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THE STUDY OF THE INFLUENCE OF PROTECTIVE SCREEN ON REDUCING THE LEVEL OF AIR POLLUTION

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Abstract. The task of assessing the areas of chemical pollution near the highway, where the protective screen is located, is considered. The protective screen locally changes the aerodynamics of the air flow near the highway, which contributes to the minimization of air pollution in the working zones near the highway. Recently, interest has increased in studying the effectiveness of the use of protective screens of complex shape, which are located near highways. The purpose of the work is to develop a numerical model for calculating pollution zones formed near the protective screen, as well as conducting a laboratory experiment to analyze the patterns of formation of pollution zones near the T-shaped screen. For mathematical modeling of the process of formation of pollution zones near the protective screen, the equation of convective-diffusion transfer of impurities is used. This equation takes into account atmospheric diffusion, wind speed, emission intensity of a chemically hazardous substance, the location of the emission source, and the shape of the protective screen. Two models of aerodynamics are used to calculate the air flow velocity field when flowing around a protective screen. The first model is the Navier-Stokes equations. These equations are written in the variables "eddy current function". The second model is a two-dimensional equation for the velocity potential. For the numerical integration of the vortex transport equation, the splitting method is used, followed by the explicit finite-difference method. For the numerical integration of the Poisson equation for the stream function, the Liebman method is used. To numerically integrate the equation for the velocity potential and the equation for the convective-diffusion transfer of impurities, a locally one-dimensional difference scheme is used. The calculation of unknown parameters is implemented by an explicit formula. A package of application programs was created on the basis of the developed numerical model. The constructed numerical model and software package allow to study the process of the formation of pollution areas near the highway almost in real time. The results of the computational experiment are presented. The results of a laboratory experiment on the study of the structure of the contamination zone near the protective screen are presented.

Keywords: atmospheric air pollution, protective screen, numerical simulation, laboratory experiment, emission from motor vehicles, working area.

1. Introduction

Road transport is widely used at the facilities of the mining and industrial complex (Fig. 1). When cars move, intense zones of chemical air pollution appear, which are spread by the wind flow. The creation of areas of chemical air pollution leads to pollution of work zones located near transport highways even when cars are no longer on the road. Such pollution poses a threat to the health of workers who work in the area affected by highways [1].

Vegetation and protective screens are often used to protect working areas from chemical contamination [6–12]. These obstacles make it possible to change the direction of the air flow and, thanks to this, to change the direction of the movement of impurities in the air. As a result, the intensity of pollution of working areas decreases. Installation of screens does not require significant time and special equipment, that is, this method of protecting air from pollution can be implemented very quickly. For practice, it is important to be able to determine the effectiveness of screens for specific conditions of their operation (traffic intensity, weather conditions, etc.). To solve this problem, experimental research methods are used, but setting up an experiment on an object or in laboratory conditions requires a significant amount of time to obtain the desired result. It is important for engineers to have theoretical methods for determining the effectiveness of protective screens, because such methods allow you to quickly get an answer to a set of questions that determine the effectiveness of the protective function of screens. The development of such calculation methods is an important task in the field of labor protection and environmental protection.

Figure 1 – Use of trucks in the quarry (https://cutt.ly/qK3ADZB)

Analysis of recent research and publications. A common practice of studying the regularities of the formation of pollution zones and determining the effectiveness of protective screens is to conduct research in wind tunnels (Fig. 2). Such studies make it possible to determine the influence of the position of the screens on the size and shape of the pollution zone under different operating conditions. When using special equipment, it is also possible to determine the concentration of impurities in the research area. But conducting such experiments requires the use of very expensive equipment. In addition, in a number of cases, laboratory tests do not meet the Reynolds number similarity criterion.

