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PREDICTION OF ATMOSPHERE POLLUTION IN CASE OF EMISSIONS FROM MAIN MINE FANS

Purpose. Emissions from mine ventilation system can create intensive atmosphere air pollution. As a rule, a huge amount of dust from mine fan enters atmosphere low layers. An important task is the development of methods to assess levels of the atmosphere pollution near mines and settlements. To solve this problem it is important to have physically proved mathematical models. Nowadays to predict the atmosphere pollution near settlements which are effected by mine fan the empirical model OND–86 is used. This model does not take into account many important physical factors. So, the purpose of this study is the development of quick computing mathematical model to predict the atmosphere pollution in case of dust emissions from mine fan. **Methodology.** To predict levels of the atmosphere pollution in case of mine fan work 3D equation of dust convective – diffusive flow was used. This equation takes into account gravity fallout, wind velocity, atmosphere turbulent diffusion, location of dust emission source. To sole modeling equation the implicit difference scheme of splitting was used. **Findings**. Developed mathematical model allows quick prediction of the level of atmosphere pollution in case of dust emissions from mine ventilation fan. The models allow to obtain zones of contamination near settlements which are situated in vicinity of mine. **Originality**. The developed mathematical model takes into account a number of physical factors, which at the present time are not considered on the days when prediction of the atmosphere pollution in settlements near mine is carried out. **Practical value**. On the basis of the developed mathematical model program code was created. This code can be used for evaluation of atmosphere pollution in settlements which are effected mine fan emissions.

Keywords: atmosphere pollution; mine fan; mathematical modelling; numerical model

Introduction

The task of assessing the level of air pollution from the different techno sources of emission (accidents, industrial chimneys, main fans at mines, dumps of wastes, etc) [1, 2, 3, 6, 7–13] has a huge interest. The main pollution of the atmosphere by coal mining enterprises occurs during coal mining. The gas – methane released from the formations together with coal dust is emitted through the diffuser of the ventilation shaft into the atmosphere. The volumetric flow rate of the dust-gas-air mixture is 14 000 m^3/min. The concentration of dust in the gas-air mixture is 5.5 mg/m^3, methane – 0.1 % per ton of produced coal. When unloading coal and storing it in a warehouse, coal dust is emitted into the atmospheric air. When coal moves through a closed gallery, the rocks are periodically cleaned and spilled, which is dumped through the hatch. Inorganic dust containing silicon dioxide enters the atmospheric air. With the passage of the mine workings, a large part of the rock mass (90 %) is removed to the rock heap, and a small part (10 %) is used for laying the worked-out space. When

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loading and unloading the rock and forming the dump by the bulldozer, inorganic dust with a high content of silicon dioxide enters the air.

Significant role in air pollution is performed by the main ventilation fans (MVF), as they operate around the clock, discharging the exhaust mine air into the atmosphere. Mine air emissions contain gaseous impurities (CO, CO_2, NO_x) and solid particles of coal and rock dust. The dust emissions of the «West Donbas Mine» are about 2000 tons/year.

The pathogenic effect of dust is determined by the mass of dust, the time of its impact, the material composition and dispersion.

The material composition of coal and rock dust is determined by the composition of coal rocks. The host rocks contain: quartz, mica, hydromica, calcite, dolomite, magnesite, sulfides.

The degree of dust dispersion is influenced by the physical and mechanical properties of coal, loading and transportation of rock, the degree of turbulence in ventilation flows. The dispersed composition of dust is not constant and can vary: 5 mkm – 12 %; 5–10 mkm – 23 %; 10–30 mkm – 59 %; more than 30 mkm – 6 %.

The maximum permissible concentration for the most harmful types of industrial dust is in the range of 0.01 – 10 mg/m^3, depending on the characteristics of the dust and the silicon dioxide content of SiO_2; for the settlements, this concentration is lower and amounts to 0.5 – 1.5 mg/m^3.

Currently, to calculate the concentration of impurities in atmospheric air experimental, empirical, analytical, numerical methods are used.

Experimental methods are effective, but they allow to take into account only accomplished events with specific meteorological parameters, they are performed locally, they require high-quality expensive equipment, and material and time costs.

Most computer programs regarding the calculation of pollutant transport in the surface layer of the atmosphere from various sources are based on the model of M. E. Berland – OND–86. This technique is very simple to implement, but it is difficult to use it to calculate the dynamics of the process, since it uses the dimensionless and empirical coefficients obtained on the basis of average annual values of the parameters of the pollution source. The results obtained by this method are somewhat underestimated, their error increases with increasing distance from the source of emission.

Analytical methods of solving allow solving differential equations taking into account real physical parameters: wind speed, diffusion coefficient, particles sedimentation rate, ejection source power. However, all these solutions are obtained according to the introduced simplifications, since the analytical solution of the three-dimensional transport equations is rather complicated.

Numerical methods of calculation take into account all the factors listed, are implemented on the basis of the Navier-Stokes equations or by finite difference methods. These methods are operational. They have a smaller calculation error, but require skills of numerical simulation.

