

This work considers the process of dust pollution of the air at an industrial site when using a protective perforated screen. The removal of dust from contaminated land surfaces in areas where there are coal storage facilities leads to intensive air pollution in working areas. This poses a threat to the health of workers. Therefore, for practice, an important solution is to reduce the level of dust pollution of the air at industrial sites.

A likely engineering solution to such a task is to use protective screens, in particular, protective screens with perforations. These screens reduce the speed of the oncoming wind flow, which, in turn, reduces the intensity of dust formation. The location of the screens at an industrial site is important.

A laboratory experiment was conducted to determine the patterns of air flow velocity distribution behind a protective screen with perforations. The experimental data showed that the screen makes it possible to reduce the wind flow velocity by 5–6 times over an extension of the order of $2H$ from the screen (H is the height of the screen). The air flow velocity increases intensively behind the screen in the area $2H-4H$. These results make it possible to determine the rational location of the screen relative to the dust formation area.

For theoretical assessment of the effectiveness of these screens, a numerical model was built based on the fundamental equations of continuum mechanics. The modeling equations include the dust mass transfer equation and the potential motion equation. Using the constructed numerical model, a computational experiment was conducted, which confirmed the effectiveness of using perforated protective screens: the area of dust air pollution in height decreased almost 3 times. The cost of computer time for conducting a computational experiment is 2 seconds. This makes it possible, when carrying out design work, to perform a series of calculations in a short period of time.

Keywords: air pollution, protective screen, mathematical model, physical experiment, computational experiment

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CONSTRUCTION OF A MATHEMATICAL MODEL FOR DUST TRANSPORT PROCESS AT AN INDUSTRIAL SITE WITH A PERFORATED PROTECTIVE SCREEN

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1. Introduction

Air pollution at industrial sites by dust is a very common phenomenon in various industries. Particularly intense

pollution is observed at industrial sites where coal piles are located. The removal of small coal fractions contributes to the formation of significant areas of contamination of both the underlying surface and the air, which poses a threat to

the health of workers. Therefore, special attention is paid to means of reducing the level of dust pollution in the air.

Since large open areas are subject to dust protection, one of the most effective means, from the point of view of economy, is protective screens (barriers). In this regard, the widespread practice for reducing the spread of dust at industrial sites is the use of protective screens (barriers). In this case, there is a need to optimize their design to minimize recirculation zones; therefore, along with solid protective screens, perforated protective screens are widely used (Fig. 1).

Protective screens are simple, economical; screens can be installed very quickly as they do not require special equipment. Industrial waste can be used as a material for the manufacture of protective barriers (Fig. 2).

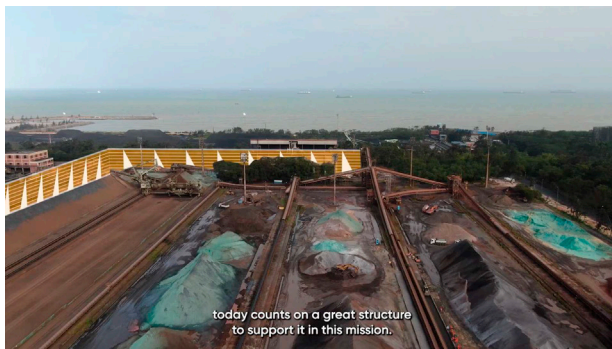


Fig. 1. Installing a protective screen with transparent windows [1]

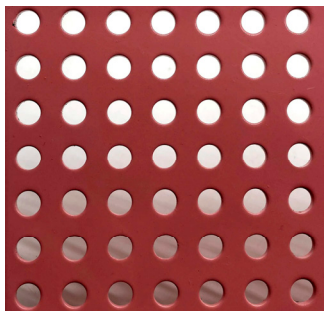


Fig. 2. Protective screen element with holes [2]

A protective screen creates an obstacle in the path of the wind flow, so these protective structures have another name – windbreak screens. The presence of an obstacle such as a screen leads to a change in the speed of the air flow behind the screen, that is, in the area where the dust formation zones are located. Reducing the wind speed behind the screen helps reduce the intensity of dust formation. But to ensure the effective use of protective screens, it is necessary to determine their impact on the aerodynamics of the flow at the design stage and predict dust concentration fields when using the screen at different wind speeds.

Therefore, research into the construction of mathematical models for analyzing the aerodynamic regime at industrial sites when using protective screens is relevant and has a clear applied focus.

2. Literature review and problem statement

In [3], the effectiveness of air curtains for dust removal in mine shafts is experimentally investigated. The advantages

of air flow control over traditional ventilation and spraying methods are substantiated. A physical model has been built that optimizes the ratio of air volumes. This allows for the effective removal of fine dust and the avoidance of stagnation zones. The results make it possible to implement these recommendations for achieving “clean production” in the mining industry. However, the authors did not pay attention to the influence of special screens on the distribution of dust particle settling zones or perforated surfaces.

