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IDENTIFYING REGULARITIES IN THE PROPAGATION OF AIR IONS IN ROOMS WITH ARTIFICIAL AIR IONIZATION

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The object of the study is the dynamics of air ion spread in rooms from the source of artificial air ionization under different starting conditions. There is currently the problem of distribution of air ions in the room with regulatory concentrations in all critical zones. An effective method of ensuring proper air ion concentrations is to model their propagation from ionization sources. Existing approaches to calculating the dynamics of air ions of both polarities have been improved in this study. Unlike known solutions, the impact on their concentration of electrostatic field and the interaction of air ions with suspended particles was taken into account.

A model of air ion propagation in rooms with artificial air ionization and the principles of its numerical modeling was built. The use of Laplace Equation in the aerodynamic model instead of the Navier-Stokes equation for the potential of the flow rate has made it possible to design an "Ion 3D" tool, which reduces the time of implementation of one scenario from several hours to 7 seconds. Modeling of the propagation of air ions of both polarities in the room under different initial conditions was carried out. Two-dimensional and three-dimensional models with their visualization was implemented. The peculiarity of the resulting models is that they make it possible to determine the concentrations of air ions in any section of the room by three coordinates. Given this, the rapid selection of the variants of the source data makes it possible to achieve the normative values of concentrations of air ions in the area of breathing – exceeding 500 cm^{-3} of each polarity. Simulation makes it possible to design a room in which, under the condition of artificial ionization of air, the concentrations of air ions close to the optimal values of 3000–5000 cm^{-3} are provided

Keywords: air quality in the room, artificial ionization, modeling of air ion propagation, air ion concentration

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1. Introduction

Air ion concentrations are an important indicator of air quality. Deionized air adversely affects the health and performance of people [1]. Therefore, this parameter is normalized by the international standard SBM-2015 (the minimum permissible concentration of air ions is 500 cm^{-3} of each polarity) [2]. And the concentration of $3.0–5.0\times10^3$ cm^{-3} is considered to be optimal. But in modern industrial and living premises there are numerous factors of air deionization. These are system units of personal computers, portable computers, split air-cooling systems, etc. In addition, the concentrations of air ions are affected by static charges that accumulate on polymer surfaces due to triboelectric effects [3]. In this case, the external atmospheric air in the populated areas is deionized through the formation of a large amount of fine dust and aerosols. Their source is road transport, enterprises emissions, etc. Therefore, air with low concemtrations of air ions is supplied to the inflow ventilation systems. An additional factor that complicates the formation of a regulatory air ionic regime in the premises is the presence of a source of ionization of air (laser printers, copying devices, etc.). Generation of ions by technological equipment, as well as air deionization by electrostatic charges, is unpredictable in terms of quantity and polarity. Therefore, the devices of artificial ionization of air with controlled performance and the predominant polarity of generation have become widespread. But in this case, there is a problem of air ion propagation in the room with regulatory concentrations in all critical zones. The solution to this problem is possible by modeling the processes of air ion propagation from the source of air ionization. Therefore, research aimed at constructing air ion propagation models in rooms with artificial air ionization is relevant and could make it possible to rationalize the arrangement of furniture, equipment, and workplaces in the premises.

2. Literature review and problem statement

The most appropriate sources of generation of a large number of air ions are ultrasonic ionizers. Paper [4] investigates the generation and propagation of air ions from the ultrasonic emitter due to the balloelectric effect. There is a lack of adverse phenomena – ozone and nitrogen compounds generation. But the area of influence of the ionizer is negligible and the simultaneous distribution of air ions of both polarities occurs. With such air ionization, an imbalance of air ionic composition of air is possible due to the presence in the premises of ionization sources or deionization of air of a certain polarity. Study [3] shows the possibility of controlling the predominant polarity of air ions and their propagation by their directional flow of air with the preservation of normative concentrations. Under this ionization technique, there is a problem of redistribution of air ions due to the presence of obstacles to the spread of air flow, the rationalization of the location of ionization sources, taking into account the location of the openings of inflow and exhaust ventilation, etc. This is possible by modeling the propagation of air ions under different conditions. The principles of modeling of air ion propagation are laid in classical work [5]. In the mathematical apparatus of the cited work, the interaction of air ions with suspended particles is outlined, but real small-sized aerosols carry an electric charge that is not taken into account [6]. In part, this drawback has been eliminated in paper [7]. But the modeling error is large and gives significant differences with the experiment. The model of air ion propagation, in this case, is two-dimensional. The three-dimensional model was implemented in [8]. But it applies mainly to the mobility of air ions. At the same time, there are more modern approaches to modeling transfer processes [9]. In particular, taking into account the temperature factor [10], which can be added to the mobility of air ions.

