

## UDC 502.3:613.648.4

T. I. RUSAKOVA<sup>1\*</sup>

<sup>1</sup>Dep. «Aerohydrodynamics and Energy Mass-transfer», Oles Honchar Dnipro National University, Kazakov St., 18, Dnipro, Ukraine, 49010, tel. +38 (056) 776 82 05, e-mail rusakovati1977@gmail.com, ORCID 0000-0001-5526-3578

## METHOD FOR PREDICTING PARAMETERS OF THE AEROIONIC MODE IN OPEN TERRAIN GROUND AREAS

**Purpose.** The scientific work is devoted to the development of a new method for forecasting aeroionic mode in working areas at industrial sites, taking into account ionizing sources and surrounding obstacles. **Methodology.** To find the concentration of positive aeroions, dust and negative aeroions, we use 3D mass transfer equations that take into account the rate of recombination of ions having different polarity and the rate of recombination of ions with dust particles. The numerical solution is based on the integration of the mass transfer equations using the finite-difference method, which turns out to be stable for any step in time. To determine the components of the air velocity vector, a three-dimensional model of the potential flow is used, where the Laplace equations for the velocity potential are the modeling equations. **Findings.** The mathematical method of numerical calculation of the concentration of positive, negative aeroions and dust has been developed. A feature of the method is the possibility of predicting the aeroionic mode, taking into account all physical factors that significantly affect the formation of concentration zones of aeroions in working areas at industrial sites. The method is not tied to a particular industrial site, it allows us to estimate the value of the concentration of aeroions both locally and in the entire calculated region. **Originality.** A method for prediction of aeroionic mode in working areas is developed based on 3D modeling of the propagation of negative, positive aeroions and dust under the influence of wind and diffusion, which allows to obtain results at each point of space or in a specific cross-section. **Practical value.** The proposed method of forecasting was used to solve the problem of estimating aeroionic mode in industrial zones in the open area of the industrial site of the Dnipro oil extraction plant in the presence of emission sources: positive aeroions during the operation of vehicles and respiration of workers; dust during the movement of workers and vehicles; negative aeroions of the ionizer installed in the working zone. The regularities of changes in the concentration of aeroions of various polarity and dust at a height of 1.7 m are determined, which corresponds to the position of the respiratory organs of workers. Quantitative results are needed in assessing the permissible working conditions in the workplaces of industrial sites of enterprises when creating new jobs and reengineering existing ones.

**Keywords:** ionization of air; sources of ion emission; numerical method; industrial site; concentration of aeroions

### Introduction

Providing a certain degree of ionization of the air environment in the working area is one of the most important factors in maintaining a good state of health and high efficiency of staff. It has been established that a significant decrease in the content of charged particles (ions) in the air coincides with the appearance of unusual sickness in working people, fatigue complaints, depression, nausea, insomnia, irritability, respiratory disorders, and others. At the same time, the presence of people in conditions with moderately high ionization of the atmosphere, with the vast majority of negative ions - on the contrary, there is a beneficial effect on the body. The process of ionization of air consists in the transformation of neutral atoms and air molecules into electrically

charged particles (ions). Ions in the air (aeroions) can be formed as a result of natural and artificial ionization.

Natural ionization occurs as a result of the influence on the air of space and solar radiation and ionizing radiation (particles) that arise during the decay of long-lived radionuclides of the earth's crust (potassium-40, uranium-238, thorium-232, etc.). Natural ionization of the air environment is everywhere and constant in time. Artificial aerionization occurs under the influence of ionizing factors, which accompany some technological processes (X-ray and ultraviolet radiation, thermo-emission, photoelectric effect, etc.); as well as the effect of special devices – ionizers. The degree of ionization of air depends on the ratio of ionization and deionization processes. The latter is due to the recombination of

## ЕКОЛОГІЯ ТА ПРОМИСЛОВА БЕЗПЕКА

two ions of different polarities, adsorption of light ions on uncharged nuclei, condensation, neutralization of light and heavy ions by charges of the opposite sign, and others.

Assessment of the aeration degree of the environment is carried out by comparing the measured values with the standard ones. Artificial ionizers (high-voltage, induction, radiation, etc.) and efficient, well-organized ventilation of premises are widely used to normalize the ionic mode of the air environment, as the external clean air contains 2-5 times more ions than the air of indoor premises (50-100 ions/cm<sup>3</sup>).

Many works of domestic authors are devoted to the study of aeroionic mode. Modeling of aeroionic mode in working zones under conditions of artificial ionization is presented in the work [1]. The problem of the evaluation and the relationship between aerosol pollution and the aeroionic composition of air in the working zone is considered in the works [8–9]. The works [2, 11] are devoted to the modeling of the aeroionic mode in premises with artificial ionization using the means of numerical Modeling. The proposed program information system for the optimization of the microclimate in the premises is in [6]. The study of ways to improve the aeroionic mode of the working environment is presented in work [7]. The study of the microclimatic parameters influence of air exchange on the aeroionic composition of the air in the working premises and the modeling and prediction of the aeroionic composition dynamics of air are given in the works [4–5]. The methods for determining the concentration of aeroions and dust content are presented in the work [3]. The normalization of the aeroionic composition of air in office premises is considered in the work [15]. A large number of foreign works are devoted to the study of ionization processes for improving the health of employees [12–14, 16].

### Purpose

The purpose of this study is to develop a new method for forecasting aeroionic mode in working areas at industrial sites, taking into account ionizing sources and surrounding obstacles (buildings).