In study [4], a theoretical framework for dust suppression in coal transfer zones was developed. Using CFD modeling (ANSYS Fluent (USA)) and the discrete particle method, the authors investigated two-phase flows taking into account the geometry of the workings. The traction effect of conveyors and vortex air structures contribute to the accumulation of fractions smaller than 20 microns. Based on the analysis, a pneumatic spiral spraying system is proposed. Such an aerosol curtain ensured effective particle capture. The dust level was reduced by more than 90%. However, the work does not provide a comparative analysis of the energy consumption of the proposed pneumatic system in comparison with traditional hydraulic nozzles. There is also no comparison with stationary means of physical obstacles that do not require energy consumption at all.

In study [5], a novel water-based dust suppression technology for use in large mining faces was presented. Using the ANSYS Fluent software (USA), it was established that intensive pollution (up to 1840 mg/m^3) is formed already at the 60th second of the combine movement. However, dynamic equilibrium occurs only at the 600th second. Zones of the greatest dust accumulation were identified at a distance of 30–120 m from the support. Based on these data, a multi-stage humidification technology was introduced, which significantly reduced dust in the operator’s area. The time characteristic of the formation of dust clouds was determined. However, the volume of empirical data presented in the study requires additional investigation before the proposed approach can be applied to large open-pit coal deposits.

In study [6], the propagation and deposition of explosive dust in a confined space were modeled using CFD-DPM (Computational Fluid Dynamics–Discrete Phase Model) simulations (ANSYS Fluent, USA). Most attention is paid to the mechanisms of interaction of particles with walls (adhesion/percentage) for predicting accumulation zones. Using the Lagrangian approach, the authors simulated dust concentrations of $15\text{--}45 \text{ g/m}^3$ in a confined space. The dynamic equilibrium of suspended dust occurs after 30 seconds of spraying for these conditions. It is proven that small fractions are distributed over the volume, and large ones settle near the source. The model allows one to calculate the critical time before reaching an explosive state (more than 5% of the area of the room). However, the work does not assess the influence of surface perforation. The influence of the chamber volume is also insufficiently studied.

In work [7], the main sources of dust formation in open pit areas are analyzed. The main production stages that form high concentrations of hazardous aerosol are considered. The physical properties of limestone dust and the distribution of particles by their size are described. Modern dust suppression technologies for each individual technological process are systematized. The high efficiency of the implementation of the proposed set of protective measures is experimentally confirmed. It is reported that the concentration of harmful dust has been reduced by more than eighty percent. However,

the paper lacks numerical modeling of the aerodynamics of complex dust flows.

In [8], the optimization of the dust-absorbing shelter of the primary crushing station of an open pit is considered. The problem of high dustiness and low efficiency of traditional dust removal means is examined. A dry induction shelter with closed circulation of contaminated air is proposed. The study is based on numerical modeling of a complex gas-dust two-phase flow. The CFD (computational fluid dynamics) (ANSYS Fluent (USA)) modeling method was used for a detailed analysis of the aerodynamics inside the device. A significant negative impact of the external wind on the overall dust suppression efficiency was determined. Structural optimization of the design was carried out using internal screens and fans. A decrease in dust concentration to the established environmentally acceptable values was experimentally recorded. However, the paper only limitedly considered the influence of variable temperature and climatic factors.

In work [9], modern methods of combating coal dust in underground mines are investigated. An analysis of the effectiveness of chemical reagents, foam compositions, and ultrasonic spraying is reported. Traditional water irrigation often does not cope with fine and hydrophobic particles. The technical advantages and disadvantages of various dust suppression systems are compared. The design of environmentally safe biological nano-films for surfaces is termed an important direction. The use of microbial technologies is considered as a promising method of controlling secondary dust. Optimization of wetting agents is proposed to increase the efficiency of work. However, the review has a number of limitations typical of scientific works of a generalizing type. The authors focus on laboratory indicators, not sufficiently analyzing economic feasibility.

In [10], express modeling of dust distribution at industrial facilities using numerical methods is described. A mathematical model is proposed for rapid prediction of pollutant concentrations. The work uses the mass transfer equation to calculate the dynamics of dust flows. The model takes into account the influence of wind speed and geometric parameters of industrial buildings. Special attention is paid to the aerodynamic shadow zones, where the largest amount of dust accumulates. The study allows for a quick assessment of risks for the environmental safety of working areas and to optimize the placement of protective screens on the territory of the enterprise. However, the study does not take into account the influence of sharp temperature inversions on particle dispersion. The author's model also requires further verification with field measurement data under different weather conditions.