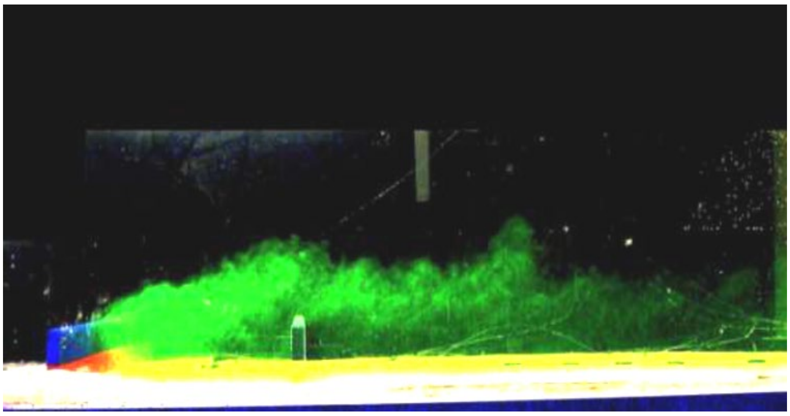


Figure 2 – Experimental study of the effectiveness of the use of a protective screen [12]

Another approach is to use the method of mathematical modeling. In the future, two approaches are used in the theoretical assessment of the level of air pollution during the emission of chemical substances from cars and when using screens. The first approach is air quality forecasting based on the Gaussian model [9, 12]. But when using this model, calculations are made only for a rectangular vertical screen. The second approach is the use of CFD modeling [5, 10–12]. However, it should also be noted that CFD models, as a rule, were used to analyze the formation of pollution zones in the case of vertical screens located near highways [5], screens with a more complex geometric shape were practically not studied by CFD modeling. It should be emphasized that an urgent problem is the development of effective, fast-calculating CFD models that allow obtaining the necessary predictive data on low- and medium-power computers. This is important from a practical point of view - the ability to make a significant number of calculations during one working day.

Formulation of the purpose of the work. The purpose of the work is to develop effective computer models for rapid assessment of the effectiveness of the use of a protective screen near the highway.

2. Methods

Research methods. The method of numerical modeling was used for theoretical study of effectiveness of the protective screen use. To analyze the regularities of the formation of pollution zones near the T-shaped protective screen, the method of laboratory modeling was used.

Presenting main material. To determine the effectiveness of the use of screens, two main tasks must be solved - to calculate the air flow velocity field near the road (the problem of aerodynamics), and to calculate the process of spreading impurities in the air from the source of pollution. Navier-Stokes equations [2] are used to solve the problem of aerodynamics:

$$\frac{\partial \omega}{\partial t}+\frac{\partial u\omega}{\partial x}+\frac{\partial v\omega}{\partial y}=\frac{1}{Re}\left(\frac{\partial^2 \omega}{\partial x^2}+\frac{\partial^2 \omega}{\partial y^2}\right) \tag{1}$$

$$\frac{\partial^2 \psi}{\partial x^2}+\frac{\partial^2 \psi}{\partial y^2}=-\omega, \tag{2}$$

where: $\omega=\partial v/\partial x-\partial u/\partial y$ – whirlwind; $Re=V_0L/\upsilon$ – Reynolds number; L – characteristic size; V_0 – characteristic speed; υ – kinematic viscosity coefficient; ψ – current function; $u=\partial\psi/\partial y$, $v=-\partial\psi/\partial x$ – components of the air flow velocity vector.

Boundary conditions for modeling equations are considered in [2].

For the numerical solution of equation (1), it is split as follows:

$$\frac{\partial \omega}{\partial t}+\frac{\partial u\omega}{\partial x}+\frac{\partial v\omega}{\partial y}=0, \tag{3}$$

$$\frac{\partial\omega}{\partial t}=\frac{1}{Re}\left(\frac{\partial^2\omega}{\partial x^2}+\frac{\partial^2\omega}{\partial y^2}\right). \tag{4}$$

The numerical solution of equation (3) is carried out on the basis of a two-step splitting scheme [2]:

– in the first step, the difference equation has the form:

$$\frac{\omega_{i,j}^{k}-\omega_{i,j}^{n}}{\Delta t}+{L^{+}}_{x}\omega^{k}+{L^{+}}_{y}\omega^{k}=0; \tag{5}$$

– at the second step of splitting, the difference equation has the form:

$$\frac{\omega_{i,j}^{n+1}-\omega_{i,j}^{k}}{\Delta t}+{L^{-}}_{x}\omega^{n+1}+{L^{-}}_{y}\omega^{n+1}=0. \tag{6}$$