Thus, there is a shortage of operational control methods, in particular, dust emissions, which does not allow them to assess objectively, promptly identify the reason for their increase, select the desired mode of operation based on the dust factor or carry out dust suppression measures.

Fig. 1. West Donbas Mine:
1 – main ventilation fan

Emissions from MVF pose a threat of dust pollution of atmospheric air in the areas adjacent to the mine. To assess the impact of these emissions on air pollution, it is necessary to have effective mathematical models. On the basis of such models, it is possible to predict the change in the quality of atmospheric air for different weather situations characteristic of a particular region and for different intensity of coal dust emission, which may vary during the operation of the mine.

At present, the forecast of the atmospheric air pollution level is being carried out on the basis of

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simplified models that do not take into account the velocity profile of the wind flow. In addition, the OND–86 model used in practice, the Gauss model and the Berland model carry out a forecast only for a permanently operating source of emissions. For practice, it is important to have mathematical models of wider use.

Purpose

The purpose of this work is to create a numerical model and software for the rapid conduct of computational experiments to analyze and predict the level of air pollution by dust emissions from the main ventilation fan. On the basis of such an assessment, the risk for the population in the zone of influence of emissions from this fan is analyzed.

Methodology

In this paper, the solution of two problems is considered related to the simulation of atmospheric air pollution from dumps.

The process of dispersion of dust from the fan was modeled by the following equation [1, 4, 5]:

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}+\frac{\partial (w-w_s)C}{\partial z}=$$

$$=\frac{\partial}{\partial x}(\mu_x\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(\mu_y\frac{\partial C}{\partial y})+\frac{\partial}{\partial z}(\mu_z\frac{\partial C}{\partial z})+$$

$$+Q_0(t)\delta(x-x_0)\delta(y-y_0)\delta(z-z_0)\,. \quad (1)$$

where C – dust concentration (mg/m3); u, v, w – airflow components (m/s); ws – dust settling rate (m/s); μ = (μx, μy, μz) – turbulent diffusion coefficients (m/s2); x0, y0, z0 – the coordinates of the point source of the main ventilation fan MVF (m); Q0 – the averaged value of the dust intensity at the location of the point source of emission (mg/s); δ(x – x0)δ(y – y0)δ(z – z0) – Dirac's delta-function, which is used to simulate the arrival of dust from MVF. The values of the diffusion coefficient is calculated by dependencies μx = (0.1-1)·U, μy = (0.1-1)·U, μz = k(z/z1)m, where U – wind speed (m), z – height above ground level (m), z1 – height, where wind speed is given U (m), m ≈ 1, k = 0.2.

The composition of the dust is not uniform, taking into account the settling of individual fractions of dust is achieved by setting a different sedimentation rate w_s for each fraction, so the calculation on this model must be performed for each fraction. This parameter is calculated using the Stokes formula (2) or is given from epy known experimental data.

$$w_s^2 c_x=\frac{4d(\rho_p-\rho_a)g}{3\rho_a}\,, \quad (2)$$

where d – the equivalent particle diameter of the pollutant (m); ρ_p – particle density of the pollutant (mg/m^3); ρ_a – air density (mg/m^3); c_x = 24/Re + $4/\sqrt{\text{Re}}$ – the dependence of the drag coefficient on the Reynolds number.

An extremely important feature of this model is taking into account the stability of the atmosphere due to the task according to M.E. Berland of different values of the vertical diffusion coefficient μ_z. It should be noted that the normative methodology of OND-86 does not allow to take into account the different stratification of the atmosphere.

Two approaches are used.

The first approach is based on splitting of the model equations into four fractional steps. At each splitting step, two physical processes are taken into account: convective transport and atmospheric diffusion; in addition, at each splitting step, the influence of the dust emission source on the formation of the contaminated zone is taken into account.

To build a numerical model, an implicit alternating triangular difference scheme is used, approximating the modeling equation (1). It is built on a rectangular differential grid. The concentration is determined in the center of the difference cells, the components of the air velocity vector are set at the boundaries of the difference cells [5]. For approximation of time derivatives the formula is used:

$$\frac{\partial C}{\partial t}=\frac{C_{\text{ijk}}^{\text{n+1}}-C_{\text{ijk}}^{\text{n}}}{\Delta t}\,.$$

Prior to discretization, convective derivatives are written as the sum of signed variables:

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$$\frac{\partial uC}{\partial x}=\frac{\partial u^{+}C}{\partial x}+\frac{\partial u^{-}C}{\partial x},\qquad \frac{\partial \mathrm{v}C}{\partial y}=\frac{\partial \mathrm{v}^{+}C}{\partial y}+\frac{\partial \mathrm{v}^{-}C}{\partial y},$$

$$\frac{\partial \mathrm{w}C}{\partial z}=\frac{\partial \mathrm{w}^{+}C}{\partial z}+\frac{\partial \mathrm{w}^{-}C}{\partial z},$$

where $u^{+}=\frac{u+|u|}{2}$, $u^{-}=\frac{u-|u|}{2}$, $\mathrm{v}^{+}=\frac{\mathrm{v}+|\mathrm{v}|}{2}$, $\mathrm{v}^{-}=\frac{\mathrm{v}-|\mathrm{v}|}{2}$, $\mathrm{w}^{+}=\frac{\mathrm{w}+|\mathrm{w}|}{2}$, $\mathrm{w}^{-}=\frac{\mathrm{w}-|\mathrm{w}|}{2}$.