Study [11] reports analysis of the dynamics of changes in the moisture content in coal at different air speeds. The process of moisture evaporation is considered as a key factor for calculating dust emissions. The dependence between the intensity of the air flow and the drying rate of coal material was experimentally established. A mathematical model describing the change in the humidity of the surface layer of coal is proposed. The data obtained allow one to specify the parameters of irrigation systems to maintain the required humidity level. The study is important for the design of effective dust suppression systems in coal warehouses and products. However, the paper does not take into account the influence of the initial particle size distribution of coal on the drying rate. The interaction of material humidity with chemical wetting reagents in the flow is also insufficiently studied.

In study [12], the results of investigations into aerodynamic processes occurring at the edges of noise barriers

were presented. Experiments in a wind tunnel allowed the authors to describe in detail the mechanism of the polluted plume beyond the barrier. The main scientific novelty is the development of a mathematical displacement function that parameterizes the redistribution of impurity concentrations in the barrier break zones. It is proven that local pollution maxima occur at the ends of the barriers, which significantly exceed the indicators for the central sections of the screen. The obtained data are critically important for the verification of numerical CFD (computational fluid dynamics) models (ANSYS Fluent (USA)). The zone of influence of edge effects at a distance of up to 10 barrier heights downstream. However, the model is based on experiments with a thin flat plate, which ignores the real thickness and profile of real structures that can create additional turbulence at the joints.

Our review of the literature [3–12] demonstrates the transition from traditional irrigation methods to high-tech solutions: air curtains, pneumatic spiral spraying, and bio-technologies. The main research tool is numerical modeling (CFD-DPM (computational fluid dynamics–Discrete Phase Model), FLUENT (ANSYS Fluent (USA))).

However, our analysis revealed a systemic scientific gap: the influence of geometric and structural features of surfaces (perforation, screens) on the dynamics of air flow and the efficiency of dust particle deposition has not been sufficiently studied. There is also a shortage of economic justifications and the impact of climate variability on the actual implementation of the models built.

All this allows us to assert that it is advisable to conduct research on determining the effectiveness of protective equipment used to reduce dust air pollution at industrial sites. It should be noted that an effective solution to this problem is the use of the mathematical modeling method.

3. The aim and objectives of the study

The purpose of our study is to construct a mathematical model of mass transfer, which makes it possible to determine the impact of a perforated protective screen on reducing dust pollution of the air at an industrial site. Determining this impact makes it possible to assess the effectiveness of perforated screens for protecting working areas from dust pollution.

To achieve the goal, the following tasks were set:

- to break down a numerical model for solving the aerodynamic problem – calculating the air flow velocity field at an industrial site in the presence of a protective perforated screen;
- to build a numerical model of mass transfer for calculating the dust concentration field at an industrial site when using a protective perforated screen;
- to conduct experimental studies to determine the regularity of changes in the air flow velocity value behind a protective perforated screen;
- to conduct computational experiments based on the constructed numerical models to study the effectiveness of using protective perforated screens for protection against dust pollution of working areas.

4. The study materials and methods

The object of our study is the process of dust pollution of the air at an industrial site when using a protective perforated screen.

The working hypothesis assumes that the location of a protective perforated screen at an industrial site makes it possible to reduce the level of dust pollution of the air. As an assumption, it was adopted that the air passing through the holes in the screen generates jets that make it possible to reduce the total flow velocity near the surface of the industrial site. It was also assumed that the influence of air viscosity on the velocity of these jets can be neglected.

To verify the working hypothesis, a computational experiment was conducted on the basis of the constructed numerical models. When building numerical models, data from the conducted physical experiment were used to determine the patterns of air velocity changes behind a perforated protective screen. The construction of numerical models was carried out under the following assumptions: air viscosity does not affect the velocity field at the industrial site, only the diagonal components of the diffusion coefficient tensor are taken into account; the flow motion is vortex-free.

Theoretical study of dust air pollution at an industrial site using a perforated protective screen is carried out by numerical integration of modeling equations of mass transfer and aerodynamics using numerical methods.

For numerical modeling, our original software is used – the “SCREEN-2a” computer program, which was developed in the FORTRAN programming environment (USA).

5. Results of the study on the construction of a mathematical model of dust air pollution when using a screen

5.1. Construction of a two-dimensional numerical model for calculating the wind speed field at an industrial site

Fig. 3 shows a diagram of the calculation area. Below is the procedure for building a numerical model for determining the wind speed field at an industrial site.

