них респіраторів у промислових умовах з урахуванням величини підсмоктування за смугою обтюрації й зміни концентрації пилу в повітря робочої зони.

Практична значимість. Доведено, що фільтруючі респіратори типу РПА можна безпечно використовувати при концентрації пилу до 100 мг/м^3.

Ключові слова: *протипиловий респіратор, фільтр, коефіцієнт захисту, пилове навантаження, вугільна шахта*

Цель. Определить границу концентрации угольной пыли для использования фильтрующих респираторов на угольных шахтах.

Методика. Расчет эффективности защиты фильтрующих респираторов основывается на определении среднегеометрического значения производственного коэффициента защиты фильтрующего респиратора, предложенного специалистами Американской ассоциации промышленных гигиенистов (ANSI) и Национального института охраны труда США (NIOSH).

Результаты. Установлена зависимость подмасочной концентрации пыли от запылённости воздуха в горных выработках, коэффициента защиты респиратора и изолирующих свойств полумасок. В результате моделирования распределения вероятности значений концентрации пыли под маской респиратора РПА установлено, что граница его безопасного использования составляет до 10 ПДК.

Научная новизна. Заключается в научном обосновании коэффициентов защиты отечественных фильтрующих респираторов в производственных условиях с учетом величины подсосов по полосе обтюрации и изменения концентрации пыли в воздухе рабочей зоны.

Практическая значимость. Установлено, что фильтрующие респираторы типа РПА можно безопасно использовать при концентрации пыли до 100 мг/м^3.

Ключевые слова: *противопылевой респиратор, фильтр, коэффициент защиты, пылевая нагрузка, угольная шахта*

Рекомендовано до публікації докт. техн. наук В. Є. Колесником. Дата надходження рукопису 08.03.16.

UDC 504.3.054:519.6

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DETERMINATION OF AREAS OF ATMOSPHERIC AIR POLLUTION BY SULFUR OXIDE EMISSIONS FROM MINING AND METALLURGICAL AND ENERGY GENERATING ENTERPRISES

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ВИЗНАЧЕННЯ ЗОН ЗАБРУДНЕННЯ ГІРНИЧО-МЕТАЛУРГІЙНИМИ ТА ЕНЕРГОГЕНЕРУЮЧИМИ ПІДПРИЄМСТВАМИ АТМОСФЕРНОГО ПОВІТРЯ ОКСИДАМИ СІРКИ

Purpose. Development of methods and software for determining levels and zones of atmospheric air pollution by emissions from mining and power generating companies that contain significant volumes of sulfur oxides.

Methodology. The forecast of the level of atmospheric air pollution by sulfur-containing emissions from mining and power generating companies is based on a mathematical model for calculating the concentration of sulfur dioxide, which takes into account the processes of its oxidation, as well as the formation and evaporation of sulfuric acid in the atmosphere. The numerical method is based on the joint solution of the equations of convective-diffusion transport of pollutants that come directly from enterprises or are formed additionally due to chemical reactions in the atmosphere. The technique is implemented using implicit difference schemes.

Findings. The developed methodology and software allow predicting the levels of atmospheric air pollution by large industrial enterprises taking into account chemical transformations of sulfur oxides in the environment. A number of numerical experiments have been carried out to estimate the levels and zones of atmospheric air pollution in the city of Dnipro with sulfur dioxide near industrial enterprises, taking into account various meteorological conditions.

Originality. The regularities of atmospheric air pollution by sulfur-containing emissions from industrial enterprises are established on the basis of a joint solution of transport process equations as for impurities coming from sources of pollution and transformation as a result of chemical reactions in the atmosphere.

Practical value. The developed forecast method and software allow determining the concentration of pollutants in the atmosphere and assessing the level of environmental hazard of large industrial enterprises. The obtained patterns of dispersion of sulfur oxides make it possible to predict pollution levels of environmental objects on the territory of industrial cities and to introduce air protection measures in a timely manner.

Keywords: *industrial enterprise, emission, dispersion, chemical interaction, numerical model*

Introduction. Enterprises of mining and metallurgical and fuel and energy complexes are the main sources of pollution of environmental objects [1]. Annually, as a result of their functioning, up to 35 % of the pollution from all stationary sources enters the environment. This leads to significant contamination of territories adjacent to industrial enterprises. High levels of contamination of environmental objects in the areas of functioning of metallurgical enterprises with heavy metals have been established.

