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Numerical model for evaluation efficiency of coal pile wetting

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Abstract. Wetting the surface of coal piles is a common method of reducing dust emissions. The problem of modeling air pollution near coal after its wetting is considered. A two-dimensional mass transfer equation was used to model the process of coal dust distribution from the pile. This equation takes into account the convective and diffusion transport of coal dust in the atmosphere. The developed mathematical model takes into account different emission rates of coal dust from different parts of the coal pile. The model takes into account the effect of water evaporation from the coal pile on the rate of intensity of coal dust emission. A potential flow model was used to model the wind flow over the coal pile. Finite-difference splitting schemes have been used for numerical integration of modeling equations. Computer code based on the proposed numerical model has been developed. The developed code can be used to predict the efficiency of wetting coal piles over time. The results of a computational experiment are presented.

1. Introduction

Coal production plays a significant role in Ukrainian economics. It is well known that production of coal, its transportation or storage are sources of different problems from ecological point of view [1, 10]. It is known that coal piles are powerful sources of air pollution in work areas. Various pollutants (dust, CO, etc.) are removed from the surface of the coal pile. Dust pollution of working areas near coal piles is especially intensive. Predicting the level of air pollution near the piles is a particularly important problem.

To reduce the level of air dust contamination in working areas, various means are used: screens; wetting the surface of the coal pile (figure1); application of special solutions, which are supplied to the surface of the pile etc.

For practice, it is important to evaluate the efficiency of coal surface wetting at the stage of developing a project to protect the air from pollution near coal piles. One of the important methods of such evaluation is a mathematical modeling.

Various mathematical models are used to predict the level of air pollution when dust is emitted from the pile, for example, the OND-86 model, the Gaussian model, and numerical models [1, 2, 3, 7, 10, 12]. These models allow, using computers of low and medium power, to evaluate quickly the intensity and size of pollution zones under certain weather conditions, different intensity of the source of pollution, etc. Models require typical initial information, which is important for practice. But these models are difficult to apply to adequately evaluate the effectiveness of various means of air contamination prevention. This is due to the fact that these models consider the coal pile as a "point", i.e., without taking into account its geometric shape and aerodynamics of the flow near the pile. Therefore, there is an important problem in creating effective methods for evaluation the effectiveness of various means of air contamination prevention near the coal piles.

Figure 1. Wetting of pile http://www.evkalipt.com.ua/inzhiniring/pylepodavlenie-orosheniem/ugolnaja-pyl/.

The purpose of the work is development of numerical model to evaluate the efficiency of coal pile surface wetting to reduce the level of air pollution near coal pile.

2. Methods

2.1. Theoretical part

The following equation has been used to simulate coal dust dispersion from the coal pile [1, 2, 3, 5, 9]:

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial (v_{\mathrm{y}}-w)C}{\partial y}=\mathrm{div}(\mu \cdot \mathrm{grad}C)+\sum_{i=1}^{N} Q_i(t)\delta(x-x_i)\delta(y-y_i) \tag{1}$$

where C is concentration of coal dust, mg·m^{-3}; μ_{x}, μ_{y} are turbulent diffusion coefficients, m^2·s^{-1}; w is fallout velocity, m·s^{-1}; Q is rate of coal dust emission from the surface of the pile, mg·m^{-1}·s^{-1}; $\delta(x-x_i)\delta(y-y_i)$ is Dirac delta function, m^{-2}; (x_i, y_i) are Cartesian coordinates, m; t is time, s; u, v_{y} are components of wind velocity vector, m·s^{-1}.

Boundary conditions for the governing equation are discussed in [1, 8].