Therefore, it is advisable to improve mathematical functions that describe the dynamics of air ions, to determine the required boundary conditions, and to carry out three-dimensional modeling of the propagation of air ions in the premises, taking into account all critical factors. Taking into account the impact of electrostatic fields and the interaction of air ions with suspended particles will increase the adequacy of the model. The use of more acceptable original equations will increase the speed of calculation under different initial conditions.

3. The aim and objectives of the study

The purpose of this study is to determine the patterns of distribution of air ions in rooms from the source of artificial air ionization of air under different initial conditions. This will make it possible to design a room in which in places of permanent stay of people, with the artificial air ionization provided, air ion concentrations close to the optimal ones are ensured.

The following tasks are defined to achieve the purpose of the study:

– to improve the mathematical model that describes the dynamics of air ions under different boundary conditions and to build a numerical model for the implementation of three-dimensional modeling of air ion propagation in the premises;

– to model the propagation of air ions indoors with different locations of the source of air ionization, openings of inflow and exhaust ventilation, and obstacles to air flow in the room.

4. The study materials and methods

The object of our study is the dynamics of air ion propagation in the air under different starting conditions.

The research hypothesis assumes the ability to use ratios that describe the phenomena of transfer, to model air ion propagation in the air of the premises.

It is very important to have tools for predicting the concentration of air ions of the desired polarity both inside the room and in certain parts in order to design the arrangement of equipment and workplaces. Below we consider the construction of a mathematical model that makes it possible to implement such a forecast. The room in which there is an air ionizer (source of negative ions) is considered. The room contains a source of positive air ions, which is a conditional technical tool. The room is equipped with inflow and exhaust ventilation. There are two workplaces in the room, which are obstacles to the air flow.

5. Results of studying the propagation of air ions in the premises

5. 1. Constructing a numerical model of indoor air ion propagation

The source of the emission of positive ions is a technological device. The dust source is the floor. The task of forecasting the concentration of positive and negative air ions, as well as dust, in the room with the set parameters of air exchange is set. The room has sizes L_x, L_y, L_z (Fig. 1). The room has obstacles (furniture, equipment, etc.), which affect the movement of air flow and the formation of concentration fields of air ions, dust in the room. The air ionizer is characterized by a given intensity of emission of specific polarity ions. The position of the ionizer in the room is determined by its coordinates.

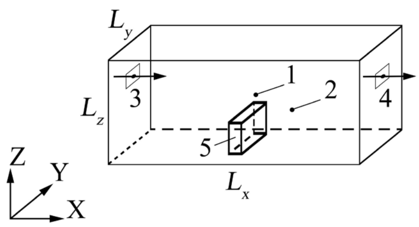


Fig. 1. Scheme of the calculated area: 1 – ionizer; 2 – source of positive ions; 3 –ventilation opening (inflow); 4 – exhaust ventilation opening; 5 – furniture

The formation of an air ion concentration field is influenced by the set of physical factors: air flow, diffusion, the presence of obstacles in the room, air exchange. In addition, since the ions have a charge, they generate an electric field E. When scattering ions, the interaction of ions of different polarities and their interaction with dust particles occur. To account for these processes, three-dimensional transfer equations are used when modeling the scattering of air ions in the room, which is a form of conservation law for positive ions, negative ions, and dust. The modeling equation system looks like:

– to describe the process of scattering positive ions:

$$\frac{\partial C_p}{\partial t}+\frac{\partial(u+bE_x)C_p}{\partial x}+\frac{\partial(v+bE_y)C_p}{\partial y}+$$
$$+\frac{\partial(w+bE_z)C_p}{\partial z}=\frac{\partial}{\partial x}\left(\mu_x\frac{\partial C_p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_y\frac{\partial C_p}{\partial y}\right)+$$
$$+\frac{\partial}{\partial y}\left(\mu_z\frac{\partial C_p}{\partial z}\right)-\lambda C_p C_n-$$
$$-\beta C_p C_d+\sum_{i=1}^{n}Q_{pi}(t)\delta(x-x_i)\delta(y-y_i)\delta(z-z_i); \qquad (1)$$