One of the main pollutants of the environment in the operation of mining and energy enterprises is sulfur compounds. The most dangerous for life and health of people is sulfur dioxide SO_2, which is formed by burning of organic fuel (coal, oil) containing sulfur, as well as during industrial processing of sulfur-containing raw materials. And emissions of sulfur dioxide, caused by the operation of thermal power plants burning organic fuels, exceed 100 million tons per year [2].

More than 60 % of the released amount of SO_2 is due to the combustion of coal and oil [3]. In connection with the requirements for reducing air pollution with SO_2, oil with low sulfur content is in great demand and therefore is sold at a higher price.

The harmful effect is caused not only by sulfur dioxide itself, the main damage is caused by sulfur trioxide SO_3, formed during the oxidation of SO_2. Sulfur dioxide is difficult to oxidize in clean air. However, in the presence of dusty metal oxide particles under the influence of O_2, sulfur dioxide very quickly turns into SO_3. The reaction proceeds on the surface of the particles, which play the role of a heterogeneous catalyst. The ejected gases contain a significant amount of finely divided solids – ash, suspended in air. The oxidation of SO_2 is also facilitated by the presence of moisture droplets in the air, and SO_2 dissolved in water oxidizes rather quickly [3].

An additional source of air pollution are vehicles that emit pollutants into the environment, which worsen the living conditions of the population in large industrial centers [4]. To improve the efficiency of the capture of pollutants with vehicle exhaust, a mathematical model has been developed that takes into account the relevant performance characteristics [5].

Analysis of the recent research and publications. The works by Batluk V.A., Bakhareva V.S., Galich R.V., Pitsyk Yu.V., Proskurina I.V., Shaparya A.G., Shvartsman V.M., Yakuba O.R. etc. are dedicated to the study of the environmental consequences of the operation of large mining and metallurgical and power enterprises in urban areas.

Currently used are: empirical models – the normative methodology OND-86 (All-Union normative document – 86) *The Methods of Calculations for the Concentration of Harmful Substances in the Atmospheric Air from Enterprises Wastes*; analytical model of Gausse [3] and its varieties, numerical models [6]. To assess the effectiveness of compliance with environmental and sanitary and hygienic standards in residential development in the area of the emissions of waste gases from firing ovens, the level of surface concentrations of pollutants in the ambient air was calculated using the "PLENER-1.25" software complex [7]. In work [8], the effectiveness of reducing the negative impact of coke plants on the environment has been established.

The authors of [9] proposed criteria that take into account the negative impact of pollutants on human health. This allows us to determine the main directions of reducing the level of danger by choosing the optimal management decisions.

Empirical and analytical models allow calculating the pollutant concentration field at a stationary point source of contamination. The use of numerical models based on the solution of the Navier-Stokes equations with different turbulence models for this class of problems is usually carried out on expensive software packages such as *Ansys*. Mathematical models have also been developed for solving problems of protecting the atmosphere, hydrosphere and underlying surface on the basis of three-dimensional unsteady mesoscale processes in the atmosphere and stratified reservoirs [1, 3].

It should be noted that the proposed models and criteria do not fully take into account the processes of dispersion and chemical transformations of sulfur oxides in the atmospheric air of industrial cities.

Therefore, there is a need to develop a methodology for assessing the detail of the spatial distribution of atmospheric air pollution by harmful impurities, which are emitted by large industrial enterprises.

Unsolved aspects of the problem. When SO_2 is emitted in the atmosphere, the following reactions are possible: gas-phase molecular oxidation, gas-phase oxidation by radicals, oxidation on the surface of solid particles, and oxidation of liquid-droplet particles. The intensity of the reactions depends on the time of day, season, latitude, the number of particles, their size, the physical and chemical properties of the surface, as well as the probability of the molecule entering the liquid-droplet phase (clouds and fogs). It should be noted that the rate of sulfur oxidation decreases with distance from the source of emissions [4].

The main way to convert SO_2 to SO_3 is photochemical oxidation. Absorption of a photon by a molecule of SO_2 with a wavelength of more than 300 nm can lead to the transition of one of its electrons from one orbit to another, a higher one. In this case, the molecule passes into an excited state, its reactivity increases. Sulfur trioxide SO_3, formed in one way or another, depending on the specific state of the atmosphere, dissolves in droplets of moisture to form sulfuric acid. As a result of increasing emissions of sulfur oxides into the atmosphere, the content of sulfuric acid in precipitation increases sharply.