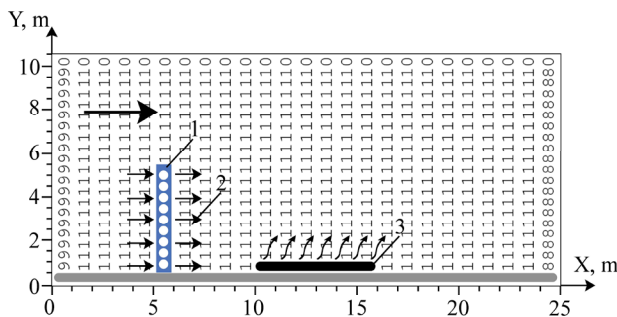


Fig. 3. Diagram of the calculation area: 1 – perforated screen; 2 – flow through the screen; 3 – dust formation area

The basic equation for determining the wind speed field at an industrial site when using a protective perforated screen is the potential air movement model

$$\frac{\partial P^2}{\partial x^2} + \frac{\partial P^2}{\partial y^2} = 0, \tag{1}$$

where P is the velocity potential.

The boundary conditions for equation (1) are as follows:

– on the boundary where the air flow enters the calculation area with a velocity U , the boundary condition takes the form $\partial P / \partial x = U$. Such a boundary condition (internal condi-

tion) is met behind a perforated protective screen where the air flow “leaves” the screen with a certain velocity U_e .

It should be noted that when conducting a computational experiment, $U = \text{const}$ is assumed – this is a known velocity; the velocity U_e is also known but, to substantiate its value, a physical experiment was conducted, the results of which are given below;

– on the boundary of the air flow exiting the calculation area, the Dirichlet condition is set: $P = P_0 + \text{const}$, where P_0 is an arbitrary constant. When performing the calculation, $P = 500$ is assumed;

– on solid boundaries: $\partial P / \partial n = 0$, n is the unit vector of the external normal to the boundary.

The components of the air flow velocity vector are defined as follows

$$u = \frac{\partial P}{\partial x}, \quad v = \frac{\partial P}{\partial y}. \tag{2}$$

Numerical integration of equation (1) is carried out on a rectangular difference grid. The value of the velocity potential is determined inside the control elements (difference cells), the components of the vector velocity of the air flow are determined on the sides of the control elements.

First, the equation for the velocity potential (1) is reduced to the following form

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

where t is the fictitious time.

Next, the value of the cell velocity potential is calculated using the explicit formula

$$P_{ij}^{n+1} = P_{ij}^n + \Delta t \frac{P_{i+1,j}^n - 2P_{ij}^n + P_{i-1,j}^n}{\Delta x^2} + \Delta t \frac{P_{i,j+1}^n - 2P_{ij}^n + P_{i,j-1}^n}{\Delta y^2}. \tag{4}$$

The solution process stops when

$$|P_{i,j}^{n+1} - P_{i,j}^n| \leq \varepsilon,$$

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

The air velocity value (component) is determined as

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

5.2. Construction of a two-dimensional numerical model for calculating the dust concentration field at an industrial site

The following mass transfer equation is used to estimate the dust concentration at an industrial site

$$\begin{aligned} \frac{\partial C}{\partial t} + \frac{\partial uC}{\partial x} + \frac{(\partial v - w)C}{\partial y} = \\ = \frac{\partial}{\partial x} \left(\mu_x \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu_y \frac{\partial C}{\partial y} \right) + Q_i \delta(x - x_i) \delta(y - y_i), \end{aligned} \tag{5}$$

where C is the dust concentration in the air; u, v are the components of the wind speed vector; x_i, y_i are the Cartesian coordinates of the dust emission source, t is time; μ_x, μ_y are the turbulent diffusion coefficients in the atmosphere; $\delta(x_i, y_i)$ is the Dirac delta function; Q is the dust emission intensity; w is the

rate of gravitational deposition of dust particles. The turbulent diffusion coefficients in the atmosphere were determined as follows

$$\mu_x = 0,1 \cdot u, \quad \mu_y = 0,1 \cdot v.$$

The boundary conditions for the mass transfer equation were as follows:

- 1) at the boundary of the air flow entering the calculation area: $C = 0$;
- 2) at the boundary of the flow exiting the calculation area: $\partial C / \partial n = 0$;
- 3) at solid boundaries: $\partial C / \partial n = 0$.

Here n is the unit vector of the external normal to the surface.

For time $t = 0$, the initial condition was $C = 0$.

Numerical integration of the mass transfer equation (4) was carried out using difference schemes and a rectangular grid. Markers were used to form the geometric shape of the calculation area (the shape of the protective screen, its position).