– to describe negative ion transfer:

$$\frac{\partial C_n}{\partial t}+\frac{\partial(u+bE_x)C_n}{\partial x}+$$
$$+\frac{\partial(v+bE_y)C_n}{\partial y}+\frac{\partial(w+bE_z)C_n}{\partial z}=$$
$$=\frac{\partial}{\partial x}\left(\mu_x\frac{\partial C_n}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_y\frac{\partial C_n}{\partial y}\right)+$$
$$+\frac{\partial}{\partial y}\left(\mu_z\frac{\partial C_n}{\partial z}\right)-\lambda C_p C_n-$$
$$-\beta C_p C_d+\sum_{i=1}^{n}Q_{pi}(t)\delta(x-x_i)\delta(y-y_i)\delta(z-z_i); \qquad (2)$$

– to describe dust transfer:

$$\frac{\partial C_d}{\partial t}+\frac{\partial(uC_d)}{\partial x}+\frac{\partial(vC_d)}{\partial y}+\frac{\partial(w-w_g)C_d}{\partial z}=$$
$$=\frac{\partial}{\partial x}\left(\mu_x\frac{\partial C_d}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_y\frac{\partial C_d}{\partial y}\right)+\frac{\partial}{\partial y}\left(\mu_z\frac{\partial C_d}{\partial z}\right)+$$
$$+\sum_{i=1}^{n}Q_{pi}(t)\delta(x-x_i)\delta(y-y_i)\delta(z-z_i). \qquad (3)$$

Equation (1) describes the scattering of positive ions in the room, equation (2) – negative ions, equation (3) – scattering of dust particles. The following designations are adopted in these equations:

C_p (x, y, t), C_n (x, y, t) – concentration of positive, negative air ions, inos/m^3;

C_d (x, y, t) – dust particle concentration, particles/m^3;

u, v, w – components of the air flow velocity vector, m/s;

μ_x, μ_y, μ_z, – diffusion coefficients, m^2/s;

t – time, s;

w_g – rate of gravitational deposition of dust particles;

α – rate of recombination of ions having different polarities, m^3/(s·ions);

β – rate of recombination of ions with dust particles, m^3/(s·ions);

$Q_{p_i}(t)$, $Q_{n_i}(t)$ – emission intensity of positive, negative ions, ions/(s·m^3);

$Q_{d_i}(t)$ – dust emission intensity, particles/(s·m^3);

δ (x, y) – Dirac delta function;

b – ion mobility coefficient, m^2/(V·s);

E – electric field strength, V/m.

When modeling the scattering of positive ions, in equation (1), their "drift" is taken into account due to the formation of an electric field of intensity E.

Dust particles have different origin, shape, size that affects the speed of their gravitational deposition w_g. In the mathematical model of dust particles propagation, this speed is set based on the results of measurements or calculation. In express calculation, you can use the Stokes formula for determining this parameter or take it equal to zero (fine-dispersed dust).

The intensity and position of the sources of positive, negative ions and dust are modeled using Dirac delta function and by setting point sources of known intensity:

$$Q_{p_i}(t), Q_{n_i}(t), Q_{d_i}(t).$$

Their number can be arbitrary.

For equations (1) to (3), the following boundary conditions are imposed:

1. At the border of the entry of the air flow to the room, the concentration of negative and positive ions is set by zero C_p=0, C_n=0 (one can also specify a different concentration value, for example, background).

2. At the boundary of the output of the air flow from the room for the value of the concentration of dust, ions of different polarities, the following "soft" boundary condition is set:

$$\frac{\partial C_d}{\partial x}=0,\quad \frac{\partial C_p}{\partial x}=0,\quad \frac{\partial C_n}{\partial x}=0.$$

3. On hard surfaces (floor, walls, equipment, etc.), a boundary condition of the following form is set:

$$\frac{\partial C}{\partial n}=0,$$

where n is a unit vector of external normal to the solid surface, C is the concentration of ions or dust.

At the location of the air ionizer, the intensity of its emission is set.

At the initial point in time, it is believed that the concentration of negative, positive ions and dust in the air environment of the room is zero. If necessary, one can set any other value of the concentration of negative, positive ions and dust, for example, determined by experimental measurements or some background value.