It is known, that to reduce the rate of coal dust emission from pile, watering of coal pile surface is often used. To evaluate the effectiveness of this method for reducing of air pollution near the coal pile, a submodel was developed. The following considerations were made to develop a submodel. Water that gets on the surface of the pile increases the moisture W of coal. This increases the "threshold" value V_{t}, m·s^{-1}, which corresponds to the speed when separation of coal dust particles from the surface begins. As a result, rate of coal dust emission Q decreases and that influences the intensity of air pollution near the coal pile. But, when air flows over the surface of the pile, water evaporates. The intensity of evaporation depends on a set of factors, but the speed of air flow has a very important role in this process. Due to the evaporation of water, the moister of coal W is reduced and this results in decrease of parameter V_{t}. As a result, rate of coal dust emission Q increases over time after watering the coal pile.

To describe mathematically these processes, the following algorithm was proposed. It can be assumed, volume of water W_{wat}, m^3, has been leaked at the pile surface S_{coal}, m^2. Then the depth of wetting zone is equal to, m:

$$h_{\mathrm{wat}}=\frac{W_{\mathrm{wat}}}{S_{\mathrm{coal}}P_{\mathrm{coal}}},$$

where P_{coal} is porosity.

Wetting of coal causes change of moisture in coal and new value of moisture can be defined as:

$$W^n = \frac{M^n}{M_{\text{coal}}} \cdot 100\% ,$$

where M_{coal} is mass of coal in wetting zone, kg; $M^n = M^n_{\text{water}} + m_0$ is mass of water at time "n", kg; $M^n_{\text{water}} = W^n \rho$ is mass of supplied water, kg; ρ is water density, kg·m^{-3}; m_0 is initial mass of water in the zone before wetting, kg.

Moisture in coal is changed due to water evaporation as follows:

$$W^{n+1} = \frac{M^n - \mathrm{d}m_0}{M_{\text{coal}}} 100\% ,$$

where dm_0 is evaporated mass of water during time period dt, kg; M^n_{water} is mass of water at the previous time step, kg.

To calculate evaporated quantity of water the following empirical model is used [5]:

$$Q_{\text{w}} = \left(5.83 + 4.1 \cdot V\right) P_{\text{H}} \sqrt{M} ,$$

where Q_{w} is rate of water evaporation, g·m^{-2}·h^{-1}), V is local wind speed, m·s^{-1}; P_{H} is saturated water vapor pressure, mm Hg; M is molecular mass of water.

As a result of water evaporation "threshold" speed V_{t} changes and it can be calculated as follows [11]:

$$V_{\text{t}} = 4.97 + 0.268 \cdot W^{1.58} ,$$

where W is relative moisture.

Change of V_{t} results in change of coal dust emission rate which can be calculated as [10]:

$$Q = 4.2 \cdot (V - V_{\text{t}}) ,$$

where V is local wind velocity near coal pile surface, m·s^{-1}.

Worthy of note, that local wind velocity is different at different parts of coal pile. So, it is important to calculate this velocity to model adequately the process of coal dust emission from surface and further its dispersion in atmosphere. To simulate wind flow over coal pile, model of potential flow was used. Governing equation of this model is the following equation [1, 8]:

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} = 0 , \qquad (2)$$

where P is potential of velocity.

Boundary conditions for (2) are discussed in [1, 8].

If potential of velocity has been calculated, then components of wind velocity are calculated as follows:

$$u = \frac{\partial P}{\partial x}; \; v = \frac{\partial P}{\partial y} .$$

2.2. Numerical method

Numerical integration of governing equations has been carried out using rectangular grid. Potential of velocity and coal dust concentration have been calculated in the centers of computational cells. To solve numerically (2), it is transformed in the "unsteady" form [6]:

$$\frac{\partial P}{\partial t}=\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}, \tag{3}$$

where t is a fictitious time.