The following transformations [2] are used in dependencies (5), (6):

$$\frac{\partial u\omega}{\partial x}=\frac{\partial u^{+}\omega}{\partial x}+\frac{\partial u^{-}\omega}{\partial x},$$

$$\frac{\partial v\omega}{\partial y}=\frac{\partial v^{+}\omega}{\partial y}+\frac{\partial v^{-}\omega}{\partial y},$$

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

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

$$\frac{\partial u^{+}\omega}{\partial x}\approx\frac{u_{i+1,j}^{+}\omega_{i,j}^{n+1}-u_{i,j}^{+}\omega_{i-1,j}^{n+1}}{\Delta x}=L_{x}^{+}\omega^{n+1},$$

$$\frac{\partial u^{-}\omega}{\partial x}\approx\frac{u_{i+1,j}^{-}\omega_{i+1,j}^{n+1}-u_{i,j}^{-}\omega_{i,j}^{n+1}}{\Delta x}=L_{x}^{-}\omega^{n+1},$$

$$\frac{\partial v^{+}\omega}{\partial y}\approx\frac{v_{i,j+1}^{+}{\omega^{n+1}}_{i,j}-v_{i,j}^{+}{\omega^{n+1}}_{i,j-1}}{\Delta y}=L_{y}^{+}\omega^{n+1},$$

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

The unknown value of ω in each equation (5), (6) is determined by the explicit "running account" formula.

The following dependence is used for the numerical solution of equation (4).

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

Thus, the unknown value of the vortex at each time step is determined by an explicit formula.

For the numerical integration of the Poisson equation (2), the following difference approximation [4] is used:

$$\frac{\psi_{i+1,j,k} - 2\psi_{i,j,k} + \psi_{i-1,j,k}}{\Delta x^2} + \\ - \frac{\psi_{i,j+1,k} - 2\psi_{i,j,k} + \psi_{i,j-1,k}}{\Delta y^2} = -\omega_{ij}. \tag{7}$$

The value of the function ψ is determined from (7) by an explicit formula.

In addition to the aerodynamic model of a viscous fluid, a model for calculating the air flow velocity field based on the potential motion model was also developed. The modeling equation (Laplace equation) in this case has the form [2]

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

where P – speed potential.

For the numerical integration of Laplace's equation for the velocity potential, it is written in the form of an "unsteady" equation:

$$\frac{\partial P}{\partial t} = \frac{\partial^2 P}{\partial^2 x} + \frac{\partial^2 P}{\partial^2 y}, \tag{8}$$

where t – fictitious time.

Next, the geometric splitting of equation (8) is carried out as follows:

$$\frac{\partial P}{\partial t}=\frac{\partial^2 P}{\partial x^2}, \tag{9}$$

$$\frac{\partial P}{\partial t}=\frac{\partial^2 P}{\partial y^2}. \tag{10}$$

To determine the unknown value of P on the basis of equation (9), the following dependence is used:

$$P_{i,j}^{n+1}=P_{i,j}^{n}+\mathrm{V}t\frac{P_{i+1,j}^{n}-P_{i,j}^{n}}{\Delta x^2}+\mathrm{V}t\frac{-P_{i,j}^{n}+P_{i-1,j}^{n}}{\Delta x^2}.$$

The following relationship is used to determine the unknown value of P on the basis of equation (10):

$$P_{i,j}^{n+1}=P_{i,j}^{n}+\mathrm{V}t\frac{P_{i,j+1}^{n}-P_{i,j}^{n}}{\Delta y^2}+\mathrm{V}t\frac{-P_{i,j}^{n}+P_{i,j-1}^{n}}{\Delta y^2}.$$

The calculation based on these dependencies ends when the condition is met:

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

where ε – a small number; n – iteration number.