In an atmosphere where NH_3 ammonia is locally contained, an acid-base interaction can occur, resulting in the formation of ammonium hydrogen sulfate $NH_4(HSO_4)$ or ammonium sulfate $(NH_4)2SO_4$ in contact with a concentrated ammonia solution.

The dense haze enveloping many large industrial areas consists mainly of air-dispersed ammonium sulphate formed in this way. It's not safe to breathe this air. As a result of the release of sulfur and nitrogen oxides into the atmosphere, acids are formed that cause the acid precipitation. When falling into a reservoir or soil, such precipitation affects surface waters, soil, terrestrial and aquatic ecosystems, various structures, buildings. Negative effects of sulfate on humans when inhaled are already observed at a concentration of 6–10 $\mu g/m^3$, while the maximum allowable concentrations for SO_2 are 50 $\mu g/m^3$, and for H_2SO_4 are 100 $\mu g/m^3$.

As a result of chemical, photochemical, physicochemical reactions between pollutants and atmospheric components, other secondary pollutants are formed. The main source of pyrogenic pollution on the planet are thermal power plants, metallurgical and chemical enterprises, boiler plants, consuming more than 70 % of the annually produced solid and liquid fuels.

According to the foregoing, the current task is to assess the pollution of atmospheric air from industrial and power plant emissions. The solution of this class of problems requires the creation of mathematical models for the rapid assessment of the level of air pollution. The process of dissipating SO_2 in the atmosphere is accompanied by a number of chemical reactions, which are practically impossible to model in simulation. Therefore, in practice, they are limited to considering some of them.

Formulation of the purpose of the work. The aim of the work is to develop a methodology and software for the rapid numerical calculation of levels and zones of air pollution in areas adjacent to large industrial enterprises, taking into account chemical transformations of pollutants in the atmosphere, depending on the meteorological parameters of the environment.

Presentation of the main research. In solving this problem, we will take into account the process of formation of sulfuric acid in the interaction of SO_2 with water vapor. In this case, the modeling equations are

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}= =\operatorname{div}(\mu \operatorname{grad} C)+\sum_{i=1}^{N} Q_i(t)\delta(x-x_i)\delta(y-y_i); \quad (1)$$

$$\frac{\partial C}{\partial t}=-\sigma\cdot C\cdot W; \quad (2)$$

$$\frac{\partial W}{\partial t}+\frac{\partial uW}{\partial x}+\frac{\partial vW}{\partial y}=\operatorname{div}(\mu \operatorname{grad} W); \quad (3)$$

$$\frac{\partial A}{\partial t}+\frac{\partial uA}{\partial x}+\frac{\partial vA}{\partial y}=\operatorname{div}(\mu \operatorname{grad} A); \quad (4)$$

$$\frac{\partial A}{\partial t}=\sigma\cdot C\cdot W, \quad (5)$$

where C is the concentration of SO_2; W is the concentration of water vapor; A is the concentration of sulfuric acid H_2SO_4; u, v – components of the wind speed vector averaged over the transfer height (Marchuk G. I.); $\mu = (\mu x, \mu y)$ is the coefficient of turbulent diffusion; Q – emission intensity of pollutant SO_2; $\delta(x - x_i)\ \delta(y - y_i)$ is the Dirac delta function; x_i, y_i are the coordinates of the emission source; σ is a coefficient that takes into account the chemical decomposition of SO_2, $\sigma = 0.027\ h^{-1}$ (Arguchintsev V. K.); t is time. The content of water vapor in the atmosphere is 60 %.

Equations (1–4) describe the dispersion of SO_2, water vapor and sulfuric acid emissions by wind and atmospheric diffusion. Equations (2) and (5) take into account changes in SO_2 concentration due to the formation of sulfuric acid and changes in its concentration due to the chemical transformation of SO_2. In addition, we will take into account the process of interaction of SO_2 with ammonia, which is contained in the atmospheric air of industrial cities. The presence of ammonia in the atmospheric air of settlements can be taken at the level of an average daily allowable concentration of 0.04 mg/m^3. To take into account the interaction of SO_2 with ammonia, it is necessary to integrate, at each time step, the following equation

$$\frac{\partial C}{\partial t}=-\sigma_A\cdot N\cdot C, \quad (6)$$

where N is the concentration of ammonia in the ambient air, $\sigma_A = 0.003h^{-1}$.