When modeling the air ion propagation process, the impact of the electric field on this process should be taken into account. Because the air ions have a charge, they generate an electric field of intensity E. The following equation is used to simulate the electric field:

$$\frac{\partial E_x}{\partial x}+\frac{\partial E_y}{\partial y}+\frac{\partial E_z}{\partial z}=\frac{q_e}{\varepsilon_0}, \tag{4}$$

where ε_0 is dielectric permeability; q_e is a volume charge density.

From equation (4), one can go to scalar potential by considering the following dependence:

$$E_x=-\frac{\partial\phi}{\partial x},\quad E_y=-\frac{\partial\phi}{\partial y},\quad E_z=-\frac{\partial\varphi}{\partial z}. \tag{5}$$

Then we get the Poisson equation:

$$\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}+\frac{\partial^2\varphi}{\partial z^2}=-\frac{q_e}{\varepsilon_0}, \tag{6}$$

where $q_e=-eC_p\ (x,y,t)$, $C_p(x,y,t)$ is the concentration of positive ions; φ is scalar potential; e is an elementary charge. According to the results of this equation, an electric field modeling is erformed, which is formed by positive ions.

The boundary condition for the modeling equation (6) is the condition of electrical insulation of surfaces in the room:

$$\frac{\partial\phi}{\partial n_N}=0,$$

where n_N is a unit vector of external normal to the surface.

Equation (6) is used to calculate the speed of "drift" of positive ions in the room, equation (1).

5. 1. 1. Aerodynamic model

The movement of the air environment in the room leads to the formation of an uneven field of air velocity, which complicates the theoretical solution of the problem of determining the field of concentration of ions. Inside the room, there are various elements of furniture, equipment that interfere with the movement of air flow. In addition, the location of the inflow and exhaust openings also determines the aerodynamics of air flows indoors. Therefore, to solve the problem of forecasting of ion concentration, dust in the room, taking into account the transfer equations (1) to (3) and (6), it is necessary to calculate the components of the velocity vector of air flow in this room, that is, to solve the task of aerodynamics. A model of potential flow is used to solve this aerodynamic problem. To determine the values of the components of the velocity vector in the room, it is necessary to integrate the Laplace equation for the potential of speed P:

$$\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}+\frac{\partial^2 P}{\partial z^2}=0. \tag{7}$$

The components of the air velocity vector are related to the velocity potential as follows:

$$u=\frac{\partial P}{\partial x};\ v=\frac{\partial P}{\partial y};\ w=\frac{\partial P}{\partial z}, \tag{8}$$

where P is the velocity potential.

The boundary conditions of equation (7):

1. $\frac{\partial P}{\partial n}=0$ at solid borders (floor, walls, equipment); n is a unit vector of external normal to the solid surface.

2. $\frac{\partial P}{\partial n}=V_n$ at the border where the air flow enters the room (V_n is a known flow rate).

3. P=const on the boundary of the "exit" of the air flow from the room.

5. 1. 2. Numerical simulation

For numerical integration of modeling equations (1) to (3), (6), (7), difference methods are typically used. The calculation is performed on a rectangular grid. The components of the air flow velocity vector are determined on the faces of difference cells; other parameters (concentration of different polarity ions, dust concentration, speed potential, and scalar potential value in equation (6)) are determined in the centers of difference cells.

To integrate the Laplace equation (7), we use the method of total approximation. Initially, Laplace equation (7) is brought to the equation of an "evolutionary" form:

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

where t – fictitious time.

Next, the method of total approximation is used, which is written as a difference splitting scheme:

$$\frac{P_{i,j,k}^{n+\frac{1}{2}}-P_{i,j,k}^{n}}{\Delta t}=\left[\frac{-P_{i,j,k}^{n+\frac{1}{2}}+P_{i-1,j,k}^{n+\frac{1}{2}}}{\Delta x^2}\right]+$$
$$+\left[\frac{-P_{i,j,k}^{n+\frac{1}{2}}+P_{i,j-1,k}^{n+\frac{1}{2}}}{\Delta y^2}\right]+\left[\frac{-P_{i,j,k}^{n+\frac{1}{2}}+P_{i,j,k-1}^{n+\frac{1}{2}}}{\Delta z^2}\right], \tag{10}$$

$$\frac{P_{i,j,k}^{n+1}-P_{i,j,k}^{n+\frac{1}{2}}}{\Delta t}=\left[\frac{P_{i+1,j,k}^{n+1}-P_{i,j,k}^{n+1}}{\Delta x^2}\right]+$$
$$+\left[\frac{P_{i,j+1,k}^{n+1}-P_{i,j,k}^{n+1}}{\Delta y^2}\right]+\left[\frac{P_{i,j,k+1}^{n+1}-P_{i,j,k}^{n+1}}{\Delta z^2}\right]. \tag{11}$$

The calculation for dependences (10), (11) ends when the following condition is met:

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

where ε is a small number (one can take ε=0.001): n is an iteration number.