After calculating the speed potential field, the components of the air flow speed vector are determined based on the following dependencies:

$$u=\frac{P_{i+1,j}-P_{i,j}}{\Delta x},\quad v=\frac{P_{i,j+1}-P_{i,j}}{\Delta y}.$$

The equation of convective-diffusion spread of impurities is used to model the process of the movement of pollutants from the source of pollution (car) [2, 3]:

$$\begin{gathered}\frac{\partial S}{\partial t}+\frac{\partial uS}{\partial x}+\frac{\partial vS}{\partial y}=\\ =\frac{\partial}{\partial x}\left(\mu_x\frac{\partial S}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_y\frac{\partial S}{\partial y}\right)+\\ +\sum_{i=1}^{n}Q_{S_i}(t)\delta(x-x_i)\delta(y-y_i),\end{gathered} \tag{11}$$

where S – impurity concentration; u,v – components of the air flow velocity vector; $\mu=\left(\mu_x,\mu_y\right)$ – coefficients of turbulent diffusion; Q_{S_i} – the intensity of emissions from cars; $\delta\left(x-x_i\right)\left(y-y_i\right)$ – the Dirac delta function; $\left(x_i,y_i\right)$ – coordinates of the emission source; t – time.

Boundary conditions for equation (8) are considered in [2, 3].

For the numerical integration of equation (11), the following splitting is carried out [2]:

$$\frac{\partial S}{\partial t}+\frac{\partial uS}{\partial x}=\frac{\partial}{\partial x}\left(\mu_x\frac{\partial S}{\partial x}\right), \tag{12}$$

$$\frac{\partial S}{\partial t}+\frac{\partial vS}{\partial y}=\frac{\partial}{\partial y}\left(\mu_y\frac{\partial S}{\partial y}\right), \tag{13}$$

$$\frac{\partial S}{\partial t}=\sum_{i=1}^{n}Q_{Si}(t)\delta\left(x-x_i\right)\left(y-y_i\right). \tag{14}$$

For the numerical solution of equation (12), the following two-step splitting scheme is used:

– the first step uses the dependency:

$$S_{i,j}^{n+\frac{1}{2}}=S_{i,j}^{n}-\Delta t\frac{u_{i+1,j}^{+}S_{i,j}^{n+\frac{1}{2}}-u_{i,j}^{+}S_{i-1,j}^{n+\frac{1}{2}}}{\Delta x}+$$

$$+\Delta t\,\mu_x\frac{-S_{i,j}^{n+\frac{1}{2}}+S_{i-1,j}^{n+\frac{1}{2}}}{2\Delta x^2}+\Delta t\,\mu_x\frac{-S_{i,j}^{n}+S_{i+1,j}^{n}}{2\Delta x^2},$$

– the second step uses the dependency:

$$S_{i,j}^{n+1}=S_{i,j}^{n+\frac{1}{2}}-\Delta t\frac{u_{i+1,j}^{-}S_{i+1,j}^{n+1}-u_{i,j}^{-}S_{i,j}^{n+1}}{\Delta x}+$$

$$+\Delta t\,\mu_x\frac{-S_{i,j}^{n+\frac{1}{2}}+S_{i-1,j}^{n+\frac{1}{2}}}{2\Delta x^2}+\Delta t\,\mu_x\frac{-S_{i,j}^{n+1}+S_{i+1,j}^{n+1}}{2\Delta x^2},$$

where $u^{+}=\dfrac{u+|u|}{2}, u^{-}=\dfrac{u-|u|}{2}$.

Similarly, the difference splitting scheme for the numerical integration of equation (13) is written. The Euler method [4] is used for the numerical integration of equation (14).

Based on the developed numerical model, a code was created in the FORTRAN programming language.

3. Results and discussion

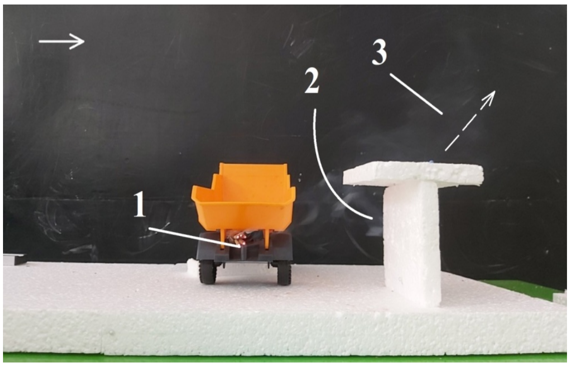
At the first stage of the research, a physical experiment was conducted to determine the regularities of the formation of the air pollution zone when using a T-shaped barrier. To create a source of emission, "flavored sticks" were smoked, which create smoke that can be recorded on a camera. These sticks were located in the lower part of the model car. A GD-3301 gas analyzer was used to measure *CO* concentration. A blower was used to create the air flow. The air flow rate was determined by using the GM 8908 device.