Difference approximations of the first derivatives are written as:

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

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

$$\frac{\partial \mathrm{v}^{+}C}{\partial y}\approx\frac{\mathrm{v}^{+}_{\mathrm{ij+1k}}C^{\mathrm{n+1}}_{\mathrm{ijk}}-\mathrm{v}^{+}_{\mathrm{ijk}}C^{\mathrm{n+1}}_{\mathrm{ij-1k}}}{\Delta x}=L^{+}_{\mathrm{y}}C^{\mathrm{n+1}},$$

$$\frac{\partial \mathrm{v}^{-}C}{\partial y}\approx\frac{\mathrm{v}^{-}_{\mathrm{ij+1k}}C^{\mathrm{n+1}}_{\mathrm{ij+1k}}-\mathrm{v}^{-}_{\mathrm{ijk}}C^{\mathrm{n+1}}_{\mathrm{ijk}}}{\Delta x}=L^{-}_{\mathrm{y}}C^{\mathrm{n+1}},$$

$$\frac{\partial \mathrm{w}^{+}C}{\partial z}\approx\frac{\mathrm{w}^{+}_{\mathrm{ijk+1}}C^{\mathrm{n+1}}_{\mathrm{ijk}}-\mathrm{w}^{+}_{\mathrm{ijk}}C^{\mathrm{n+1}}_{\mathrm{ijk-1}}}{\Delta z}=L^{+}_{\mathrm{z}}C^{\mathrm{n+1}},$$

$$\frac{\partial \mathrm{w}^{-}C}{\partial z}\approx\frac{\mathrm{w}^{-}_{\mathrm{ijk+1}}C^{\mathrm{n+1}}_{\mathrm{ijk+1}}-\mathrm{w}^{-}_{\mathrm{ijk}}C^{\mathrm{n+1}}_{\mathrm{ijk}}}{\Delta x}=L^{-}_{\mathrm{z}}C^{\mathrm{n+1}},$$

where

$$L^{+}_{\mathrm{x}}=\frac{u^{+}_{\mathrm{i+1jk}}C^{\mathrm{n+1}}_{\mathrm{ijk}}-u^{+}_{\mathrm{ijk}}C^{\mathrm{n+1}}_{\mathrm{i-1jk}}}{\Delta x},$$

$L^{-}_{\mathrm{x}}=\frac{u^{-}_{\mathrm{i+1jk}}C^{\mathrm{n+1}}_{\mathrm{i+1jk}}-u^{-}_{\mathrm{ijk}}C^{\mathrm{n+1}}_{\mathrm{ijk}}}{\Delta x}$ etc. – notation for difference operators in the approximation of convective derivatives.

Difference approximations of second order derivatives are written this way:

$$\frac{\partial}{\partial x}\left(\mu_{\mathrm{x}}\frac{\partial C}{\partial x}\right)\approx\mu_{\mathrm{x}}\frac{C^{\mathrm{n+1}}_{\mathrm{i+1jk}}-C^{\mathrm{n+1}}_{\mathrm{ijk}}}{\Delta x^{2}}$$

$$-\mu_{\mathrm{x}}\frac{C^{\mathrm{n+1}}_{\mathrm{ijk}}-C^{\mathrm{n+1}}_{\mathrm{i-1jk}}}{\Delta x^{2}}=M^{-}_{\mathrm{xx}}C^{\mathrm{n+1}}+M^{+}_{\mathrm{xx}}C^{\mathrm{n+1}},$$

$$\frac{\partial}{\partial y}\left(\mu_{\mathrm{y}}\frac{\partial C}{\partial y}\right)\approx\mu_{\mathrm{y}}\frac{C^{\mathrm{n+1}}_{\mathrm{ij+1k}}-C^{\mathrm{n+1}}_{\mathrm{ijk}}}{\Delta y^{2}}$$

$$-\mu_{\mathrm{y}}\frac{C^{\mathrm{n+1}}_{\mathrm{ijk}}-C^{\mathrm{n+1}}_{\mathrm{ij-1k}}}{\Delta y^{2}}=M^{-}_{\mathrm{yy}}C^{\mathrm{n+1}}+M^{+}_{\mathrm{yy}}C^{\mathrm{n+1}},$$

$$\frac{\partial}{\partial z}\left(\mu_{\mathrm{z}}\frac{\partial C}{\partial z}\right)\approx\mu_{\mathrm{z}}\frac{C^{\mathrm{n+1}}_{\mathrm{ijk+1}}-C^{\mathrm{n+1}}_{\mathrm{ijk}}}{\Delta z^{2}}$$

$$-\mu_{\mathrm{z}}\frac{C^{\mathrm{n+1}}_{\mathrm{ijk}}-C^{\mathrm{n+1}}_{\mathrm{ijk-1}}}{\Delta z^{2}}=M^{-}_{\mathrm{zz}}C^{\mathrm{n+1}}+M^{+}_{\mathrm{zz}}C^{\mathrm{n+1}}.$$