For numerical integration of equation (5), a variable-triangular difference splitting scheme was used. The splitting takes the form:

- in the first step $k = \frac{1}{4}$ the difference equation takes the form

$$\begin{aligned} & \frac{C_{ij}^{n+k} - C_{ij}^n}{\Delta t} + \frac{1}{2} (L_x^+ C^k + L_y^+ C^k) + \frac{\sigma}{4} C_{ij}^k = \\ & = \frac{1}{4} \left(M_{xx}^+ C^k + M_{xx}^- C^k + \right) + \sum_{l=1}^N \frac{Q_l}{4} \delta_l; \end{aligned} \quad (6)$$

- in the second step of splitting $k = n + \frac{1}{2}$, $c = n + \frac{1}{4}$ the difference equation takes the form

$$\begin{aligned} & \frac{C_{ij}^k - C_{ij}^c}{\Delta t} + \frac{1}{2} (L_x^- C^k + L_y^- C^k) + \frac{\sigma}{4} C_{ij}^k = \\ & = \frac{1}{4} \left(M_{xx}^- C^k + M_{xx}^+ C^c + \right) + \sum_{l=1}^N \frac{Q_l}{4} \delta_l; \end{aligned} \quad (7)$$

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

$$\begin{aligned} & \frac{C_{ij}^k - C_{ij}^c}{\Delta t} + \frac{1}{2} (L_x^- C^k + L_y^- C^k) + \frac{\sigma}{4} C_{ij}^k = \\ & = \frac{1}{4} \left(M_{xx}^- C^k + M_{xx}^+ C^c + \right) + \sum_{l=1}^N \frac{Q_l}{4} \delta_l; \end{aligned} \quad (8)$$

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

$$\begin{aligned} & \frac{C_{ij}^k - C_{ij}^c}{\Delta t} + \frac{1}{2} (L_x^- C^k + L_y^- C^k) + \frac{\sigma}{4} C_{ij}^k = \\ & = \frac{1}{4} \left(M_{xx}^- C^k + M_{xx}^+ C^c + \right) + \sum_{l=1}^N \frac{Q_l}{4} \delta_l; \end{aligned} \quad (9)$$

Hereafter, we assume $v = v - w$. The values of difference operators $L_x^+, L_x^-, L_y^+, L_y^-$ are given in [13].

From these difference equations, the unknown value of the dust concentration in the upper time layer is determined from the explicit running-count formula.

5. 3. Experimental studies on determining the regularity of the air flow velocity behind the screen

A perforated screen was considered, which had a porosity of 38%, the diameter of each hole was 12 mm (Fig. 4).



Fig. 4. Physical model of a perforated screen

The air flow velocity in front of and behind the screen was measured using an anemometer HT-9830 (China). Since the measurement was carried out in a turbulent flow, the anemometer showed a certain range of speeds; therefore, when processing the research results, the average value of the air flow velocity was used. The screen dimensions were 10×10 cm. The barrier height $H = 10$ cm was taken as a characteristic size. The modeling was carried out according to the Reynolds criterion

$$Re = \frac{V_0 H}{\nu},$$

where V_0 is the air flow velocity in front of the barrier (determined by measuring at a height of $0.5H$ and a distance of H in front of the barrier); H is the characteristic size; ν is the kinematic viscosity coefficient ($\nu = 15.06 \cdot 10^{-6} \text{ m}^2/\text{s}$, $t = 20^\circ\text{C}$).

A dust generation zone with dust particles up to 1 mm was formed on the model of the industrial site. Coal dust (from the mine of TOV Pavlograd Coal, Ukraine) was located within a rectangle (site) behind the protective barrier. Air temperature, 20°C . Previously, the coal dust sample was kept in a drying cabinet (drying cabinet, model 2B-151) at a temperature of $+40^\circ\text{C}$ for 1 hour. The experiment was conducted for different air flow speeds in two stages:

- stage 1: determining the air flow speed directly behind the protective screen (measurement at a height of $0.1H$ and a length of $0.5H$ from the screen);
- stage 2: determining the air flow speed at different distances from the protective screen (measurement at a height of $0.1H$).

The purpose of the first stage of research was to estimate the air flow velocity U_e at the “exit” of the flow from the perforated screen. These data were required to “close” the mathematical model of aerodynamics (1), that is, to determine the specific value of the internal boundary condition. The data obtained at stage No. 2 make it possible to determine the pattern of changes in the value of the local air velocity behind the screen.

Fig. 5 shows the value of the air flow velocity behind the protective screen at different speeds of the incoming flow. The air flow velocity was measured at a height of $0.1H$.