The experiment was carried out with the following parameters: the length of the model car *L*=460mm, width 80mm, average height of the model 110mm; flow rate; the height of the impurity emission source 30mm; length from the model car to the barrier 150mm; barrier height 100mm, the length of the horizontal plate on the barrier 100мм; air temperature 21^{0}C. *CO* concentration was measured at altitude 120mm. *CO* concentration near the emission source *Co*= 82–90 ppm. The Reynolds number was used as a similarity criterion. When calculating the Reynolds number, the length of the model car was used as a scale L, air flow rate *V*, coefficient of kinematic viscosity ν at temperature 21^{0}C ($\nu=15{,}06\cdot10^{-6}\,м^2/c$). The value of the Reynolds number was calculated as follows:

$$Re=\frac{V\cdot L}{\nu}.$$

In fig. 3 shows the zone of air pollution near the barrier. The presence of sharp edges on the model car and the barrier was the reason for the formation of vortices separation and the appearance of a turbulent flow regime. In fig. 2, vortices can be clearly seen in the study area.

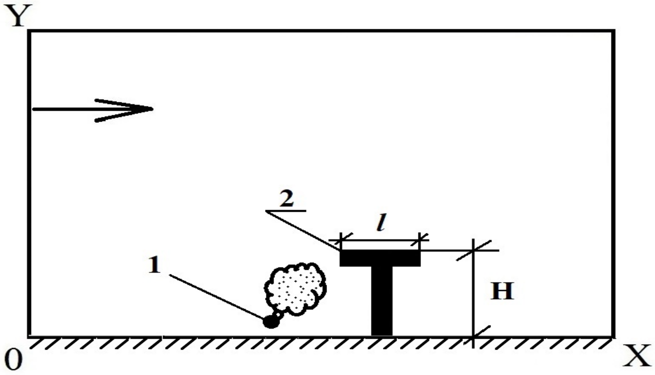
By analyzing fig. 3, it is possible to detect the regularities of the formation of the air pollution zone when using a "T"-shaped screen. Namely, near the barrier, an area with a fairly high concentration of impurities is formed, which is indicated by the "density" of the smoke (area 2, Fig. 3). This area is formed due to the fact that the vertical part of the screen acts as an obstacle to the horizontal spread of the impurity, and the additional plate on top creates an obstacle to the vertical movement of the impurity along the screen. Therefore, the flow of polluted air makes a U-turn near the edge of the horizontal plate and begins to move upwards. As a result, an additional area of contamination is formed above the plate (area 3, Fig. 3). Smoke density in this area is less than in the first area. It is important to see the movement of polluted air upwards, which is shown by the tangent arrow in fig. 3. This movement helps to reduce the level of air pollution behind the screen. Thus, due to the change in the aerodynamics of the flow near this screen, the level of contamination of the working zones behind it is reduced.



1 – place of emission of pollutant; 2 – area of contamination under the plate;
3 – area of contamination above the plate

Figure 3 – Contamination zone near the protective screen, t= 12s

At the second stage of research, a computational experiment was conducted based on the constructed numerical model. The *NO* concentration field was calculated when the T-shaped protective screen was located near the highway (Fig. 4).