The following notation is used to shorten the writing of difference equations:

$$M^{+}_{\mathrm{xx}}=-\mu_{\mathrm{x}}\frac{C^{\mathrm{n+1}}_{\mathrm{ijk}}-C^{\mathrm{n+1}}_{\mathrm{i-1jk}}}{\Delta x^{2}}\quad,$$

$$M^{-}_{\mathrm{xx}}=\mu_{\mathrm{x}}\frac{C^{\mathrm{n+1}}_{\mathrm{i+1jk}}-C^{\mathrm{n+1}}_{\mathrm{ijk}}}{\Delta x^{2}}.$$

Applying the introduced notation of difference operators, the transport equation takes the following form:

$$\frac{C^{\mathrm{n+1}}_{\mathrm{i,j,k}}-C^{\mathrm{n}}_{\mathrm{i,j,k}}}{\Delta t}+L^{+}_{\mathrm{x}}C^{\mathrm{n+1}}+L^{-}_{\mathrm{x}}C^{\mathrm{n+1}}+L^{+}_{\mathrm{y}}C^{\mathrm{n+1}}+$$

$$+L^{-}_{\mathrm{y}}C^{\mathrm{n+1}}+L^{+}_{\mathrm{z}}C^{\mathrm{n+1}}+L^{-}_{\mathrm{z}}C^{\mathrm{n+1}}+\sigma C^{\mathrm{n+1}}_{\mathrm{i,j,k}}=$$

$$=M^{+}_{\mathrm{xx}}C^{\mathrm{n+1}}+M^{-}_{\mathrm{xx}}C^{\mathrm{n+1}}+M^{+}_{\mathrm{yy}}C^{\mathrm{n+1}}+M^{-}_{\mathrm{yy}}C^{\mathrm{n+1}}+$$

$$+M^{+}_{\mathrm{zz}}C^{\mathrm{n+1}}+M^{-}_{\mathrm{zz}}C^{\mathrm{n+1}}+q(t)\delta.$$

At the next stage of the construction of the difference scheme, the splitting of this difference equation into four steps is performed with integrating over the time interval *dt*:

– in the first splitting step $k = 1/4$:

$$\frac{C^{\mathrm{n+k}}_{\mathrm{ijk}}-C^{\mathrm{n}}_{\mathrm{ijk}}}{\Delta t}+\frac{1}{2}(L^{+}_{\mathrm{x}}C^{\mathrm{k}}+L^{+}_{\mathrm{y}}C^{\mathrm{k}}+L^{+}_{\mathrm{z}}C^{\mathrm{k}})+\frac{\sigma}{4}C^{\mathrm{k}}_{\mathrm{ijk}}=$$

$$=\frac{1}{4}(M^{+}_{\mathrm{xx}}C^{\mathrm{k}}+M^{-}_{\mathrm{xx}}C^{\mathrm{k}}+M^{+}_{\mathrm{yy}}C^{\mathrm{n}}+$$

$$+M^{-}_{\mathrm{yy}}C^{\mathrm{n}}+M^{+}_{\mathrm{zz}}C^{\mathrm{n}}+M^{-}_{\mathrm{zz}}C^{\mathrm{n}})+\sum_{l=1}^{N}\frac{\overline{q}(t)_{l}}{4}\delta_{l}.$$

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– in the second splitting step $k = n + 1/2$; $c = n + 1/4$:

$$\frac{C^{\mathrm{k}}_{\mathrm{ijk}} - C^{\mathrm{c}}_{\mathrm{ijk}}}{\Delta t} + \frac{1}{2}(L^{-}_{\mathrm{x}} C^{\mathrm{k}} + L^{-}_{\mathrm{y}} C^{\mathrm{k}} + L^{-}_{\mathrm{z}} C^{\mathrm{k}}) + \frac{\sigma}{4} C^{\mathrm{k}}_{\mathrm{ijk}} =$$

$$= \frac{1}{4}(M^{-}_{\mathrm{xx}} C^{\mathrm{k}} + M^{+}_{\mathrm{xx}} C^{\mathrm{c}} + M^{-}_{\mathrm{yy}} C^{\mathrm{k}} +$$

$$+ M^{+}_{\mathrm{yy}} C^{\mathrm{c}} + M^{-}_{\mathrm{zz}} C^{\mathrm{k}} + M^{+}_{\mathrm{zz}} C^{\mathrm{c}}) + \sum_{l=1}^{N} \frac{\overline{q}(t)_l}{4} \delta_l \,.$$