The statement of the boundary conditions for this equation is considered in the papers by Arguchintsev V. K., Marchuk G. I. and Samarskiy A. A. Numerical integration of the impurity transfer equations (1, 3, 4) is carried out using an implicit difference splitting scheme developed by Samarskiy A. A. We give a description for one of the transfer equations, for example, for equation (1). Similarly, integration is performed for equations (3, 4).

The time derivative is approximated by the divided difference "back"

$$\frac{\partial C}{\partial t}\approx\frac{C_{ij}^{n+1}-C_{ij}^{n}}{\Delta t}.$$

In convective derivatives, the terms of unidirectional transfer are written as

$$\frac{\partial uC}{\partial x}=\frac{\partial u^{+}C}{\partial x}+\frac{\partial u^{-}C}{\partial x};\quad \frac{\partial vC}{\partial y}=\frac{\partial v^{+}C}{\partial y}+\frac{\partial v^{-}C}{\partial y}.$$

Taking into account the previous expression, the convective derivatives are approximated by the separated "against the flow" differences on the upper time layer

$$\frac{\partial u^{+}C}{\partial x}\approx\frac{u^{+}_{i+1,j}C^{n+1}_{i,j}-u^{+}_{i,j}C^{n+1}_{i-1,j}}{\Delta x}=L^{+}_{x}C^{n+1};$$

$$\frac{\partial u^{-}C}{\partial x}\approx\frac{u^{-}_{i+1,j}C^{n+1}_{i+1,j}-u^{-}_{i,j}C^{n+1}_{i,j}}{\Delta x}=L^{-}_{x}C^{n+1};$$

$$\frac{\partial v^{+}C}{\partial y}\approx\frac{v^{+}_{i,j+1}C^{n+1}_{i,j}-v^{+}_{i,l}C^{n+1}_{i,j-1}}{\Delta y}=L^{+}_{y}C^{n+1};$$

$$\frac{\partial v^{-}C}{\partial y}\approx\frac{v^{-}_{i,j+1}C^{n+1}_{i,j+1}-v^{-}_{i,j}C^{n+1}_{i,j}}{\Delta y}=L^{-}_{y}C^{n+1}.$$

The velocity components u are determined on the vertical faces of the difference cells, and the velocity components v – on the horizontal faces. The indices of these faces correspond to the indices of the cells located to the right of or above the corresponding face.

The second derivatives are approximated as follows

$$\frac{\partial}{\partial x}(\mu_x\frac{\partial C}{\partial x})\approx\mu_x\frac{C^{n+1}_{i+1,j}-C^{n+1}_{i,j}}{\Delta x^2}-$$
$$-\mu_x\frac{C^{n+1}_{i,j}-C^{n+1}_{i-1,j}}{\Delta x^2}=M^{-}_{xx}C^{n+1}+M^{+}_{xx}C^{n+1};$$

$$\frac{\partial}{\partial y}\left(\mu_y\frac{\partial C}{\partial y}\right)\approx\mu_y\frac{C^{n+1}_{i,j+1}-C^{n+1}_{i,j}}{\Delta x^2}-$$
$$-\mu_y\frac{C^{n+1}_{i,j}-C^{n+1}_{i,j-1}}{\Delta x^2}=M^{-}_{yy}C^{n+1}+M^{+}_{yy}C^{n+1},$$

where $L^{+}_{x},L^{-}_{x},L^{+}_{y},L^{-}_{y},M^{+}_{xx},M^{-}_{xx},M^{+}_{yy},M^{-}_{yy}$ are the symbols for the difference operators. Taking into account the above notation, the difference analog of the transfer equation is written as

$$\frac{C^{n+1}_{i,j}-C^{n}_{i,j}}{\Delta t}+L^{+}_{x}C^{n+1}+L^{-}_{x}C^{n+1}+L^{+}_{y}C^{n+1}+$$
$$+L^{-}_{y}C^{n+1}+\sigma C^{n+1}_{ij}=(M^{+}_{xx}C^{n+1}+L^{-}_{xx}C^{n+1}+$$
$$+L^{+}_{yy}C^{n+1}+L^{-}_{yy}C^{n+1})+q_{ij}\delta_{ij}.$$