### Methodology

It is known that the formation of the concentration field of aeroions is influenced by a complex of physical factors: airflow, diffusion, electric field effect and others. In addition, there is the interaction of ions of different polarity and their interaction with particles of dust. To account for these processes during the Modeling of aeroions dispersion, the 3D equation of mass transfer is used. It is written for each component (positive aeroions, dust, negative aeroions). The Modeling equations have the form:

– to describe the process of dispersion of positive ions

$$\begin{aligned} \frac{\partial A_p}{\partial t} + \frac{\partial u A_p}{\partial x} + \frac{\partial v A_p}{\partial y} + \frac{\partial w A_p}{\partial z} = \\ = \frac{\partial}{\partial x} \left( \mu_x \frac{\partial A_p}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu_y \frac{\partial A_p}{\partial y} \right) + \frac{\partial}{\partial z} \left( \mu_z \frac{\partial A_p}{\partial z} \right) - \\ - \alpha A_p A_n - \beta A_p A_d + \\ + \sum_{p_i=1}^n Q_{p_i}(t) \delta(x - x_{p_i}) \delta(y - y_{p_i}) \delta(z - z_{p_i}); \quad (1) \end{aligned}$$

– for modeling the transfer of dust

$$\begin{aligned} \frac{\partial A_d}{\partial t} + \frac{\partial u A_d}{\partial x} + \frac{\partial v A_d}{\partial y} + \frac{\partial w A_d}{\partial z} = \\ = \frac{\partial}{\partial x} \left( \mu_x \frac{\partial A_d}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu_y \frac{\partial A_d}{\partial y} \right) + \frac{\partial}{\partial z} \left( \mu_z \frac{\partial A_d}{\partial z} \right) + \\ + \sum_{d_i=1}^n Q_{d_i}(t) \delta(x - x_{d_i}) \delta(y - y_{d_i}) \delta(z - z_{d_i}); \quad (2) \end{aligned}$$

– to describe the process of dissipating negative ions

$$\begin{aligned} \frac{\partial A_n}{\partial t} + \frac{\partial (u + bE) A_n}{\partial x} + \frac{\partial (v + bE) A_n}{\partial y} + \\ + \frac{\partial (w + bE) A_n}{\partial z} = \frac{\partial}{\partial x} \left( \mu_x \frac{\partial A_n}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu_y \frac{\partial A_n}{\partial y} \right) + \\ + \frac{\partial}{\partial z} \left( \mu_z \frac{\partial A_n}{\partial z} \right) - \alpha A_n A_p - \beta A_n A_d + \\ + \sum_{n_i=1}^n Q_{n_i}(t) \delta(x - x_{n_i}) \delta(y - y_{n_i}) \delta(z - z_{n_i}). \quad (3) \end{aligned}$$

## ЕКОЛОГІЯ ТА ПРОМИСЛОВА БЕЗПЕКА

The denotations of physical parameters in these equations are as follows:

$A_p$ ,  $A_n$ ,  $A_d$  – the concentration of positive, negative aeroions and dust particles, respectively;  $u$ ,  $v$ ,  $w$  – components of the velocity vector of the air flow;  $\mu_x$ ,  $\mu_y$ ,  $\mu_z$  – coefficients of diffusion;  $t$  – time;  $\alpha$  – the rate of recombination of ions with different polarity;  $\beta$  – the rate of recombination of ions with dust particles;  $Q_{A_{p_i}}(t)$  – the intensity of the emission of positive ions at the corresponding coordinate points  $x_{n_i}$ ,  $y_{n_i}$ ,  $z_{n_i}$ ;  $\delta(x - x_{n_i})\delta(y - y_{n_i})\delta(z - z_{n_i})$  – delta-function of Dirac;  $b$  – coefficient of ions mobility;  $E$  – electric field strength.

At the boundary of the air flow inlet into the calculated area is the initial condition:

$$A_p|_{entrance} = A_{p_0}, \quad (4)$$

where  $A_{p_0}$  – the initial concentration of aeroions.

At the boundary of the area outlet from the calculated we set a «soft» boundary condition:

$\frac{\partial \varphi}{\partial \vec{n}} = 0$ , where  $\vec{n}$  – unit vector of the external normal to the solid surface.

For numerical implementation such a boundary condition is recorded:

$$A_p(i+1, j) = A_p(i, j), \quad (5)$$

where  $A_p(i+1, j)$  – the values of ions in the last boundary cell,  $A_p(i, j)$  – the value of ions in the penultimate difference cell.

On the ground surface and all solid surfaces, the boundary condition for non-permeability is set:

$$\frac{\partial A_p}{\partial \vec{n}} = 0. \quad (6)$$

This condition physically means that the flow of ions at these boundaries is zero.

Using the Modeling equations (1) – (3) speed components  $u(x, y, z)$ ,  $v(x, y, z)$ ,  $w(x, y, z)$  must satisfy the equation of continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0. \quad (7)$$

To fulfill this condition one should solve an aerodynamic problem for determining the velocity field. To determine the components of the air velocity vector, a three-dimensional model of the potential flow is used, where the Laplace equation for the velocity potential serves as the simulating equation:

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} + \frac{\partial^2 P}{\partial z^2} = 0, \quad (8)$$

where  $P$  – speed potential.

Components of the velocity vector of the air are related to the velocity potential by the following relationships:

$$u = \frac{\partial P}{\partial x}, \quad v = \frac{\partial P}{\partial y}, \quad w = \frac{\partial P}{\partial z}. \quad (9)$$

For the Laplace equation, the following boundary conditions are set:

– on firm boundaries the condition of non-permeability is set  $\frac{\partial P}{\partial \vec{n}} = 0$ ;

– on the boundary of the flow outlet from the calculated region the Dirichlet boundary condition is set  $P = const$ ;

– at the boundary of the air flow inlet into the calculated area, the boundary condition is set  $\frac{\partial P}{\partial \vec{n}} = V$ , where  $V$  – known velocity of the inflow.