After determining the velocity potential in the room, components of the air flow velocity vector are calculated by the following formulas (approximation of dependences (8)):

$$u_{i,j,k}=\frac{P_{i,j,k}-P_{i-1,j,k}}{\Delta x},$$

$$v_{i,j,k}=\frac{P_{i,j,k}-P_{i,j-1,k}}{\Delta y},$$

$$w_{i,j,k}=\frac{P_{i,j,k}-P_{i,j,k-1}}{\Delta z}.$$

Libman method (6) is used for numerical integration. Then, according to this method, the approximation of equation (6) looks like:

$$\frac{\varphi_{i+1,j,k}-2\varphi_{i,j,k}+\varphi_{i-1,j,k}}{\Delta x^2}+\frac{\varphi_{i,j+1,k}-2\varphi_{i,j,k}+\varphi_{i,j-1,k}}{\Delta y^2}+$$
$$+\frac{\varphi_{i,j,k+1}-2\varphi_{i,j,k}+\varphi_{i,j,k-1}}{\Delta z^2}=-\frac{q_e(i,j,k)}{\varepsilon_0}. \qquad (12)$$

The unknown value of the scalar potential $\varphi_{i\,j,k}$ is determined by (12) by a clear formula in the center of difference cells.

Equations (1) to (3) are the same type of transfer equations, and in general they can be written as follows:

$$\frac{\partial S}{\partial t}+\frac{\partial uS}{\partial x}+\frac{\partial vS}{\partial y}=$$
$$=\frac{\partial}{\partial x}\left(\mu_x\frac{\partial S}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_y\frac{\partial S}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_z\frac{\partial S}{\partial z}\right)+$$
$$+\sum_{i=1}^{n}Q_{Si}(t)\delta(x-x_i)\delta(y-y_i)\delta(z-z_i), \qquad (13)$$

where S expresses the concentration of positive, negative ions and dust in a generalized form.

Next is the splitting of equation (13):

$$\frac{\partial S}{\partial t}+\frac{\partial uS}{\partial x}=\frac{\partial}{\partial x}\left(\mu_x\frac{\partial S}{\partial x}\right), \qquad (14)$$

$$\frac{\partial S}{\partial t}+\frac{\partial vS}{\partial y}=\frac{\partial}{\partial y}\left(\mu_y\frac{\partial S}{\partial y}\right), \qquad (15)$$

$$\frac{\partial S}{\partial t}+\frac{\partial wS}{\partial z}=\frac{\partial}{\partial z}\left(\mu_z\frac{\partial S}{\partial z}\right), \qquad (16)$$

$$\frac{\partial S}{\partial t}=\sum_{i=1}^{n}Q_{Si}(t)\delta(x-x_i)\delta(y-y_i)\delta(z-z_i). \qquad (17)$$

For numerical integration of equations (14) to (16), alternating-triangular difference scheme of splitting is used, and for the numerical integration of equation (17) – the Euler method.

Based on the numerical model built, the computer code "Ion 3D" has been developed.

5. 2. Simulation of the propagation of air ions in premises under different initial conditions

Modeling the scattering impurities in the air environment of the premises is especially complex task. Given that it is necessary to predict the concentration of impurity (CO_2, dust, ions, etc.) in different parts of the room, the most effective theoretical method of solving the problem is the use of two-dimensional or three-dimensional mathematical models. Numerical integration methods are used for practical use of multidimensional models. However, it should be emphasized that not all numerical methods for solving multidimensional problems of a solid environment can be used to solve the problems of this class. This is due to the formation of air flows that have large curvature currents (due to the flow of various obstacles in the room). In this case, a number of numerical methods compromise stability, which creates an additional problem during research. This phenomenon can be found when conducting serial computing experiments, when, for example, while calculating, the amount of air exchange in the room changes greatly. The numerical solution method at a certain stage of calculations loses its stability, and it is not possible to solve the problem. Therefore, the first step in solving the problem of predicting the quality of the air environment in the premises is the choice of model dimensionality (two-dimensional or three-dimensional) and the choice of the method of numerical integration of modeling equations. It should provide a stable "work" of the built model in a wide range of parameters (air exchange, position of inflow and exhaust ventilation openings, power of emission sources, etc.).

