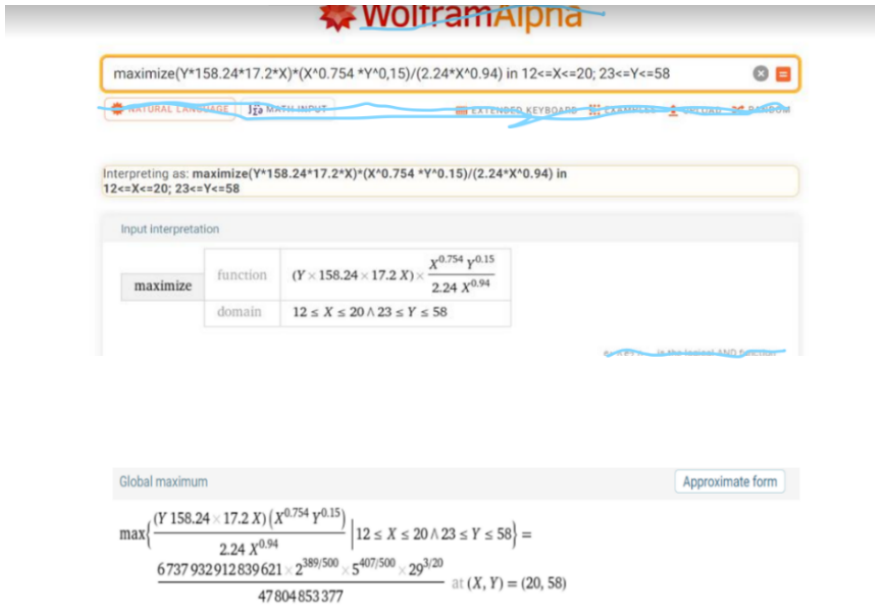
Fig. 5. Predicted criteria equations for the distribution of polluted air in real conditions when taking into account boundary conditions and the introduction of cleaning equipment according to the developed utility model patent
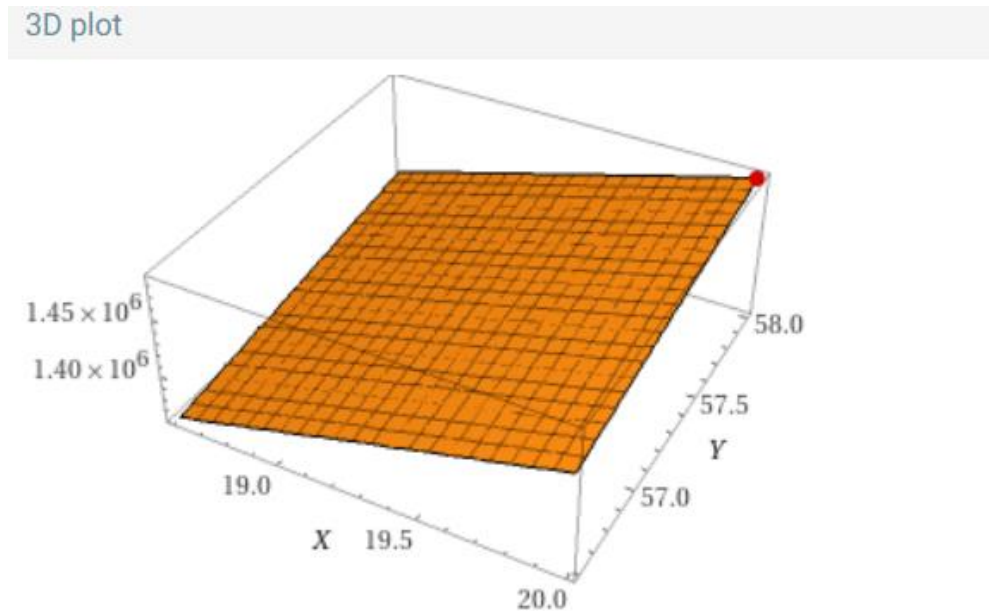

Fig. 6. 3D graph of the distribution of polluted air in real conditions, taking into account the boundary conditions and the introduction of cleaning equipment according to the developed utility model patent

Therefore, the proposed mathematical model of dispersion of solid particles with sufficient accuracy describes the process of dust propagation in atmospheric air.

3. Conclusion

The mathematical model of the transport of pollutants (DS) in the city takes into account both diffusion and turbulent transport mechanisms. The model also includes the interaction of air flow with elements of urban development, which significantly affects the distribution of pollution in height. The main aspects of the mathematical model are taken into account: diffusion transfer mechanism (distribution of pollutants due to molecular diffusion, taking into account the turbulence of air flows); interaction of air flow with urban development (the effect of a "street canyon," when high buildings limit horizontal and vertical air flows); dependence of the distribution of pollutants by height. Given the value of the Pearson correlation coefficient, which is in the range of 0.92-0.94, we can assert the adequacy of the mathematically obtained model that before the distribution of RR by the height of residential buildings, taking into account the wind speed and the ventilation coefficient, which depends on the structure of the building and its ability to provide natural circulation of air masses.

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МОДЕЛЮВАННЯ РОЗПОДІЛУ ДРІБНОДИСПЕРСНОГО ПИЛУ В АТМОСФЕРНОМУ ПОВІТРІ ЖИТЛОВИХ БУДИНКІВ

Анотація. Сталий розвиток країни включає баланс між економічним зростанням, соціальним добробутом та екологічною безпекою. Це означає управління всіма аспектами життя, щоб забезпечити добробут людей і не завдати шкоди навколишньому середовищу. Це важливо для того, щоб майбутні покоління могли жити в безпеці. Особливо важливою є якість атмосферного повітря, оскільки вона безпосередньо впливає на здоров'я людей. Цементна промисловість займає одне з перших позицій стосовно масштабів викидів шкідливих речовин, включаючи вуглекислий газ (CO_2). За своєю структурою, викиди пилу з цементних заводів розглядаються, в основному, як аеродисперсні системи. У цих системах дисперсна фаза складається з твердих частинок (пилу) або дрібних крапель, тоді як дисперсна фаза являє собою газоповітряну суміш. Ця газоповітряна суміш може містити різноманітні забруднюючі компоненти, як органічного, так і неорганічного походження. Прогнозування та регулювання якості повітря в районах, прилеглих до

цементних заводів, може бути досягнуто шляхом моделювання поширення цементного пилу. Дане моделювання дозволяє визначити концентрацію пилу в повітрі на різних відстанях від джерела викидів і допомагає розробити ефективні заходи щодо зниження техногенного навантаження на навколишнє середовище.

Цементний пил є одним з пріоритетних забруднювачів, який необхідно враховувати при організації моніторингу якості повітря. Ефективний атмосферний моніторинг пилового забруднення повітряного середовища дозволяє отримати актуальні дані про концентрацію пилу, аналізувати тенденції зміни та оцінювати вплив на здоров'я людей і навколишнє середовище.

Зменшення техногенного впливу аеродисперсних систем, що утворюються в результаті виробництва цементу, є важливим завданням для забезпечення екологічної безпеки довкілля.

Нами проведений детальний аналіз літературних даних даної проблеми і розроблена математична модель прогнозування розповсюдження цементного пилу в житлових забудовах. Запропоновано удосконалення пиловловлюючого обладнання при виробництві цементу, що дозволяє зменшити на 10-15% викиди цементного пилу в атмосферу.

Ключові слова: дрібнодисперсний цементний пил, нейтралізація, трепінг, екологічна безпека, моніторинг якості повітря.

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