When simulating the propagation of aeroions, it is necessary to take into account the influence of the electric field on this process. Since the aeroions have a charge, they generate an electric field  $E$ . For the Modeling of the electric field, the following equation is used [2, 12]:

$$\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z} = \frac{q_e}{\epsilon_0}, \quad (10)$$

where  $\epsilon_0$  – dielectric permeability;  $q_e$  – volumetric charge density.

From equation (5.7) we can go to the scalar potential, if we take into account such dependence:

$$E_x = -\frac{\partial \varphi}{\partial x}, \quad E_y = -\frac{\partial \varphi}{\partial y}, \quad E_z = -\frac{\partial \varphi}{\partial z}. \quad (11)$$

## ЕКОЛОГІЯ ТА ПРОМИСЛОВА БЕЗПЕКА

Then we obtain the Poisson equation:

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = -\frac{q_e}{\varepsilon_0}, \quad (12)$$

where  $q_e = -e \cdot A_p(x, y, z)$ ,  $A_p(x, y, z)$  – concentration of positive aeroions;  $\varphi$  – scalar potential;  $e$  – elementary charge. On the basis of this equation electric field Modeling is carried out.

As the boundary condition, the condition of electrical insulation is used:

$$\frac{\partial \varphi}{\partial \vec{n}} = 0,$$

where  $\vec{n}$  – unit vector of the external normal to the solid surface.

For numerical integration of the mass transfer equations, a difference scheme is used based on the geometric and physical splitting of the simulating equations (1) – (3). In each of the four fractional steps, only one direction of perturbation transfer is taken into account; the fifth split step takes into account the change in the concentration of aeroions due to the action of the emission source. The calculation is performed on a rectangular difference grid. Concentration of quantities  $A_p$ ,  $A_n$ ,  $A_d$  is determined in the centers of the difference cells, whereas the components of the velocity vector of the air are set at the boundaries of the difference cells [2, 11–12].

### Findings

To estimate the aeroionic mode in the working zones, based on the developed method, it is necessary to determine the aeroions emission intensity from the specific sources. As already noted, one of these sources is the worker, who exhales positive aeroions. Physical experiment was conducted to obtain scientifically substantiated information regarding the magnitude of such emission.

For the experiment, a group of people of different ages was selected: 16 people in each age group. The mouth area was measured  $S=9.5 \text{ cm}^2$ , the rate of air flow when exhaled was on average  $V=0.4 \text{ m/s}$ , flow rate  $Q=V \cdot S \text{ m}^3/\text{s}$ , the intensity of the emission of positive aeroions when exhaled  $I=V \cdot S \cdot C \text{ ions/s}$ , where  $C$  – concentration of positive aeroions at exhalation. The results of

measuring the average concentration of positive aeroions when exhaling for each age group are given in Table 1.

Experiment to measure the concentration of aeroions from human exhalation was carried out using the KT-401 AIRION TESTER.

Table 1

**The value of the concentration of positive aeroions when person exhales**

Age of a person, years	Concentration of positive aeroions, ions/cm <sup>3</sup> ,
8–9	166–176
18–19	232–349
40	277–329
78	210–256

The data obtained on the basis of the conducted physical experiment, were used during computational experiments. During the experiments it was taken into account that the source of positive aeroion emission during exhalation had a periodic action, namely, exhalation for 1 s in quantity  $Q$ , the inhalation – emission is absent and after 2 s again exhalation with the same emission. That is, the source of periodic emission  $Q(t)$  is known.

Verification of the developed forecast method was carried out. A test task was solved to calculate the emission of positive aeroions with exhaust gases of vehicles.

During the physical experiment, the positive aeroions at different distances from the Daewoo Matiz exhaust pipe were measured using the KT-401 AIRION TESTER. The velocity of wind and gas flow at the exhaust pipe outlet was measured using an anemometer PM 6252 B Digital Anemometer. The speed of the air flow was  $V_{\text{air}}=1.2–1.4 \text{ m/s}$ , and the speed of gas flow  $V_{\text{gas}}=1.7–1.9 \text{ m/s}$ , diameter of the exhaust pipe hole  $d=32 \text{ mm}$ .

The method of conducting the experiment was as follows: the concentration of positive aeroions was measured at a height of 320 mm from the ground surface at different distances from the exhaust pipe. To obtain data on the intensity of emissions, the calculation was made according to the ratio  $Q=V_{\text{gas}} \cdot S \cdot C$ , where  $V_{\text{gas}}$  – the velocity of the gas flow in the outlet cross section of the ex-

## ЕКОЛОГІЯ ТА ПРОМИСЛОВА БЕЗПЕКА

haust pipe,  $S$  – area of the outlet cross section of the exhaust pipe hole,  $C$  – the concentration of positive aeroions in the outlet cross section. Immediately during the experiment parameters  $V_{gas}$  and  $C$  were measured at a distance of 0.5 cm from the outlet cross section of the exhaust pipe hole. The obtained data were used as input information for numerical calculation on the basis of the developed method. Using this method, the impurity concentration values at the points of measurements were also calculated. Table 2 shows the results of experimental measurements and the calculated data obtained with the help of the developed numerical calculation method.