– in the third splitting step $k = n + 3/4$; $c = n + 1/2$:

$$\frac{C^{\mathrm{k}}_{\mathrm{ijk}} - C^{\mathrm{c}}_{\mathrm{ijk}}}{\Delta t} + \frac{1}{2}(L^{+}_{\mathrm{x}} C^{\mathrm{k}} + L^{-}_{\mathrm{y}} C^{\mathrm{k}} + L^{-}_{\mathrm{z}} C^{\mathrm{k}}) + \frac{\sigma}{4} C^{\mathrm{k}}_{\mathrm{ijk}} =$$

$$= \frac{1}{4}(M^{-}_{\mathrm{xx}} C^{\mathrm{c}} + M^{+}_{\mathrm{xx}} C^{\mathrm{k}} + M^{-}_{\mathrm{yy}} C^{\mathrm{k}} +$$

$$+ M^{+}_{\mathrm{yy}} C^{\mathrm{c}} + M^{-}_{\mathrm{zz}} C^{\mathrm{k}} + M^{+}_{\mathrm{zz}} C^{\mathrm{c}}) + \sum_{l=1}^{N} \frac{\overline{q}(t)_l}{4} \delta_{l.}$$

– in the fourth splitting step $k = n + 1$; $c = n + 3/4$:

$$\frac{C^{\mathrm{k}}_{\mathrm{ijk}} - C^{\mathrm{c}}_{\mathrm{ijk}}}{\Delta t} + \frac{1}{2}(L^{-}_{\mathrm{x}} C^{\mathrm{k}} + L^{+}_{\mathrm{y}} C^{\mathrm{k}} + L^{+}_{\mathrm{z}} C^{\mathrm{k}}) + \frac{\sigma}{4} C^{\;\mathrm{k}}_{\;\mathrm{ijk}} =$$

$$= \frac{1}{4}(M^{-}_{\mathrm{xx}} C^{\mathrm{k}} + M^{+}_{\mathrm{xx}} C^{\mathrm{c}} + M^{-}_{\mathrm{yy}} C^{\mathrm{c}} +$$

$$+ M^{+}_{\mathrm{yy}} C^{\mathrm{k}} + M^{-}_{\mathrm{zz}} C^{\mathrm{c}} + M^{+}_{\mathrm{zz}} C^{\mathrm{k}}) + \sum_{l=1}^{N} \frac{\overline{q}(t)_l}{4} \delta_l \,.$$

In discrete form, the Dirac delta function is «distributed» to a single difference cell so as to preserve the total amount q_i of the contaminant that is placed in the cell. Moreover, the function δ_l that is used in difference expressions is not zero only in the cells where the source of dust emission is located. Using the above splitting scheme allows us to obtain difference equations of a simpler form, which makes it possible to carry out their software implementation.

The initial condition for each splitting equation is as follows [10–11]:

$$\left.\overset{1}{C}\right|_{t=t^{\mathrm{n}}} = C\left(x, y, z, t^{\mathrm{n}}\right), \quad \left.\overset{\mathrm{k}}{C}\right|_{t=t^{\mathrm{n}}} = \left.\overset{\mathrm{k}-1}{C}\right|_{t=t^{\mathrm{k}-1}} ,$$

$$k = 2, 3, 4 \,, \; C\left(x, y, z, t^{\mathrm{n}+1}\right) = \left.\overset{4}{C}\right|_{t=t^{4}} ,$$

where $\overset{1}{C}, \overset{\mathrm{k}}{C}, \overset{4}{C}$ – is the impurity concentration value at one or another calculation step.

The boundary condition of non-leakage is realized due to the use of dummy cells. Based on the constructed numerical model, the software package «Dust source pollution 3D» has been developed.

In addition to the considered difference scheme, a different numerical model is used, its feature is the splitting of the modeling equation so that at each fractional step only one physical process is taken into account: convection, atmospheric diffusion, action of the emission source.

$$\frac{\partial C}{\partial t} = \frac{\partial uC}{\partial x} + \frac{\partial vC}{\partial y} + \frac{\partial (w - w_{\mathrm{s}})C}{\partial z} ,$$

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}(\mu_{\mathrm{x}} \frac{\partial C}{\partial x}) + \frac{\partial}{\partial y}(\mu_{\mathrm{y}} \frac{\partial C}{\partial y}) + \frac{\partial}{\partial z}(\mu_{\mathrm{z}} \frac{\partial C}{\partial z}) \,, \quad (3)$$

$$\frac{\partial C}{\partial t} = Q_0(t)\delta(x - x_0)\delta(y - y_0)\delta(z - z_0) \,.$$

Such splitting allows you to calculate separately the process of dust dispersion when there is calm, in this case it is necessary to solve the second equation from system (3).

Findings

The developed program allowed to carry out computational experiments to calculate the dust dispersion in the atmospheric air contained in the emissions of the fan of the main airing in the «West Donbas Mine» based on the following characteristics of the MVF and its release:

– emitted substance – coal dust;

– dispersed composition – polydisperse dust with particle sizes from 1 mkm too 60–100 mkm;

– the average density of the dust substance – 1900 kg/m^3;

– temperature of emission is 24°C, so cold ejection is considered;

– the intensity of dust emission Q_0 = 61.6 g/s;

– height of the mouth of the diffuser above ground level – 6.5 m;

– the width of the mouth of the source – 6 m;

– the length of the mouth of the source – 6 m;

– average ejection velocity – 11.9 m/s;

– the volume of gas-air mixture 430 m^3/s.