Denote δ_{ij} – the number "1" or "0", depending on whether the source of contamination is located or not in the difference cell "ij". The value of q_{ij} is equal to the intensity q_k of the corresponding k^{th} source located in the difference cell "ij" divided by the area of this cell

$$q_{ij}=q_k/(\Delta x\Delta y).$$

Split the difference equation into four difference equations so that at each step only one direction of perturbation transfer is taken into account, determined by the sign for the convective derivative. In this case, the difference equations have the form:

- at the first step of the splitting $k=\frac{1}{4}$

$$\frac{C^{n+k}_{ij}-C^{n}_{ij}}{\Delta t}+\frac{1}{2}(L^{+}_{x}C^{k}+L^{+}_{y}C^{k})+\frac{\sigma}{4}C^{k}_{ij}=$$
$$=\frac{1}{4}(M^{+}_{xx}C^{k}+M^{-}_{xx}C^{n}+M^{+}_{yy}C^{k}+M^{-}_{yy}C^{n})+\sum_{l=1}^{N}\frac{\overline{q}_l}{4}\delta_l;$$

- at the second step of the splitting $k=n+\frac{1}{2}$, $c=n+\frac{1}{4}$

$$\frac{C^{k}_{ij}-C^{c}_{ij}}{\Delta t}+\frac{1}{2}(L^{-}_{x}C^{k}+L^{-}_{y}C^{k})+\frac{\sigma}{4}C^{k}_{ij}=$$
$$=\frac{1}{4}(M^{-}_{xx}C^{k}+M^{+}_{xx}C^{c}+M^{-}_{yy}C^{k}+M^{+}_{yy}C^{c})+\sum_{l=1}^{N}\frac{\overline{q}_l}{4}\delta_l;$$

- at the third step of the splitting $k=n+\frac{3}{4}$, $c=n+\frac{1}{2}$

$$\frac{C^{k}_{ij}-C^{c}_{ij}}{\Delta t}+\frac{1}{2}(L^{+}_{x}C^{k}+L^{-}_{y}C^{k})+\frac{\sigma}{4}C^{k}_{ij}=$$
$$=\frac{1}{4}(M^{-}_{xx}C^{c}+M^{+}_{xx}C^{k}+M^{-}_{yy}C^{k}+M^{+}_{yy}C^{c})+\sum_{l=1}^{N}\frac{\overline{q}_l}{4}\delta_l;$$

- at the fourth step of the splitting $k=n+1$, $c=n+\frac{3}{4}$

$$\frac{C^{k}_{ij}-C^{c}_{ij}}{\Delta t}+\frac{1}{2}(L^{-}_{x}C^{k}+L^{+}_{y}C^{k})+\frac{\sigma}{4}C^{k}_{ij}=$$
$$=\frac{1}{4}(M^{-}_{xx}C^{k}+M^{+}_{xx}C^{c}+M^{-}_{yy}C^{c}+M^{+}_{yy}C^{k})+\sum_{l=1}^{N}\frac{\overline{q}_l}{4}\delta_l.$$

In the above difference equations, a value $\overline{q}_l=\frac{q_l}{\Delta x\Delta y}$ is used. The value of the function δ_l is identically equal to zero in all cells, except for those where the source of the ejection is located.

Since at each step of the splitting the template of the difference equations has a triangular shape, then on the upper time layer the unknown value of the function C is found using the "running account" method. On the basis of the constructed numerical model, a software package was developed in the Fortran language.

In a similar way, the numerical integration of equations (2) and (4) is performed.

The developed numerical model was applied to study the dynamics of atmospheric air pollution during steady-state emissions of sulfur dioxide by a metallurgical plant located on the territory of the city of the Dnipro.

The emission source is constantly operational. According to the data of the environmental passport of Dnipro concerning emissions of large enterprises into the atmosphere, the intensity of sulfur dioxide emission is Q = 17.4 g/s. The calculation was carried out with the following parameters: dimensions of the calculated area are 18x8 km; diffusion coefficient, according to Proskurina I.V. is $\mu=(0.1\div1)\cdot U$; averaging over the transfer height is of 600 m. In the first version of the calculation, the wind velocity was $U = 6$ m/s with the wind direction from the northwest $\alpha = 20°$ (Fig. 1), $C_{max} = 0.3426$ mg/m^3, $t = 52$ s; in the second version of the calculation, the wind speed is $U = 8$ m/s with the direction of the wind from the northwest $\alpha = 60°$ (Fig. 2), $C_{max} = 0.3226$ mg/m^3, $t = 52$ s.