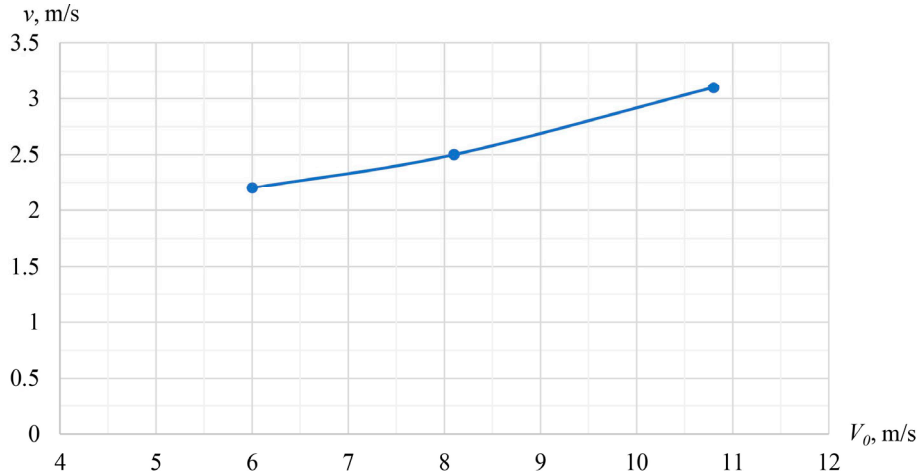


Fig. 5. Air flow velocity behind the screen

Approximation of the experimental data shown in Fig. 5 allows us to obtain the following empirical model, which can be used to estimate the air flow velocity behind a perforated screen

$$v = 1.3796 \cdot e^{0.0839 \cdot V_0} \text{ (m/s)}. \quad (5)$$

When conducting a computational experiment, model (5) was used as an internal boundary condition when solving the aerodynamic problem.

Next, Fig. 6 shows the value of the air flow velocity behind the protective screen along the model of the industrial site. The air flow velocity was measured at a height of 0.1H.

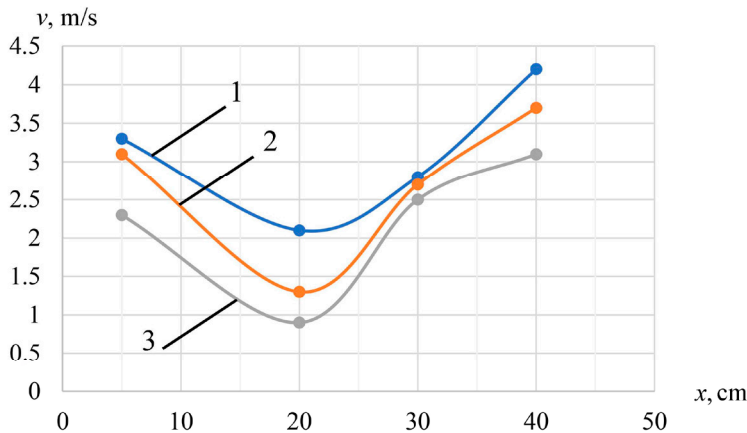


Fig. 6. Change in air flow velocity behind the protective screen:
1 – $V_0 = 10.3$ m/s; 2 – $V_0 = 8.2$ m/s; 3 – $V_0 = 6.1$ m/s

Analysis of the data in Fig. 6 revealed that the minimum value of the local air flow velocity is achieved at a distance of $2H$ from the perforated screen.

5. 4. Conducting computational experiments based on the constructed numerical models

Below are the results of solving the problem of determining the efficiency of using a perforated screen based on the constructed numerical models. The scheme of the calculation area is shown in Fig. 3.

The task was to determine the dust concentration fields with the following parameters: the dimensions of the calculation area $25 \cdot 10.5$ m; wind speed 4 m/s; length of the dust formation area 6 m; gravitational deposition

rate of dust particles 0.001 m/s; dust formation intensity 100 mass units/unit of time (in dimensionless form); screen width 1 m; screen height 5 m; screen porosity 38%; the speed behind the screen is determined based on model (5). It was assumed that the beginning of the working zone is located at a distance of 8 m from the dust formation area.

Below, Fig. 7 shows the dust concentration field in the study area in the absence of a protective screen. The dust concentration is given in a dimensionless form: each number shows the dust concentration as a percentage of its maximum value C_{max} . Thus, the number “99” corresponds to the maximum value of the dust concentration. If, for example, the number on the matrix is “14”, this means that the dust concentration in this control element is 14% of the maximum concentration value. The results are printed in INTEGER format, that is, only the integer value of the real number is printed. Such printing of the results of computer simulation made it possible to very quickly analyze the area of pollution and identify areas where significant dust pollution of the air occurs at an industrial site.

Analysis of the data in Fig. 7 revealed that in the absence of a protective screen, a significant area of dust pollution is formed in height.