The calculation was performed with the following parameters: the size of the computational area was 4 km by 2 km, the wind speed was U = 4 m/s with the direction indicated by the arrow (Fig. 2).

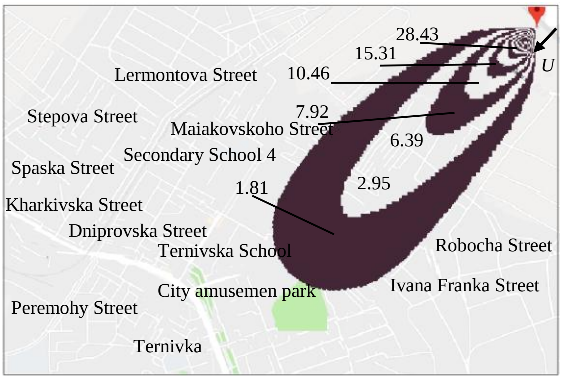

Fig. 2. Distribution of dust concentration from MVF of the «West Donbas Mine», C [mg/m^3]

As can be seen from Figure 2 zones of air pollution cover nearby villages. Obviously, when the meteorological situation changes, the position of the pollution zones will change, but these territories will fall to some extent into the pollution radius.

Figure 3 shows the concentration distribution at 1.7 m, which corresponds to the position of the human respiratory system. As can be seen from this figure, if we take MPC_{dust} = 10°mg/m^3, then at a distance of 300°m there is a violation of the MPC. When the MPC is reduced to 10°mg/m^3, the unfavorable zone increases.

Originality and practical value

Numerical models were developed to predict atmosphere pollution from main ventilator fan. The model is based on equation of dust convective – diffusive transfer. For the numerical integration of modeling equation, the implicit difference scheme of splitting was used. The developed model can be used for quick computing of influence of mine ventilator fan on the settlements, which are situated near mines.

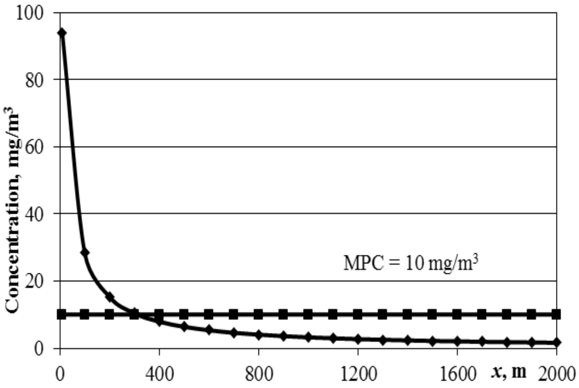

Fig. 3. Distribution of dust concentration along the plume axis, C [mg/m^3]

Conclusions

As a result of research we obtained the following.

1. Developed numerical model for predicting the level of air pollution in the zone of influence of MVF based on the three-dimensional impurity transport equation, which is solved by finite-difference methods.

2. The forecast can be performed on the basis of two numerical models. The models differ in the used splitting patterns. Both splitting schemes allow to calculate quickly the concentration of dust in ambient air. Calculation time is 10 s.

3. The developed numerical models take into account almost all the physical factors affecting the formation of pollution zones in the event of emission from MVF.

4. These models are implemented in the form of the «Dust Source Pollution 3D» program code, in which the transition to the calculation using one model for any meteorological conditions and the other, which is realized in the case of a calm situation, is foreseen.

Carrying out this class of calculations is a necessary tool for the practical assessment of a safe environmental situation during the operation of a public year survey, whose activity is related to the entry of dust into the atmosphere.