Then two steps finite difference of splitting have been used for numerical integration (3). These steps of splitting are as follows [6]:

$$\frac{P_{i,j}^{n+\frac{1}{2}}-P_{i,j}^{n}}{\Delta t}=\left[\frac{-P_{i,j}^{n+\frac{1}{2}}+P_{i-1,j}^{n+\frac{1}{2}}}{\Delta x^2}\right]+\left[\frac{-P_{i,j}^{n+\frac{1}{2}}+P_{i,j-1}^{n+\frac{1}{2}}}{\Delta y^2}\right],$$

$$\frac{P_{i,j}^{n+1}-P_{i,j}^{n+\frac{1}{2}}}{\Delta t}=\left[\frac{P_{i+1,j}^{n+1}-P_{i,j}^{n+1}}{\Delta x^2}\right]+\left[\frac{P_{i,j+1}^{n+1}-P_{i,j}^{n+1}}{\Delta y^2}\right].$$

Unknown value of P has been calculated using explicit formula at each step of splitting. The calculation is over if the following condition is fulfilled:

$$\left|P_{ij}^{n+1}-P_{ij}^{n}\right|\le\varepsilon,$$

where ε is a small number, n is an iteration number.

Velocity components have been calculated at the sides of the computational cells as follows:

$$u_{i,j}=\frac{P_{ij}-P_{i-1,j}}{\Delta x}, v_{i,j}=\frac{P_{i,j}-P_{i,j-1}}{\Delta y}.$$

For numerical integration of (1) it is split before as follows:

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}=0, \tag{4}$$

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}\left(\mu_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_y\frac{\partial C}{\partial y}\right), \tag{5}$$

$$\frac{\partial C}{\partial t}=\sum Q_i\delta(x-x_i)\delta(y-y_i). \tag{6}$$

Here, designation $v=v_y-w$ is used.

For numerical integration of (4) the following transformations are made [8]:

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

$$u^+=\frac{u+|u|}{2}, u^-=\frac{u-|u|}{2}, v^+=\frac{v+|v|}{2}, v^-=\frac{v-|v|}{2},$$

$$\frac{\partial u^+C}{\partial x}\approx\frac{u_{i+1,j}^+C_{i,j}^{n+1}-u_{i,j}^+C_{i-1,j}^{n+1}}{\Delta x}=L_x^+C^{n+1},$$

$$\frac{\partial u^-C}{\partial x}\approx\frac{u_{i+1,j}^-C_{i+1,j}^{n+1}-u_{i,j}^-C_{i,j}^{n+1}}{\Delta x}=L_x^-C^{n+1},$$

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

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

where $L^{+}_{\mathrm{x}}, L^{-}_{\mathrm{x}}, L^{+}_{\mathrm{y}}, L^{-}_{\mathrm{y}}$ are difference operators.

The splitting scheme for (4) is written as follows [8]:

– at the first step, the difference equation has the form (k=n+1/2):

$$\frac{C^{k}_{i,j} - C^{n}_{i,j}}{\Delta t} + L^{+}_{\mathrm{x}} C^{k} + L^{+}_{\mathrm{y}} C^{k} = 0;$$

– at the second step of splitting, the difference equation has the form (k=n+1/2):

$$\frac{C^{n+1}_{i,j} - C^{k}_{i,j}}{\Delta t} + L^{-}_{\mathrm{x}} C^{n+1} + L^{-}_{\mathrm{y}} C^{n+1} = 0.$$

The unknown value of C at every step of splitting is determined using explicit formula of «running account».

For numerical integration of (5) a two-stage difference splitting scheme is used [6]:

$$\frac{C^{n+\frac{1}{2}}_{i,j} - C^{n}_{i,j}}{\Delta t} = \mu_{\mathrm{x}} \left[\frac{-C^{n+\frac{1}{2}}_{i,j} + C^{n+\frac{1}{2}}_{i-1,j}}{\Delta x^{2}} \right] + \mu_{\mathrm{y}} \left[\frac{-C^{n+\frac{1}{2}}_{i,j} + C^{n+\frac{1}{2}}_{i,j-1}}{\Delta y^{2}} \right],$$

$$\frac{C^{n+1}_{i,j} - C^{n+\frac{1}{2}}_{i,j}}{\Delta t} = \mu_{\mathrm{x}} \left[\frac{C^{n+1}_{i+1,j} - C^{n+1}_{i,j}}{\Delta x^{2}} \right] + \mu_{\mathrm{y}} \left[\frac{C^{n+1}_{i,j+1} - C^{n+1}_{i,j}}{\Delta y^{2}} \right].$$

The unknown value of the dust concentration is determined from these dependences by an explicit formula.