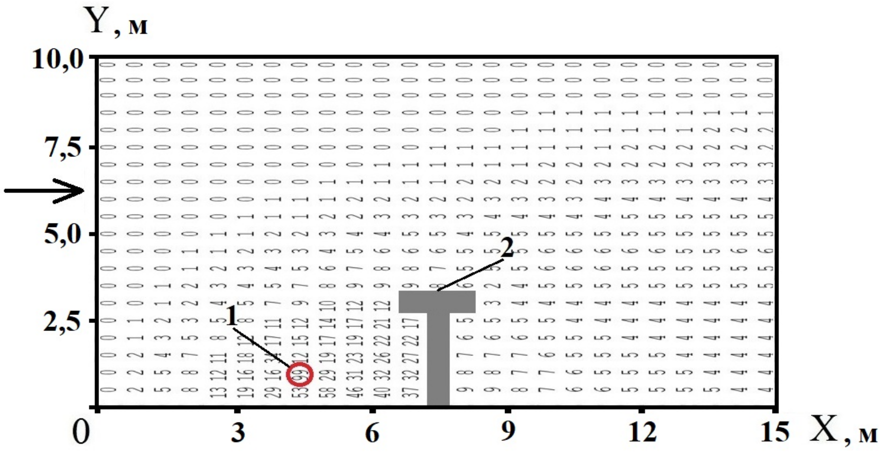
1 – emission source; 2 – protective screen

Figure 4 – Calculation scheme

The emission from the car was modeled by a point source of pollution of known intensity. The calculation was carried out for the following scenarios: the length of the upper part of the screen is *l*=1m, the height of the screen is *H*=3m (scenario №1) and *H*=3.5m (scenario №2). Another scenario: the length of the top of the screen is *l*=2m, height is *H*=3m (scenario №3). Below, in the figures, the field of *NO* concentration for three scenarios is shown. The concentration is given as a percentage of the maximum concentration value in the calculation area. The value «99» corresponds to the maximum concentration – this is the position of the impurity emission source. The concentration is printed in the «*INTENGE*R» format, that is, in the form of an «integer» number.

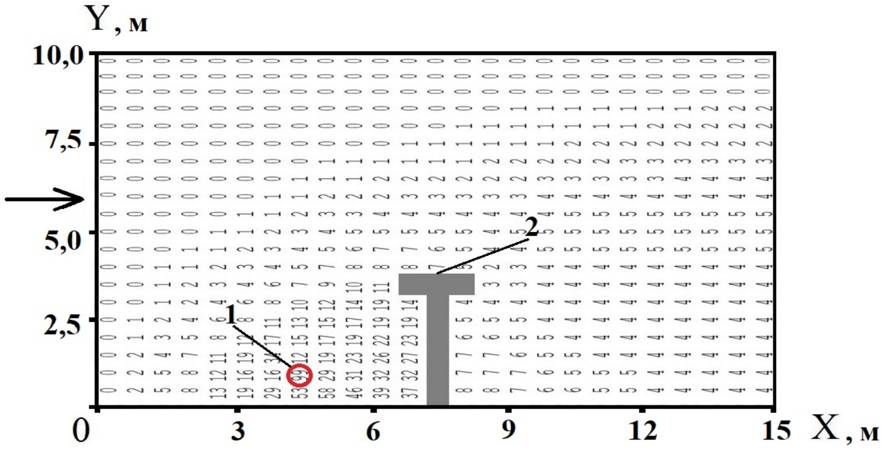
As you can see from the above figures, the most intense air pollution occurs in front of the screen. Here, the concentration of impurities in the air is of the order of 10%–99%. Behind the screen, the impurity concentration is within 5%–8%.

Note that the calculation time of one scenario is 10 seconds.



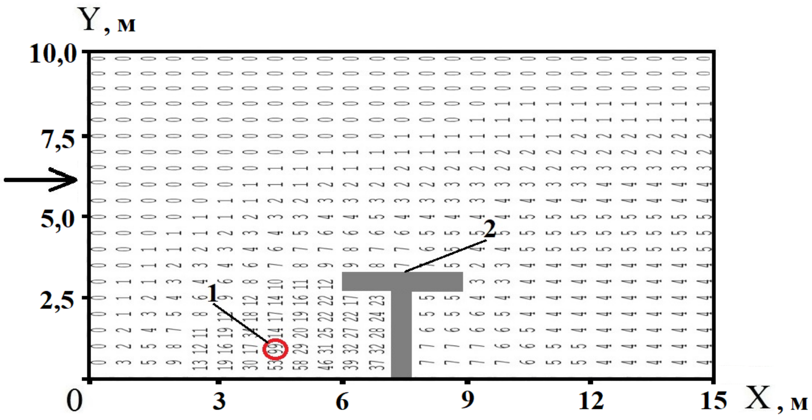
1 – emission source; 2 – protective screen