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LIST OF REFERENCE LINKS

1. Беляев, Н. Н. Защита зданий от проникновения в них опасных веществ : монография / Н. Н. Беляев, Е. Ю. Гунько, Н. В. Росточило. – Днепропетровск : Акцент ПП, 2014. – 136 с.
2. Бересневич, П. В. Аэрология карьеров : справочник / П. В. Бересневич, В. А. Михайлов, С. С. Филатов. – Москва : Недра, 1991. – 280 с.
3. Колесник, В. Е. Пылевой выброс вентилятора главного проветривания угольной шахты : монография / В. Е. Колесник, Л. А. Головина, М. В. Левченко. – Днепропетровск : Национальный горный университет, 2011. – 125 с.
4. Марчук, Г. И. Математическое моделирование в проблеме окружающей среды / Г. И. Марчук. – Москва : Наука, 1982. – 320 с.
5. Численное моделирование распространения загрязнения в окружающей среде / М. З. Згуровский, В. В. Скопецкий, В. К. Хрущ, Н. Н. Беляев. – Киев : Наук. думка, 1997. – 368 с.
6. Air pollution dispersion modeling in a polluted industrial area of complex terrain from Romania / G. Grigoras, V. Cuculeanu, G. Ene, G. Mocioaca, A. Deneanu // Romanian Reports in Physics. – 2012. – Vol. 64, No. 1. – P. 173–186.
7. Alvarez, J. T. Dust barriers in open pit blasts. Multiphase Computational Fluid Dynamics (CFD) Simulations / J. T. Alvarez, I. D. Alvarez, S. T. Lougedo // WIT Transactions on Ecology and the Environment. –2008. – Vol. 116. – P. 86–93. doi:10.2495/AIR080101
8. Anand Kumar Varma, S. Mathematical modeling of air pollution in a thermal power project [Electronic resource] / S. Anand Kumar Varma. – Available at: https://www.researchgate.net/publication/318284616_mathematical_modeling_of_air_pollution_in_a_thermal_power_project – Title from the screen. – Accessed : 05.11.2019.
9. Biliaiev, M. M. Numerical Simulation of Indoor Air Pollution and Atmosphere Pollution for Regions Having Complex Topography / M. M. Biliaiev, M. M. Kharytonov // NATO Science for Peace and Security. Series C: Environmental Security. – Dordrecht, 2012. – P. 87–91.doi: 10.1007/978-94-007-1359-8_15
10. Jyotsna, K. A mathematical model to study the impact of mining activities and pollution on forest resources and wildlife population / K. Jyotsna, A. Tandon // Journal of Biological Systems. – 2017. – Vol. 25, No. 02. – P. 207–230. doi: 10.1142/S0218339017500115
11. Protective Action Criteria. A Review of Their Derivation, Use, Advantages and Limitations [Electronic resource] // Environmental Public Health Science Unit, Health Protection Branch, Public Health and Compliance Division, Alberta Health. – Edmonton, Alberta, 2017. – Available at: http://open.alberta.ca/publications/9781460131213 – Title from the screen. – Accessed : 05.11.2019.
12. Škuta, R. Assessment of mining activities with respect to the environmental protection / R. Škuta, R. Kučerová, Z. Pavelek, V. Dirner // Acta Montanistica Slovaca. – 2017. – Vol. 22 (1). – P. 79–93.
13. The analysis of the use of mathematical modeling for emergency planning purposes [Electronic resource] / O. Zavila, P. Dobes, J. Dlabka, J. Bitta // The science for population protection. – 2015. – № 2. – Available at: http://www.population-protection.eu/prilohy/casopis/eng/22/112.pdf – Title from the screen. – Accessed : 05.11.2019.

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ПРОГНОЗУВАННЯ ЗАБРУДНЕННЯ АТМОСФЕРИ В РАЗІ ВИКИДІВ З ОСНОВНИХ ШАХТНИХ ВЕНТИЛЯТОРІВ

Мета. Викиди із системи вентиляції шахти можуть створювати інтенсивне забруднення атмосферного повітря. Як правило, величезна кількість пилу з шахтного вентилятора потрапляє в атмосферу в приземних шарах. Важливим завданням є розробка методів оцінки рівня забруднення атмосфери поблизу шахт і населених пунктів. Для вирішення цієї проблеми важливо мати фізично обґрунтовані математичні моделі. У наш час для прогнозування забруднення атмосфери шахтним вентилятором поблизу населених пунктів, використовують емпіричну модель OND–86. Ця модель не враховує багато важливих фізичних факторів. Тому метою нашого дослідження є розробка швидкодіючої математичної моделі для прогнозування забруднення атмосфери в разі викидів пилу з шахтного вентилятора. **Методика.** Для прогнозування рівня забруднення атмосфери під час роботи шахтного вентилятора використано тривимірне рівняння пилового конвективно-дифузійного потоку. Це рівняння враховує гравітаційні випадання, швидкість вітру, турбулентну дифузію в атмосфері, розташування джерела викидів пилу. Як єдине модельне рівняння використано неявну різницеву схему розщеплення. **Результати**. Розроблена математична модель дозволяє швидко прогнозувати рівень забруднення атмосфери в разі викидів пилу від шахтного вентилятора. Модель дозволяє виявити зони забруднення поблизу населених пунктів, які знаходяться в безпосередній близькості від шахти. **Наукова новизна.** Розроблена математична модель враховує ряд фізичних факторів, які наразі не беруть до уваги в дні, коли здійснюють прогноз забруднення атмосфери в населених пунктах, розташованих поблизу шахти. **Практична значимість.** На основі розробленої математичної моделі створено програмний код. Цей код може бути використаний для оцінки забруднення атмосфери в населених пунктах, де відбуваються викиди від шахтних вентиляторів.