Table 2

**Concentration of positive aeroions at different distances from the emission source**

Distance from exhaust pipe of a car, cm	Concentration of positive aeroions, ions/cm <sup>3</sup> (experiment)	Concentration of aeroions, ions/cm <sup>3</sup> (calculation)
5	1 400–1 443	1 425
10	1 080–1 097	1 092
20	650–738	721
30	420–546	465
40	143–158	152
50	67–76	72
60	43–57	52

Data analysis shows the adequacy of the numerical calculation method. The corresponding deviation is due to the flow turbulization caused by the influence of the car body on the aerodynamics of the flow.

The source of positive aeroions on the street is primarily people, cars. During calculations, a complex of factors was taken into account, which had been overlooked in scientific publications: aeroion emission from cars; aeroion emission from humans; the influence of various obstacles in the street on the aeroionic mode formation; the influence of the uneven wind velocity field on the formation of aeroionic mode; the influence of the uneven field of atmospheric diffusion on the formation of the aeroionic mode; modeling of aeroions dispersion in a three-dimensional formulation (3D modeling).

Taking into account the listed factors extremely complicates the solving of these problems:

The task solution is based on three stages:

1. Modeling the formation of a field of concentration of positive, negative aeroions and dust under the influence of wind and atmospheric diffusion.
2. Modeling the transport of aeroions under the action of an electric field.
3. Change the field of concentration of aeroion, dust due to their interaction.

The developed method of forecasting was used to solve the task of estimating the level of pollution of working areas in the open air in the presence of a source of emissions: positive aeroions – emissions from vehicles and people; dust – traffic; sources of negative aeroions – an ionizer installed in the working zone and the screen (fence), which changes the aerodynamics of the aeroions and dust.



Fig. 1. Modeling area (Google Earth Image, 2019)  
Dnipro Oil Extraction Plant:  
1 – cargo scales

As a research object, the Dnipro Oil Extraction Plant was chosen, namely, the territory where the cargo scales (Fig. 1) operate, where the lorries with seeds arrive. This area is a source of dust, positive aeroions, and workers responsible for unloading cars are constantly under the influence of these negative factors.

Scheme of the calculated area is presented in Fig. 2

There are the results of the computational experiment for calculating the field of positive, negative aeroion and dust concentration in the working area of the industrial site (Fig. 3, Fig. 5, Fig. 7). The speed of the air flow was set at 5 m/s, the size of the calculated area was 8x4 m, the intensity of the sources of aeroions was 1000 ions/cm<sup>3</sup>. Fig. 4,

ЕКОЛОГІЯ ТА ПРОМИСЛОВА БЕЗПЕКА

Fig. 6, Fig. 8 show the percentage distribution of negative, positive aeroions and dust concentrations in the working area at the height of 1.7 m.

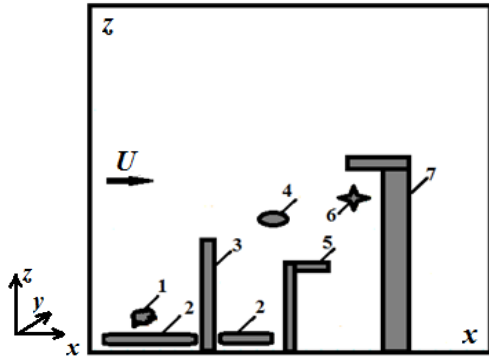


Fig. 2. Scheme of the calculated area:  
 1 – emission source (car), 2 – emission source (dust),  
 3 – screen, 4 – source of positive aeroions,  
 5 – working area,  
 6 – source of negative aeroions (ionizer),  
 7 – temporary building

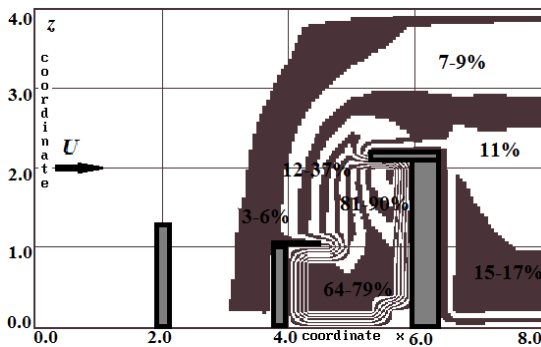


Fig. 3. Distribution of negative aeroions concentration, intersection  $y=4$  m

In Fig. 3 it is evident that at the distance of 3 m from the beginning of the calculated area there are no negative aeroions, since there is no source of emission on this site, and on another section a complex picture of the distribution, which is caused by the movement of the air flow and the action of atmospheric diffusion, is observed.

The value of the concentration at the height  $H = 1.7$  m slowly increases under the influence of the emission source and diffusion (Fig. 4).

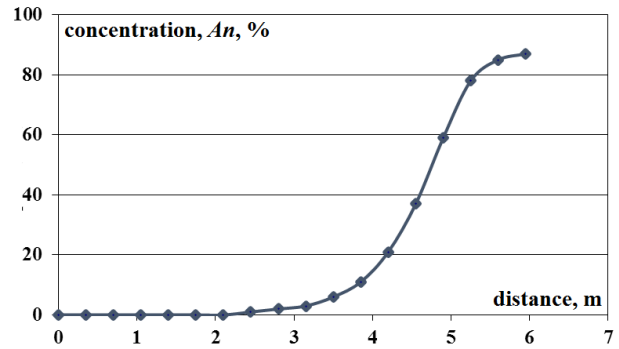


Fig. 4. Distribution of the concentration of negative aeroions at the height  $H = 1.7$  m, intersection  $y=4$  m