Euler's method is used for numerical integration of (6), the calculated dependence has the form:

$$C^{n+1}_{i,j} = C^{n}_{i,j} + \Delta t \sum Q_{i} \delta(x - x_{i}) \delta(y - y_{i}).$$

The code is created on the basis of the developed numerical model "COAL-P", programming language – FORTRAN.

3. Results

Developed numerical model was used for prediction of air dust pollution near coal pile after it wetting. A coal pile had complex geometric shape (figure 1). Coal surface had been wetting in quantity 1 $\mathrm{l \cdot m^{-2}}$. Initial coal moister was 4%; coal porosity was 10%; wind flow velocity was 17 $\mathrm{m \cdot s^{-1}}$, coefficients of atmosphere diffusive were $\mu_{\mathrm{x}} = \mu_{\mathrm{y}} = 4$ $\mathrm{m^{2} \cdot s^{-1}}$, $w = 0.001$ $\mathrm{m \cdot s^{-1}}$. Worthy of note, that it was a "pilot" numerical experiment in order to study the "capability" of developed numerical model.

The figure 2-figure 4 below show how the intensity of the dust pollution zone near the coal pile changes over time. Each number in the figures shows the percentage of dust concentration from the maximum dust concentration in the calculation region.

The analysis of the given figures shows that due to the intensive evaporation of water from the surface of the pile, the intensity of dust removal from the pile increases and, as a result, the concentration of dust in the working area behind the coal pile increases very quickly. Over time, the upper boundary of pollution zone, which is marked by isoline $C = 7.8$ $\mathrm{mg \cdot m^{-3}}$, also changes its position: it moves upward from the pile. It means, that the contamination zone increases over time and it is necessary to repeat wetting of coal pile.

Worthy of note that computational time was 7 seconds.

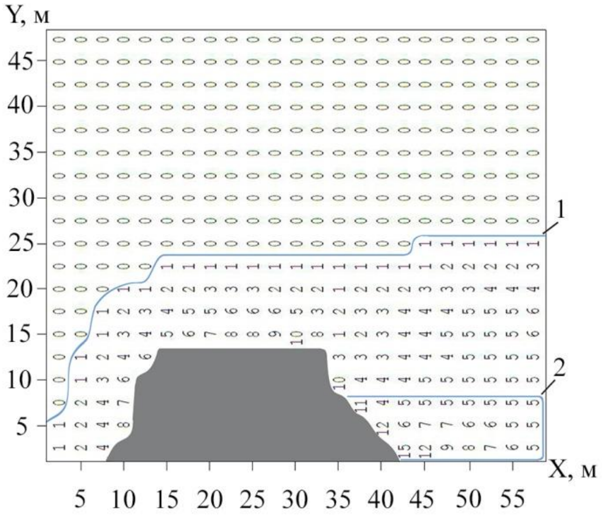

Figure 2. Coal dust concentration near coal pile, t = 140 s: 1 – $C = 7.8$ mg·m^{-3}; 2 – dust concentration in the range 31.2 – 117.3 mg·m^{-3}.

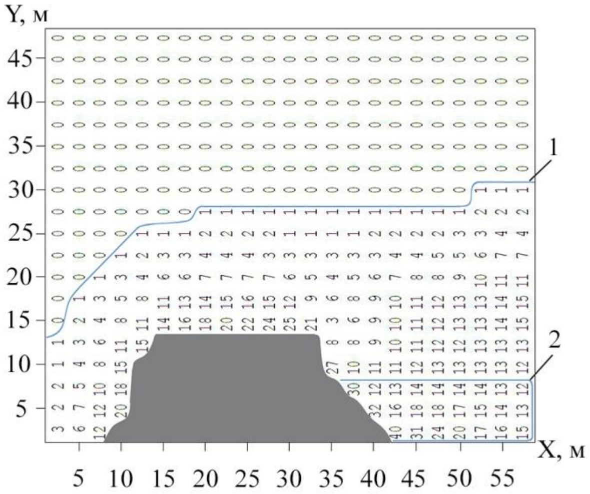

Figure 3. Coal dust concentration near coal pile, t = 350 s: 1 – $C = 7.8$ mg·m^{-3}; 2 – dust concentration in the range 93.6 – 312.2 mg·m^{-3}.