Next, Fig. 8 shows the dust concentration field in the study area in the absence of a protective screen. The dust concentration is also given in dimensionless form: each number shows the dust concentration as a percentage of its maximum C_{max} value.

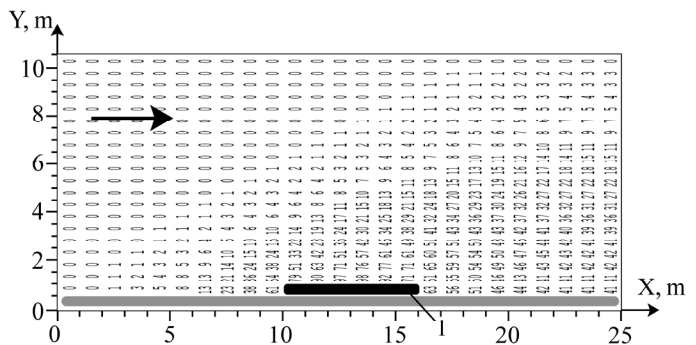


Fig. 7. Dust concentration at the industrial site:
1 – dust generation area ($C_{max} = 10.26$)

Analysis of the data in Fig. 8 revealed that when using a protective screen of this type, a small area of dust pollution is formed. The area of dust pollution took the form of a plume extending along the surface of the earth.

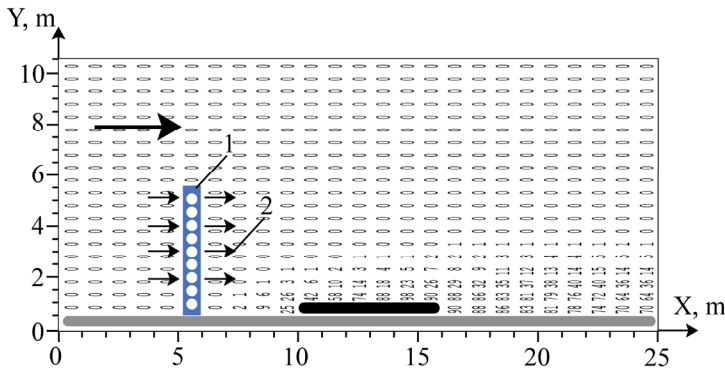


Fig. 8. Dust concentration at the industrial site: 1 – perforated screen; 2 – flow through the screen ($C_{max} = 10.52$)

It should be noted that the calculation time is 2 s.

6. Discussion of results based on the study on the construction of a numerical model of air pollution in the presence of a perforated screen

A feature of the proposed model is that the consideration of perforation (holes on the surface of the screen) in the mathematical model is carried out “indirectly”. This is done by specifying the air flow velocity behind the screen, which is calculated on the basis of the empirical model (5). Model (5) makes it possible to specify the screen configuration using only one parameter – the porosity of this screen.

The numerical model for calculating the air flow velocity field is based on the use of an explicit formula for integrating the equation for the velocity potential. This significantly reduces the complexity of the software implementation of the calculation procedure for determining the potential velocity field and components of the air flow velocity vectors. A feature of the constructed numerical model of aerodynamics (3), (4) is the use of an internal boundary condition for the velocity potential, which is implemented near the perforated screen. This boundary condition is based on the use of empirical data obtained experimentally. This approach makes it possible to model the movement of air through a perforated screen without forming a specific shape and position of the holes in the perforated screen in the numerical model. This approach makes it possible to carry out simple software implementation of the numerical model.

The numerical model built for calculating the dust concentration field is based on splitting the mass transfer equation into a sequence of solutions to four simplified equations (6) to (9). With the help of such a split, the software implementation of the equations of the numerical model is significantly simplified.

The results of the physical experiment made it possible to obtain an empirical model for determining the air flow velocity behind a perforated screen. This model was used

to “close” the numerical model for calculating the dust concentration field at an industrial site. The results of experimental studies made it possible to determine the following pattern of changes in the air flow velocity behind a perforated screen: the flow velocity decreases sharply behind the perforated screen, reaching a minimum at a point at a length of $2H$ (H is the screen height), Fig. 6. This minimum is 5–6 times less than the value of the velocity of the incoming air flow. The explanation for this result is that a stagnant zone (zone of “silence”) is created behind the screen, where the air flow velocity smoothly decreases, but the length of this stagnant zone is limited to a distance of about $2.5H$ from the protective screen, Fig. 6. Then the impact of the oncoming wind flow on the air environment of the site begins.

Determining the pattern of changes in the local air flow velocity behind a perforated screen makes it possible to determine the place of rational location of the screen on an industrial site provided that the local air flow velocity is less than the velocity at which dust formation begins. For example, if the air velocity at which dust formation begins (this velocity is called the “suspension speed”) is 2.5 m/s, then the protective function of the screen, i.e., ensuring a flow velocity of less than 2.5 m/s, will have an effect at a distance of $3H$ from the perforated screen, followed by an increase in the air flow velocity, which leads to the onset of the dust formation process.