Figure 5 – Pollution zone, scenario №1



1 – emission source; 2 – protective screen

Figure 6 – Pollution zone, scenario №2



1 – emission source; 2 – protective screen

Figure 7 – Pollution zone, scenario №3

Scientific novelty and practical value. A numerical model is proposed for the analysis of pollution areas formed near the highway. This model also makes it possible to determine the effectiveness of using a screen with a complex geometric shape, located near the highway, to reduce the level of air pollution. A feature of the numerical model is the speed of the calculation, which lasts a few seconds. This makes it possible to carry out serial calculations at the stage of conducting scientific research works to minimize the negative impact of highways on the environment.

4. Conclusions

1. A numerical model is developed that allows predicting the level of air pollution near highways with taking into account the effect of screens on the formation of pollution zones.
2. The results of the practical use of the developed numerical model indicate that the model makes it possible to quickly obtain information about the effectiveness of the use of the screen near the highway.
3. The given results of the laboratory experiment make it possible to determine the regularities of the formation of the pollution zone near the vertical screen, which has a "T" shape.

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ДОСЛІДЖЕННЯ ВПЛИВУ ЗАХИСНОГО ЕКРАНУ НА ЗНИЖЕННЯ РІВНЯ ЗАБРУДНЕННЯ ПОВІТРЯ

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Анотація. Розглянута задача оцінки зон хімічного забруднення біля автомагістралі, де розміщено захисний екран. Захисний екран локально змінює аеродинаміку повітряного потоку біля магістралі, що сприяє мінімізації забруднення повітря в робочих зонах біля магістралі. Останнім часом посилився інтерес до вивчення ефективності застосування захисних екранів складної форми, що розташовуються біля автотрас. Метою роботи є розробка чисельної моделі для розрахунку зон забруднення, що утворюється біля захисного екрана, а також проведення лабораторного експерименту з аналізу закономірностей формування зон забруднення біля Т-подібного екрана. Для математичного моделювання процесу утворення зон забруднення біля захисного екрана використовується рівняння конвективно-дифузійного переносу домішок. Це рівняння враховує атмосферну дифузію, швидкість вітру, інтенсивність викидів хімічно небезпечної речовини, розташування джерела викидів і форму захисного екрана. Для розрахунку поля швидкості повітряного потоку під час обтікання захисного екрану використовуються дві моделі аеродинаміки. Перша модель – рівняння Нав'є-Стокса. Для вирішення задачі аеродинаміки використовуються рівняння Нав'є-Стокса. Ці рівняння записуються у змінних «вихор–функція струму». Друга модель – двомірне рівняння потенціалу швидкості. Для чисельного інтегрування рівняння перенесення вихору використовується метод розщеплення з наступним застосуванням явного кінцево-різницевого методу. Для інтегрування рівняння Пуассона для функції струму застосовується метод Лібмана. Для чисельного інтегрування рівняння потенціалу швидкості і рівняння конвективно-дифузійного переносу домішки застосовується локально одновимірна різницева схема. Розрахунок невідомих параметрів реалізується за явною формулою. Крім рівнянь моделі в'язкої рідини для розв'язання задачі аеродинаміки використовується також модель потенційного руху. Скінченно-різницеві методи використовуються для чисельного інтегрування рівнянь моделювання. На основі розробленої чисельної моделі створено пакет прикладних програм. Побудована чисельна модель та програмний комплекс дозволяють практично в режимі реального часу досліджувати процес формування зон забруднення поблизу автомагістралі. Наведено результати обчислювального експерименту. Наведено результати лабораторного експерименту з вивчення структури зони забруднення біля захисного екрану.

Ключові слова: забруднення атмосферного повітря, захисний екран, чисельне моделювання, лабораторний експеримент, викиди автотранспорту, робоча зона.