In Figs. 1 and 2, the concentration value is expressed as a percentage of the maximum concentration at a specific time.

Thus it is visible, as in the course of time the significant zone of pollution is formed. Cloud pollution very quickly covers the surrounding areas, located in the direction of the wind.

When considering the first meteorological situation (Fig. 1), the following contaminated areas fall into the contamination zone: Svoboda Ave., Mazepa Ave., Metallurgov Ave., Pushkin Ave., Alexander Pol' Ave., Gagarin Ave. The concentration of sulfur dioxide varies according to this dependence: Zavodskaya Str. – up to 55 %, Kievskaya Str. – up to 45 %, Orlovskaya Str. – up to 32 %, Rabochaya Str. – up to 20 %, Titov Str. – up to 10 %.

When considering the second meteorological situation (Fig. 2), according to which the direction of the wind was changed $\alpha = 60°$ and the wind speed was $U = 8$ m/s, the pollution zone included: Svoboda Ave., Mazepa Ave., Metallurgov Ave., Bohdan Khmelnytsky Ave. The concentration of sulfur dioxide varies according to this dependence: Zavodskaya Str. – up to 45 %; Kievskaya Str. – up to 40 %, Orlovskaya Str. – up to 30 %, Rabochaya Str. – up to 15 %, Titov Str. – up to 7 %, Victory Str. – less than 4 %.

Fig. 3 shows the zone of pollution with sulfur dioxide, which is formed from two sources: metallurgical and coking plants. The initial data, the meteorological parameters and the dimensions of the computational domain were assumed to be the same as for the first version of the calculation in the presence of one source of pollution. The pollution cloud covers: Svoboda Ave., Mazepa Ave., Metallurgov Ave., Pushkin Ave., Aleksander Pol' Ave., Bogdan Khmelnitsky Ave, Gagarin Avenue. The concentration of sulfur dioxide varies according to this dependence: Zavodskaya Str. – up to 75 %, Kievskaya Str. – up to 65 %. Orlovskaya Str. – up to 40 %, Rabochaya Str. – up to 30 %, Titov Str. – up to 25 %, Zaporozhye highway Str. – up to 20 %, Kosmicheskaya Str. – less than 12 %.

To evaluate the impact of emissions of the second enterprise on the level of atmospheric air pollution, a design point was chosen at a distance of 5 km (along the x axis) and 2.5 km (along the y axis) from the emission source. With the emission from the metallurgical plant only (Fig. 1), the concentration of contamination at the reference point is about 12 % of the concentration at the outlet from the industrial pipes (from $C_{max} = 0.3226$ mg/m^3), and in the presence of a second pollution source (the coking plant), the concentration at a given point increases and is about 30 %, i.e. the level of pollution is increased 2.2 times. Thus, using the developed numerical model, it is possible to predict the effect of emissions on the formation of atmospheric air pollution zones in a city when building new enterprises or when reconstructing existing ones.

In the operation of thermal power plants that use organic fuel, the following pollutants enter the atmosphere: sulfur oxides, nitrogen oxides, carbon dioxide, particulate matter and other substances. Emissions of thermal power plants account for 40 % of the total emission of stationary pollution sources (K. Work, C. Worner). The thermal power station (TPP) with a capacity of 1 GW at a consumption of 3 million tons of coal emits

Fig. 1. Zone of pollution by sulfur dioxide with the direction of the wind from the northwest α = 20°, one source of pollution

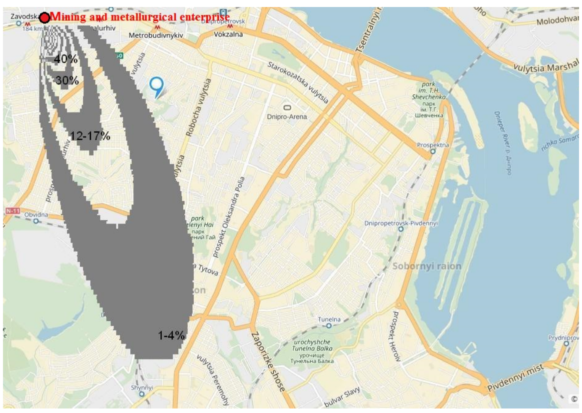

Fig. 2. Zone of pollution by sulfur dioxide with the direction of the wind from the northwest α = 60°, one source of pollution

Fig. 3. Zone of pollution by sulfur dioxide with the direction of the wind from the northwest α = 20°, two sources of pollution

into the environment: 7 million tons of CO_2, 120,000 tons of SO_x, 20,000 tons of NO_x, 750,000 tons of ash.