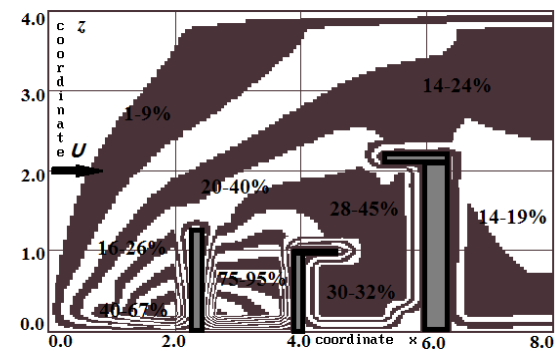


Fig. 5. Distribution of dust concentration, intersection  $y=4$  m

In Fig. 5 it is evident that the entire research area is filled with dust, due to its intensive allocation on two sites: before the screen – the emission of dust from cars; from the screen to the location of the scales – the work area of the workers. The dust is driven by wind flow and gets into the working area in the open ground. The maximum permissible concentration is  $MPC_{a.d.}=0.15$  mg/m<sup>3</sup>, so the dust concentration in this zone exceeds the  $MPC_{a.d.}$  by 20%.

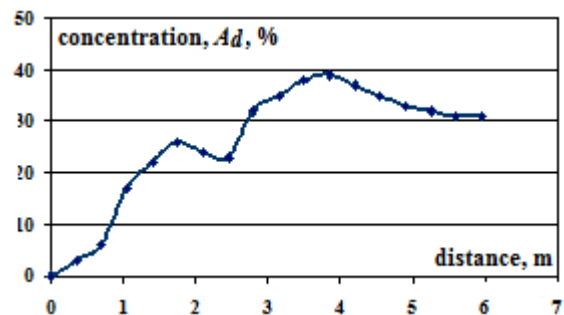


Fig. 6. Distribution of dust concentration at the height  $H = 1.7$  m, intersection  $y=4$  m

## ЕКОЛОГІЯ ТА ПРОМИСЛОВА БЕЗПЕКА

The dust concentration at the height of  $H = 1.7$  m slowly increases under the influence of the emission source (motor vehicles), then it is reduced due to the screen action and decreases at insignificant distance, but under the influence of the source of emissions (workers) increases again and decreases due to changing the flow direction near the awning of the temporary building and diffusion (Fig. 6).

Fig. 7 shows the distribution of positive aeroions.

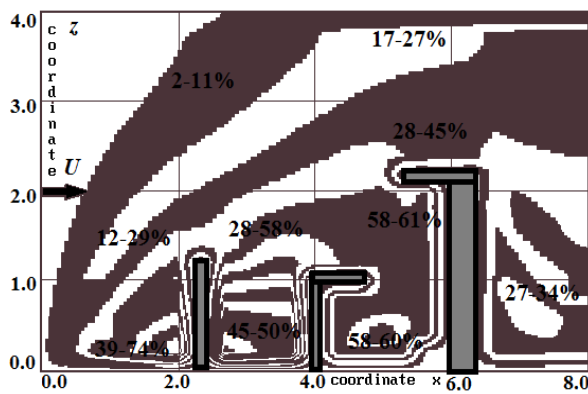


Fig. 7. Distribution of the concentration of positive aeroions, intersection  $y=4$  m

Apparently, in the working zone there is a dynamics of growth of positive aeroions, which is caused by the transport of positive aeroions from vehicles (source of emissions – cars) and the emission of positive aeroions from people in the working zone, that is, the interaction of sources of aeroion emissions takes place.

As the dust concentration values, the concentration of positive aeroions slowly increases at the height  $H = 1.7$  m under the action of the emission source of positive aeroions (vehicles), then it is reduced by the screen action and decreases at insignificant distance, but under the influence of the source of emissions (workers) increases again and decreases due to changing the flow direction near the awning of the temporary building and diffusion (Fig. 8).

The optimal level of positive aeroions 1500-3000 ions/cm<sup>3</sup>, the maximum allowable level is 50000 ions/cm<sup>3</sup>, in the working area is observed exceeding the permissible level by 10%.

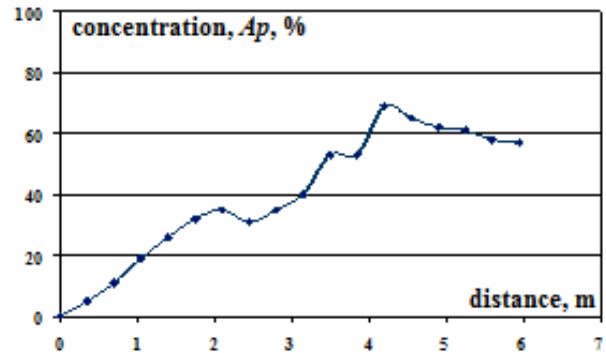


Fig. 8. Distribution of the concentration of positive aeroions at the height of  $H=1.7$  m, intersection  $y=4$  m

### Originality and practical value

1. The method of aeroionic mode forecasting in working zones is developed, which is based on three-dimensional modeling of the distribution of negative, positive ions and dust under the influence of wind and diffusion.

2. The peculiarity of the proposed method is the possibility of forecasting the aeroionic mode, taking into account almost all physical factors that significantly affect the formation of concentration fields of aeroions in working areas at industrial sites.

3. The proposed method of forecasting was used to solve the problem of aeroion assessment in open areas in industrial site in the presence of emission sources: positive aeroions – emissions of vehicles and breathing of people; dust – the movement of workers and vehicles; sources of negative aeroions – ionizer installed in the working zone and the screen, which changes the aerodynamics of aeroions and dust.