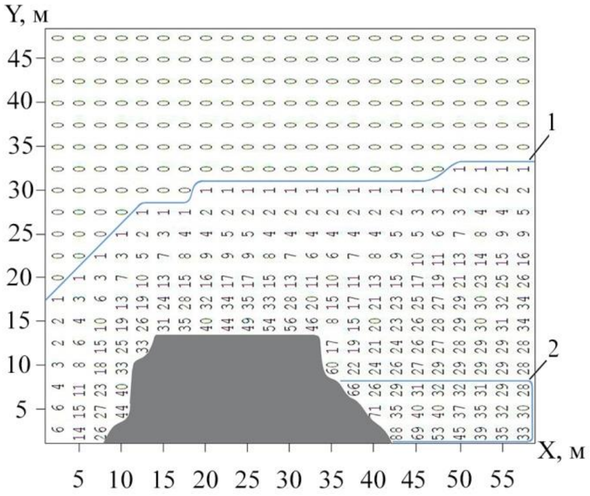

Figure 4. Coal dust concentration near coal pile, t = 770 s: 1 – $C = 7.8$ mg·m^{-3}; 2 – dust concentration in the range 202.4 – 553.1 mg·m^{-3}.

4. Conclusions

Briefly, two-dimensional numerical model was developed to evaluate the efficiency of coal pile wetting which is used to reduce coal dust concentration near pile. The model is focused on evaluation of the level of air pollution in the working areas near the coal pile. Developed numerical model takes into account geometrical form of coal pile and non-uniform wind velocity pattern. This numerical model uses some empirical models to describe mathematically relation between the dust emission rate and moisture. It is obviously that evaluation of air pollution level much depends on the credibility of these empirical models for specific conditions (type of coal, etc.).

References

[1] Biliaiev M M, Oladipo M O and Kirichenko P S 2018 *Zaschita okruzhayuschey sredyi pri transportirovke uglya* (Krivoy Rog: Izd. R.A. Kozlov) p 92
[2] Berlyand M E 1985 *Prognoz i regulirovanie zagryazneniya atmosferyi* (Leningrad: Gidrometeoizdat) p 272
[3] Bruyatskiy E V 2000 *Teoriya atmosfernoy diffuzii radioaktivnyih vyibrosov* (Kyiv: In-t gidromehaniki NAN Ukrainyi) p 443
[4] Marchuk G I 1982 *Mathematical modeling in environmental problems* (Moskow: Nauka) 320
[5] Matsak V G 1959 *Gigienicheskoe znachenie skorosti ispareniya i davleniya para toksicheskih veschestv, primenyaemyih v proizvodstve* (Moskva: Medgiz) p 231
[6] Samarskiy A A 1983 *Teoriya raznostnyih shem* (Moskva: Nauka) p 616
[7] Uork K *Zagryaznenie vozduha. Istochniki i kontrol* (Moskva: Mir) p 539
[8] Zgurovskii M Z, Skopetskii V V, Khrutch V K and Biliaiev M M 1997 *Numerical modeling of pollutant dispersion in environment* (Kyiv: Naukova dumka) p 368
[9] Biliaiev M 2012 *NATO Science for Peace and Security* Series C: Envir. Sec. 87-91
[10] Biliaiev M, Kozachyna V and Oladipo M O 2019 *East European Scientific Journal* **3** (43) 10-15
[11] Weiman C and Zhibao D 1996 *Journal of Arid Environments* **34** 391–402
[12] Tripathy D P, Dash T R, Badu A and Kanungo R 2015 *Global NEST Journal* **17** (4) 825-834