Analysis of data on air emissions of large enterprises of the city of Dnipro showed that the greatest amount of SO_2 comes due to the operation of Pridneprovskaya TPP – 55434 tons/year.

The developed numerical model was used to estimate the zone of pollution with sulfur dioxide at operating Pridneprovskaya TPP. The emission intensity of sulfur dioxide is $Q = 1.78$ kg/s. The dimensions of the calculated area are 15×7.2 km; the diffusion coefficient, according to Proskurina I. G. is $\mu = (0.1 \div 1) \cdot U$; averaging over the transfer height of 600 m, the wind speed from the southeast was $U = 6$ m/s, $C_{max} = 0.582$ mg/m^3, $t = 52$ s.

The maximum permissible concentration of SO_2 (maximum one-time – 0.5 mg/m^3, daily average – 0.05 mg/m^3).

When considering this meteorological situation (Fig. 4), the following areas fall into the contamination zone: Soborny district, Heroyev Ave., Gagarin Ave., Aleksander Pol' Ave., Pushkin Ave. The concentration of sulfur dioxide varies according to this dependence: in the area of the southern bridge it is up to 54 %, Sicheslavskaya embankment – up to 30 %, Gagarin Ave. – up to 15 %, Alexander Pol' Ave. – up to 10 %, Vladimir Antonovich Str. it is less than 6 %. At the reference point, the Heroev Ave., the SO_2 concentration is 22 %, namely $C = 0.1281$ mg/m^3, which is less than the maximum one-time concentration, but twice the daily average.

As a result of the conducted researches, the authors developed a software package in the language of Fortran, which realizes the numerical solution of the equations of convective-diffusion transport of pollutants and the equations of their chemical transformation in the atmosphere with the help of implicit difference splitting schemes. The error in the calculations is determined by the grid step size, the accuracy of the input meteorological parameters, and the intensity of the pollutant emission. The error in the calculations is 15–17 %.

Conclusions and recommendations for further research. As a result of the research, the following results were obtained:

- regularities of dispersion and chemical transformations of pollutants coming from large mining and metallurgical and power generating enterprises were established;

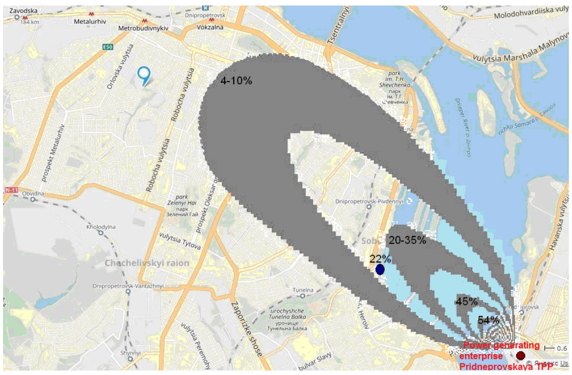

Fig. 4. Zone of pollution by sulfur dioxide with wind direction from the southeast $\alpha = 30°$*, source of pollution – Pridneprovskaya TPP*

- a methodology for estimating the levels of air pollution at different distances from large enterprises, allowing to take into account both the specific chemical transformations of pollutants in the air and the effect of meteorological conditions on their dispersion was devised;

- a numerical model for calculating the dispersion of emissions in the atmosphere, taking into account the change in the magnitude and direction of wind speed, the vertical diffusion coefficient with altitude was thought out;

- a software package has been developed that makes it possible to conduct computational experiments to assess the level of atmospheric air pollution from large industrial enterprises, taking into account the chemical reactions of pollutants in the atmosphere;

- a study was carried out on the level of atmospheric air pollution by sulfur dioxide in the zone of influence of both a single enterprise and the joint operation of several industrial facilities;

- studies of the levels of atmospheric air pollution with sulfur dioxide in the zone of influence of a mining and smelting enterprise and a thermal power station were conducted.

The study of the level of atmospheric air pollution by industrial enterprises is necessary for the environmentally safe operation of these facilities. Conducting this class of calculations is an indispensable tool for the practical assessment of the environmental situation when large industrial enterprises operate, whose activities are associated with the entry of harmful contaminants into the atmosphere.