4. The regularities of the change in the concentration of aeroions and dust at the height of 1.7 m are established, which corresponds to the position of the respiratory organs of the workers.

5. The developed mathematical method of forecasting can be used to estimate the concentration of aeroions of different polarity and dust.

6. The method is implemented in the form of application program for the calculation of aeroionic mode in the working areas in the open field of industrial sites.



## ЕКОЛОГІЯ ТА ПРОМИСЛОВА БЕЗПЕКА

**Findings**

As a result of the conducted research the following results were obtained:

- the mathematical method of numerical calculation of the concentration of positive, negative aeroions and dust is proposed;
- the method is not tied to a specific industrial site, it allows estimating the value of the concentration of aeroions both locally and in the entire calculated area;
- a physical experiment was conducted demon-

strating the adequacy of the numerical calculation method;

– the results of calculations are useful in terms of ensuring acceptable working conditions in the workplaces of industrial sites, in creating new jobs and reengineering the existing ones.

The prospect of development of this direction is to improve the established method for assessing the parameters of well-being of workers in outdoor areas of industrial sites in the established aeroionic mode.

**LIST OF REFERENCE LINKS**

1. Беликов, А. С. Некоторые аспекты оптимизации исследования условий труда по микроклимату в промышленной индустрии / А. С. Беликов, С. Ю. Рагимов, В. Д. Акиншин // Будівництво, матеріалознавство, машинобудування : зб. наук. пр. / ДВНЗ «Придніпр. держ. акад. буд-ва та архітектури». – Дніпропетровськ, 2010. – Вип. 52, ч. 2. – С. 3–9.
2. Беляев, Н. Н. Моделирование аэроионного режима в рабочих зонах в условиях искусственной ионизации воздуха / Н. Н. Беляев, С. Г. Цыганкова // Наука та прогрес транспорту. – 2016. – № 1 (61). – С. 39–47. doi: <http://doi.org/10.15802/stp2016/60947>
3. Водяник, А. О. Методи визначення концентрацій аероіонів та вмісту пилу у повітрі виробничих приміщень // А. О. Водяник, Т. В. Віднічук // Містобудування та територіальне планування : наук.-тех. зб. – Київ, 2013. – Вип. 50. – С. 77–81.
4. Глива, В. А. Дослідження впливу мікрокліматичних параметрів повітрообміну на аероіонний склад повітря робочих приміщень / В. А. Глива // Проблеми охорони праці в Україні : зб. наук. пр. – Київ, 2011. – Вип. 20. – С. 58–65.
5. Запорожець, О. І. Принципи моделювання динаміки аероіонного складу повітря у приміщеннях / О. І. Запорожець, В. А. Глива, О. В. Сидоров // Вісник Національного авіаційного університету. – 2011. – Т. 47, № 2. – С. 120–124. doi: <http://dx.doi.org/10.18372/2306-1472.47.24>
6. Строкань, О. В. Програмно-інформаційна система оптимізації мікроклімату у виробничому приміщенні / О. В. Строкань // Вісн. Нац. техн. ун-ту «ХПІ». Серія: Нові рішення в сучасних технологіях : зб. наук. пр. – Харків, 2014. – № 48 (1090). – С. 91–96.
7. Толкунов, І. О. Дослідження шляхів удосконалення аероіонного режиму робочого середовища приміщень спеціального призначення / І. О. Толкунов // Наука і техніка Повітряних Сил Збройних Сил України. – 2015. – № 1 (18). – С. 197–201.
8. Черный, К. А. Методологический подход к применению коронных аэроионизаторов при проведении коррекции аэроионного состава воздуха помещений / К. А. Черный // Инженерно-строительный журнал. – 2012. – № 6 (32). – С. 48–53.
9. Черный, К. А. Современное представление о природе аэроионов и их классификация / К. А. Черный // Безопасность жизнедеятельности. – 2011. – № 7 (127). – С. 15–20.
10. 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.
11. Biliaiev, M. M. Complex of numerical models for computation of air ion concentration in premises / M. M. Biliaiev, S. G. Tsygankova // Наука та прогрес транспорту. – 2016. – № 2 (62). – С. 16–24. doi: <http://dx.doi.org/10.15802/stp2016/67281>
12. Efficiency of ionizers in removing airborne particles in indoor environments / B. Pushpawela, R. Jayaratne, A. Nguy, L. Morawska // Journal of Electrostatics. – 2017. – Vol. 90. – P. 79–84. doi: <http://dx.doi.org/10.1016/j.elstat.2017.10.002>
13. Low-resistance dual-purpose air filter releasing negative ions and effectively capturing PM2.5 / X. Zhao, Y. Li, T. Hua, P. Jiang, X. Yin, J. Yu, B. Ding // ACS Applied Materials & Interfaces. – 2017. – Vol. 9. – Iss. 13. – P. 12054–12063. doi: <http://dx.doi.org/10.1021/acsami.7b00351>



14. Numerical and experimental study on airborne disinfection by negative ions in air duct flow / P. Zhou, Y. Yang, G. Huang, A. C. K. Lai // *Building and Environment*. – 2018. – Vol. 127. – P. 204–210. doi: <http://dx.doi.org/10.1016/j.buildenv.2017.11.006>
15. Sidorov, A. V. The technique of small air ions concentration measurement at the PC operator working place / A. V. Sidorov // *Машиностроение и безопасность жизнедеятельности*. – 2014. – № 1. – С. 36–41.
16. The impact of the air distribution method in ventilated rooms on the aerosol particle dispersion and removal: The experimental approach / A. Jurelionis, L. Gagytė, T. Prasauskas [et al.] // *Energy and Buildings*. – 2015. – Vol. 86. – P. 305–313. doi: <http://dx.doi.org/10.1016/j.enbuild.2014.10.014>