The results of our computational experiment show a significant influence of the perforated screen on the size of the dust pollution area at an industrial site. Thus, in the absence of a protective screen, the height of the dust pollution area reaches the order of 10 m at a distance of 8 m from the dust formation area (Fig. 7). When using a screen, the height of this area is of the order of 3 m at the same distance, i.e., the height of the dust pollution area has decreased almost 3 times (Fig. 8). If we assume that intensive pollution is an area where the dimensionless value of the dust concentration in the air is within 37–99% of the maximum concentration value, then in the absence of a screen, the height of this area reaches 4 m (Fig. 7). In the presence of a screen, the height of this area is 1.5 m (Fig. 8). Thus, the use of a screen makes it possible to reduce the area of dust pollution in height, which is important for reducing the risk of dust entering the respiratory organs of workers at an industrial site.

It is necessary to emphasize the special feature of the proposed numerical model – the speed of calculation of the dust concentration field on computers of low and medium power. Such speed of calculation is explained by the use of the potential motion model to determine the air flow velocity. If the viscous flow model were used to determine the air flow velocity, then several hours of computer time would be required to determine the air flow velocity.

A limitation of our results is that they can be used only for perforated screens with 38% perforation. To use the constructed numerical model for other perforated screens, it is necessary to specify the air flow velocity and the area of its exit from the screen. That is, to conduct predictive calculations for screens with different porosity, additional experimental studies must be performed.

The disadvantage of the proposed mathematical model of dust transport at an industrial site is that the model does not take into account the influence of flow viscosity when solving the problem of air flow around a protective screen. Thus, the process of vortices formation in the boundary layer and their separation from the screen surface are not taken into account. However, the construction of a numerical model that will take into account such a process requires numerical integration of additional equations of continuum mechanics, justification of a specific turbulence model, and determination of a number of empirical constants. This significantly increases the time for the construction of a numerical model and its implementation on a computer.

Further advancement of this model involves the construction of a numerical model of aerodynamics, which is based on the Navier-Stokes equations.

7. Conclusions

1. A numerical model has been built to solve the aerodynamic problem in the presence of a protective perforated screen at an industrial site. An important feature of the constructed numerical aerodynamic model is the use of an internal boundary condition for the velocity potential, which makes it possible to quickly determine the air flow velocity field for a perforated screen. To implement this procedure, the results of the experiment are used, on the basis of which an empirical model was obtained for determining the air flow velocity behind a perforated screen. As a result of numerical modeling, it was established that the use of a perforated screen makes it possible to reduce the height of the dust pollution area by 3 times.

2. A numerical mass transfer model has been built to calculate the dust concentration field at an industrial site when using a protective screen. The constructed numerical model takes into account the perforation of the screen, its position on the industrial site, weather conditions, dust generation intensity, screen dimensions, and the dependence of diffusion coefficients on the local value of the air flow velocity.

3. Experimental studies were conducted to determine the regularity of change in the air flow velocity behind a protective perforated screen with a porosity of 38%. The experimental study allowed us to determine the regularity of change in the local air flow velocity behind a perforated screen, namely, the air velocity behind the screen is 5–6 times less than the value of the velocity of the oncoming air flow; the length of the stagnation zone behind the screen is on the order of $2.5H$ (H is the height of the screen).

4. Our computational experiments showed that when using the screen, the height of the dust pollution area decreases by almost 3 times. The constructed numerical models make it possible to quickly determine the intensity and size of the dust pollution area at industrial sites. The models could be used to justify the parameters of protective screens at the “fore-sketch” design stage.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors declare that generative artificial intelligence tools were used exclusively to search for relevant articles in highly rated Q1 publications and translate those papers into Ukrainian, which was under full human control.

Artificial intelligence was not used to generate, process, or interpret scientific data, draw conclusions, or other elements of the scientific results of this manuscript.

Tool used: ChatGPT (OpenAI GPT-5, version 2025).

The authors bear full responsibility for the content, reliability, and scientific correctness of the submitted material.

Authors' contributions

Mykola Biliaiev: Conceptualization, Project administration; **Viktoriia Biliaieva:** Formal analysis; **Polina Mashykhina:** Formal analysis; **Vitalii Kozychyna:** Methodology software; **Pavlo Semenenko:** Methodology software; **Oleksandr Berlov:** Data curation; **Pavlo Kirichenko:** Methodology software; **Valerii Savin Resources;** **Andrii Usenko:** Formal analysis; **Svitlana Foris:** Resources.

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