Ключові слова: забруднення атмосфери; шахтний вентилятор; математичне моделювання; чисельна модель

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ПРОГНОЗИРОВАНИЕ ЗАГРЯЗНЕНИЯ АТМОСФЕРЫ В СЛУЧАЕ ВЫБРОСОВ ИЗ ОСНОВНЫХ ШАХТНЫХ ВЕНТИЛЯТОРОВ

Цель. Выбросы из системы вентиляции шахты могут создавать интенсивное загрязнение атмосферного воздуха. Как правило, огромное количество пыли из шахтного вентилятора попадает в атмосферу в приземных слоях. Важной задачей является разработка методов оценки уровня загрязнения атмосферы вблизи шахт и населенных пунктов. Для решения этой проблемы важно иметь физически обоснованные математические модели. В настоящее время для прогнозирования загрязнения атмосферы шахтным вентилятором вблизи населенных пунктов, используют эмпирическую модель OND–86. Эта модель не учитывает многие важные физические факторы. Поэтому целью данного исследования является разработка быстродействующей математической модели для прогнозирования загрязнения атмосферы в случае выбросов пыли из шахтного вентилятора. **Методика.** Для прогнозирования уровня загрязнения атмосферы при работе шахтного вентилятора использовано трехмерное уравнение пылевого конвективно-диффузионного потока. Это уравнение учитывает гравитационные выпадения, скорость ветра, турбулентную диффузию в атмосфере, расположение источника выбросов пыли. В качестве единственного модельного уравнения использована неявная разностная схема расщепления. **Результаты.** Разработанная математическая модель позволяет быстро прогнозировать уровень загрязнения атмосферы при выбросах пыли от шахтного вентилятора. Модель позволяет определить зоны загрязнения вблизи населенных пунктов, которые находятся в непосредственной близости от шахты. **Научная новизна**. Разработанная математическая модель учитывает ряд физических факторов, которые в настоящее время не учитываются в дни, когда осуществляют прогноз загрязнения атмосферы в населенных пунктах, расположенных вблизи шахты. **Практическая значимость.** На основе разработанной математической модели создан программный код. Этот код может быть использован для оценки загрязнения атмосферы в населенных пунктах, где происходят выбросы от шахтных вентиляторов.

Ключевые слова: загрязнение атмосферы; шахтный вентилятор; математическое моделирование; численная модель

REFERENCES

1. Biliaiev, N. N., Gunko, E. Y., & Rostochilo, N. V. (2014). *Zashchita zdaniy ot proniknoveniya v nikh opasnykh veshchestv: Monografiya.* Dnepropetrovsk: Aktsent PP. (in Russian)
2. Beresnevich, P. V., Mikhaylov, V. A., & Filatov, S. S. (1991). *Aerologiya karerov: spravochnik.* Moscow: Nedra. (in Russian)
3. Kolesnik, V.Ye., Golovina, L.A., & Levchenko, M. V. (2011). *Pylevoy vybros ventilyatora glavnogo provetrivaniya ugolno: Monografiya*. Dnipropetrovsk: Natsionalnyy gornyy universitet. (in Russian)

doi: https://doi.org/10.15802/stp2019/184378

4. Marchuk, G. I. (1982). *Matematicheskoye modelirovaniye v probleme okruzhayushchey sredy.* Moscow: Nauka. (in Russian)
5. Zgurovskiy, M. Z., Skopetskiy, V. V., Khrushch, V. K., & Biliaiev, N. N. (1997). *Chislennoe modelirovanie rasprostraneniya zagryazneniya v okruzhayushchey srede.* Kyiv: Naukova dumka. (in Russian)
6. Grigoras G., Cuculeanu V., Ene G., Mocioaca G., & Deneanu A. (2012). Air pollution dispersion modeling in a polluted industrial area of complex terrain from. *Romanian Reports in Physics, 64(1),* 173-186. (in English)
7. Alvarez, J. T., Alvarez, I. D., & Lougedo, S. T. (2008). Dust Barriers In Open Pit Blasts. Multiphase Computational Fluid Dynamics (CFD) Simulations. *WIT Transactions on Ecology and the Environment*, 116, 86-93. doi: 10.2495/AIR080101 (in English)
8. Anand Kumar Varma, S. Retrieved from https://www.researchgate.net/publication/318284616_mathematical_modeling_of_air_pollution_in_a_thermal_power_project (in English)
9. Biliaiev, M. M., & Kharytonov, M. M. (2012). Numerical Simulation of Indoor Air Pollution and Atmosphere Pollution for Regions Having Complex Topography. *NATO Science for Peace and Security. Series C: Environmental Security,* 87-91. doi: 10.1007/978-94-007-1359-8_15 (in English)
10. Jyotsna, K., & Tandon, A. (2017). A mathematical model to study the impact of mining activities and pollution on forest resources and wildlife population. *Journal of Biological Systems*, *25(2),* 207-230. doi: 10.1142/S0218339017500115
11. Government of Alberta. (2017). Protective Action Criteria: A Review of Their Derivation, Use, Advantagesand Limitations. Environmental Public Health Science Unit, Health Protection Branch, Public Health and Compliance Division, Alberta Health. Edmonton, Alberta. Retrieved from http://open.alberta.ca/publications/9781460131213 (in English)
12. Škuta, R., Kučerová, R., Pavelek, Z., & Dirner, V. (2017). Assessment of mining activities with respect to the environmental protection. *Acta Montanistica Slovaca, 22(1),* 79-93. (in English)
13. Zavila, O., Dobes, P., Dlabka, J., & Bitta, J. (2015). The analysis of the use of mathematical modeling foremergency planning purposes. The Science for Population Protection, 2. Retrieved from http://www.population-protection.eu/prilohy/casopis/eng/22/112.pdf (in English)

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