Т. І. РУСАКОВА<sup>1\*</sup>

<sup>1\*</sup>Каф. «Аерогідромеханіка та енергомасоперенос», Дніпровський національний університет імені О. Гончара, вул. Казакова, 18, Дніпро, Україна, 49010, тел. +38 (056) 776 82 05, ел. пошта [rusakovati1977@gmail.com](mailto:rusakovati1977@gmail.com), ORCID 0000-0001-5526-3578

## МЕТОД ПРОГНОЗУ ПАРАМЕТРІВ АЕРОІОННОГО РЕЖИМУ В РОБОЧИХ ЗОНАХ НА ВІДКРИТІЙ МІСЦЕВОСТІ

**Мета.** Наукова робота має на меті розробку нового методу прогнозу аероіонного режиму в робочих зонах на промислових майданчиках із урахуванням іонізуювальних джерел і навколишніх перешкод. **Методика.** Для знаходження концентрації позитивних аероіонів, пилу й негативних аероіонів використано 3D-рівняння масопереносу, що враховує швидкість рекомбінації іонів, які мають різну полярність, і швидкість рекомбінації іонів із частинками пилу. Чисельне розв'язання ґрунтується на інтегруванні рівнянь масопереносу за допомогою кінцево-різницевого методу, що виявляється стійким для будь-якого кроку за часом. Для визначення компонентів вектора швидкості повітряного потоку використано тривимірну модель потенційної течії, де моделювальним рівнянням виступає рівняння Лапласа для потенціалу швидкості. **Результати.** Розроблено математичний метод чисельного розрахунку концентрації позитивних, негативних аероіонів і пилу. Особливістю методу є можливість прогнозу аероіонного режиму з урахуванням практично всіх фізичних факторів, що суттєво впливають на формування концентраційних полів аероіонів у робочих зонах на промислових майданчиках. Метод не прив'язаний до конкретного промислового майданчика, що дозволяє оцінити значення концентрації аероіонів як локально, так і в усій розрахунковій зоні. **Наукова новизна.** Розроблено метод прогнозу аероіонного режиму в робочих зонах, який базується на тривимірному моделюванні розповсюдження негативних, позитивних аероіонів і пилу під дією вітру й дифузії, що дозволяє отримувати результати в кожній точці простору або в конкретному поперечному перерізі. **Практична значимість.** Запропонований метод прогнозу було використано для розв'язання задачі з оцінки аероіонного режиму в робочих зонах на відкритій місцевості промислового майданчика Дніпровського олійно-екстракційного заводу за наявності джерел емісії: позитивних аероіонів під час роботи автотранспорту й дихання працівників; пилу під час руху працівників та автотранспорту; негативних аероіонів іонізатора, встановленого в робочій зоні. Виявлено закономірності зміни концентрації аероіонів різної полярності й пилу на висоті 1,7 м, що відповідає розташуванню органів дихання працівників. Кількісні результати є необхідними для оцінки допустимих умов праці на робочих місцях промислових майданчиків підприємств і під час створення нових робочих місць і реінжинірингу наявних.

*Ключові слова:* іонізація повітря; джерела емісії іонів; чисельний метод; промисловий майданчик; концентрація аероіонів

Т. И. РУСАКОВА<sup>1\*</sup>

<sup>1\*</sup>Каф. «Аэрогидромеханика и энергомассоперенос», Днепропетровский национальный университет имени О. Гончара, ул. Казакова, 18, Днепро, Украина, 49010, тел. +38 (056) 776 82 05, эл. почта [rusakovati1977@gmail.com](mailto:rusakovati1977@gmail.com), ORCID 0000-0001-5526-3578

## МЕТОД ПРОГНОЗА ПАРАМЕТРОВ АЭРОИОННОГО РЕЖИМА В РАБОЧИХ ЗОНАХ НА ОТКРЫТОЙ МЕСТНОСТИ

**Цель.** Научная работа посвящена разработке нового метода прогноза аэроионного режима в рабочих зонах на промышленных площадках с учетом ионизирующих источников и окружающих препятствий. **Методика.** Для нахождения концентрации положительных аэроионов, пыли и отрицательных аэроионов использованы 3D-уравнения массопереноса, учитывающие скорость рекомбинации ионов, имеющих разную полярность, и скорость рекомбинации ионов с частицами пыли. Численное решение основывается на интегрировании уравнений массопереноса с помощью конечно-разностного метода, который оказывается устойчивым для любого шага по времени. Для определения компонент вектора скорости воздушного потока использована трехмерная модель потенциального течения, где моделирующим уравнением выступает уравнение Лапласа для потенциала скорости. **Результаты.** Разработан математический метод численного расчета концентрации положительных, отрицательных аэроионов и пыли. Особенностью метода является возможность прогноза аэроионного режима с учетом практически всех физических факторов, существенно влияющих на формирование концентрационных полей аэроионов в рабочих зонах на промышленных площадках. Метод не привязан к конкретной промышленной площадке, что позволяет оценить значение концентрации аэроионов как локально, так и во всей расчетной области. **Научная новизна.** Разработан метод прогноза аэроионного режима в рабочих зонах, основанный на трехмерном моделировании распространения отрицательных, положительных аэроионов и пыли под действием ветра и диффузии, что позволяет получать результаты в каждой точке пространства или в конкретном поперечном сечении. **Практическая значимость.** Предложенный метод прогноза был использован для решения задачи по оценке аэроионного режима в рабочих зонах на открытой местности промышленной площадки Днепропетровского маслоэкстракционного завода при наличии источников эмиссии: положительных аэроионов во время работы автотранспорта и дыхания работников; пыли во время движения работников и автотранспорта; отрицательных аэроионов ионизатора, установленного в рабочей зоне. Выявлены закономерности изменения концентрации аэроионов различной полярности и пыли на высоте 1,7 м, что соответствует расположению органов дыхания работников. Количественные результаты необходимы при оценке допустимых условий труда на рабочих местах промышленных площадок предприятий и при создании новых рабочих мест и реинжиниринге существующих.