The obtained results help form the scientific and methodological basis for the creation of a three-dimensional numerical model for the forecast of atmospheric air pollution in industrial cities. The prospect of development of this direction is the creation of a three-dimensional model that allows to take into account the terrain and the development of the terrain.

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Мета. Розробка методики й програмного забезпечення для визначення рівнів і зон забруднення атмосферного повітря викидами гірничо-металургійних і енергогенеруючих підприємств, що містять значні обсяги оксидів сірки.

Методика. Прогноз рівня забруднення атмосферного повітря сірковміщуючими викидами гірничо-металургійних і енергогенеруючих підприємств ґрунтується на математичній моделі для розрахунку концентрації діоксиду сірки, що враховує процеси його окислення, а також утворення й випаровування сірчаної кислоти в атмосфері. Чисельна методика базується на спільному рішенні рівнянь конвективно-дифузійного переносу забруднюючих речовин, що надходять безпосередньо від підприємств або утворюються додатково за рахунок хімічних реакцій в атмосфері. Методика реалізується з використанням неявних різницевих схем.

Результати. Розроблена методика й програмне забезпечення дозволяють оперативно прогнозувати рівні забруднення атмосферного повітря викидами великих промислових підприємств з урахуванням хімічних перетворень оксидів сірки в навколишньому середовищі. Проведено ряд чисельних експериментів з оцінки рівнів і зон забруднення атмосферного повітря м. Дніпро діоксидом сірки поблизу промислових підприємств з урахуванням різних метеорологічних умов.

Наукова новизна. Встановлені закономірності забруднення атмосферного повітря викидами промислових підприємств на основі спільного рішення рівнянь переносу домішок, що надходять від джерел забруднення, і трансформації в результаті хімічних реакцій в атмосфері.

Практична значимість. Розроблені прогнозна методика й програмне забезпечення дозволяють оперативно визначити концентрацію забруднюючих речовин в атмосфері, оцінити рівень екологічної небезпеки функціонування великих промислових підприємств. Отримані закономірності розсіювання оксидів сірки дозволяють прогнозувати рівні забруднення об'єктів навколишнього середовища на території промислових міст і своєчасно впроваджувати повітряохоронні заходи.

Ключові слова: *промислове підприємство, викид, розсіювання, хімічна взаємодія, чисельна модель*

Цель. Разработка методики и программного обеспечения для определения уровней и зон загрязнения атмосферного воздуха выбросами горно-металлургических и энергогенерирующих предприятий, которые содержат значительные объемы оксидов серы.

Методика. Прогноз уровня загрязнения атмосферного воздуха серосодержащими выбросами предприятий основывается на математической модели для расчета концентрации диоксида серы с учетом процессов его окисления, а также образования и испарения серной кислоты в атмосфере. Численная методика базируется на совместном решении уравнений конвективно-диффузионного переноса загрязняющих веществ, которые непосредственно поступают от предприятий или образуются дополнительно за счет химических реакций в атмосфере. Методика реализуется с использованием неявных разностных схем.

Результаты. Разработанные методика и программное обеспечение позволяют оперативно прогнозировать уровни загрязнения атмосферного воздуха выбросами крупных промышленных предприятий с учетом химических превращений оксидов серы в окружающей среде. Проведен ряд численных экспериментов по оценке уровней и зон загрязнения атмосферного воздуха г. Днепр диоксидом серы вблизи промышленных предприятий с учетом различных метеорологических условий.

Научная новизна. Установлены закономерности загрязнения атмосферного воздуха серосодержащими выбросами промышленных предприятий на основе совместного решения уравнений для процесса переноса примесей, поступающих от источников загрязнения, и трансформации в результате химических реакций в атмосфере.

Практическая значимость. Разработанные прогнозная методика и программное обеспечение позволяют оперативно определить концентрацию загрязняющих веществ в атмосфере и оценить уровень экологической опасности функционирования крупных промышленных предприятий. Полученные закономерности рассеивания оксидов серы позволяют прогнозировать уровни загрязнения объектов окружающей среды на территории промышленных городов и своевременно внедрять воздухоохранные мероприятия.

Ключевые слова: *промышленное предприятие, выброс, рассеивание, химическое взаимодействие, численная модель*

Рекомендовано до публікації докт. техн. наук В. І. Голіньком. Дата надходження рукопису 15.03.16.