**Ключевые слова:** ионизация воздуха; источники эмиссии ионов; численный метод; промышленная площадка; концентрация аэроионов

### REFERENCES

1. Belikov, A. S., Ragimov, S. Y., & Akinshin, V. D. (2010). Some aspects of the optimization of the study of working conditions on the microclimate in the industrial industry. *Construction, material science, mechanical engineering*, 52, 3-9. (in Russian)
2. Biliaiev, M. M., & Tsygankova, S. G. (2016). Modeling of the aeroionic mode in working zones in the conditions of artificial ionization of air. *Science and Transport Progress*, 1(61), 39-47. doi: <http://doi.org/10.15802/stp2016/60947> (in Russian)
3. Vodianyuk, A. O., & Vidnichuk, T. V. (2013). Metody vyznachennia kontsentratsii aeroioniv ta vmistu pyly u povitri vyrobnychkyh prymishchen. *Mistobuduvannia ta terytorialne planuvannia*, 50, 77-81. (in Ukrainian)
4. Hlyva, V. A. (2011). Doslidzhennia vplyvu mikroklimatychnykh parametrov povitroobminu na aeroionnyi sklad povitria robochykh prymishchen. *Problemy okhorony pratsi v Ukraini*, 20, 58-65. (in Ukrainian)
5. Zaporozhets, O. I., Hlyva, V. A., & Sidorov, O. V. (2011). The Principles of Modeling of Dynamics of Ionic Composition of Indoor Air. *Proceedings of the National Aviation University*, 47(2), 120-124. doi: <http://dx.doi.org/10.18372/2306-1472.47.24> (in Ukrainian)
6. Strokan, O. V. (2014). Prohramno-informatsiina systema optymizatsii mikroklimatu u vyrobnychomu prymishchenni. *Bulletin of the National Technical University «KhPI». Series: New solutions in modern technologies*, 48(1090), 91-96. (in Ukrainian)
7. Tolkunov, I. O. (2015). Study Ways to Improve the Air Ion Mode in the Work Environment Facilities for Special Purposes. *Science and technology of the air force of Ukraine*, 1(18), 197-201. (in Ukrainian)
8. Chernyy, K. A. (2012). Metodologicheskiy podkhod k primeneniyu koronnykh aeroionizatorov pri provedenii korreksii aeroionnogo sostava vozdukha pomeshcheniy. *Magazine of Civil Engineering*, 6(32), 48-53. (in Russian)

## ЕКОЛОГІЯ ТА ПРОМИСЛОВА БЕЗПЕКА

9. Chernyy, K. A. (2011). The up-to-date knowledge on the air ions nature and their classification. *Bezopasnost' Zhiznedeatel'nosti*, 7(127), 15-20. (in Russian)
10. Zgurovskiy, M. Z., Skopetskiy, V. V., Khrushch, V. K., & Belyaev, N. N. (1997). *Chislennoe modelirovanie rasprostraneniya zagryazneniya v okruzhayushchey srede*. Kyiv: Naukova dumka. (in Russian)
11. Biliaiev, M. M., & Tsygankova, S. G. (2016). Complex of numerical models for computation of air ion concentration in premises. *Science and Transport Progress*, 2(62), 16-24. doi: <http://dx.doi.org/10.15802/stp2016/67281> (in English)
12. Pushpawela, B., Jayaratne, R., Nguy, A., & Morawska, L. (2017). Efficiency of ionizers in removing airborne particles in indoor environments. *Journal of Electrostatics*, 90, 79-84. doi: <http://dx.doi.org/10.1016/j.elstat.2017.10.002> (in English)
13. Zhao, X., Li, Y., Hua, T., Jiang, P., Yin, X., Yu, J., & Ding, B. (2017). Low-Resistance Dual-Purpose Air Filter Releasing Negative Ions and Effectively Capturing PM2.5. *ACS Applied Materials & Interfaces*, 9(13), 12054-12063. doi: <http://dx.doi.org/10.1021/acsami.7b00351> (in English)
14. Zhou, P., Yang, Y., Huang, G., & Lai, A. C. K. (2018). Numerical and experimental study on airborne disinfection by negative ions in air duct flow. *Building and Environment*, 127, 204-210. doi: <http://dx.doi.org/10.1016/j.buildenv.2017.11.006> (in English)
15. Sidorov, A. V. (2014). The technique of small air ions concentration measurement at the PC operator working place. *Engineering industry and life safety*, 1, 36-41. (in English)
16. Jurelionis, A., Gagytė, L., Prasauskas, T., Čiužas, D., Krugly, E., Šeduikytė, L., & Martuzevičius, D. (2015). The impact of the air distribution method in ventilated rooms on the aerosol particle dispersion and removal: The experimental approach. *Energy and Buildings*, 86, 305-313. doi: <http://dx.doi.org/10.1016/j.enbuild.2014.10.014> (in English)

Received: Jan. 16, 2019

Accepted: May 15, 2019