At the second stage of solving the problem, schematization of the calculation area is carried out: in the room, objects are specified (furniture, machines, various equipment, etc.), which are significant and have the main influence on the formation of air flows. In addition, there are areas where there is an inflow or exit of air from the room. In this case, the position of the inflow openings can be varied, which should be taken into account by the mathematical model that is being developed. Below are the results of the computational experiment, taking into account the numerical model built. There is a premises where there are two workplaces (Fig. 2).

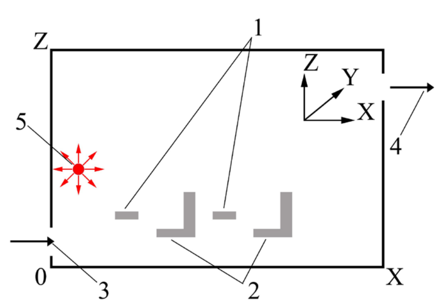


Fig. 2. Scheme of the calculated area: 1 – table; 2 – chair; 3 – inlet of the ventilation system; 4 – outlet of the ventilation system; 5 – ionizer

Room dimensions: 5×5×3.75 m; air exchange, 50 m^3/h; in a cross-section of y=2.5 m there are two desktops and chairs (Fig. 2). Two ionizer arrangement scenarios are considered:

1. The ionizer is at a height of 1.8 m (near the left wall, Fig. 2).

2. The ionizer is at a height of 3 m.

The intensity of the emission of negative ions is 32×10^{12} ions/s. It is believed that the release of positive ions is enabled by a technical tool that is in the workplace. The intensity of the emission of positive ions by each device is 150×104 ions/s. The emission of fine dust occurs under chairs, where the feet of workers are located. That is, the movement of legs causes the emission of dust at the floor level. The intensity of dust emission under each chair is 2 mg/s.

Below, Fig. 3, 4 show a forecast field of concentration of negative, positive ions and dust indoors for the analyzed scenarios. The results of the computational experiment are given in two forms: in the form of a matrix of distribution of the dimensionless value of the concentration of ions (or dust) and in the form of isolines. It should be noted that on the matrix each number shows the percentage ratio of the concentration of impurity at a given point to the maximum concentration of admixture $C_{\max}$ in the study area. For example: in the Fig. the dimensionless concentration value is 46, therefore, at this point it is 46 % of the maximum concentration. On the basis of each matrix of distribution of dimensionless concentration, isolines were constructed in the calculation area. It should be noted that the matrix of distribution of a dimensionless concentration makes it possible to quickly determine (from the quantitative side) a zone with increased or reduced concentration of a particular impurity in the room. Fig. 3, 4, which show the isoline of a dimensionless concentration, make it possible to identify patterns of formation of areas of impurity distribution in the calculation region and the influence of various obstacles on the geometric shape of these areas. On all the figures, the red "point" shows the position of the source of impurity (negative, positive ions, dust).

Fig. 3, 4 show the negative ion concentration field in the room for both scenarios.

Analysis of forecast data shown in Fig. 3 reveals that for the first employee in the area of his head, the value of the dimensionless concentration of negative ions is 46, and for the second employee this value is 34. The maximum value of the concentration of negative ions is 9747 ion/cm^3. Thus, the forecast value of the concentration of negative ions in the breathing area of the first worker is:

C=0.46×9747 ion/cm^3=4483 ion/cm^3.

For the second employee:

C=0.34×9747 ion/cm^3=3313 ion/cm^3.

These values fall into the range of the optimal value of the concentration of negative ions of 3000–5000 ions/cm^3.

Similarly, for the second scenario (Fig. 4), given that the maximum value of the concentration of negative ions in this section is 12770 ion/cm^3, the forecast value of the concentration of negative ions in the breathing area of the first worker is:

C=0.36×12770 ion/cm^3=4597 ion/cm^3.

For the second employee:

C=0.27×12770 ion/cm^3=3447 ion/cm^3.

These values also fall into the range of optimal value of the concentration of negative ions of 3000–5000 ions/cm^3.

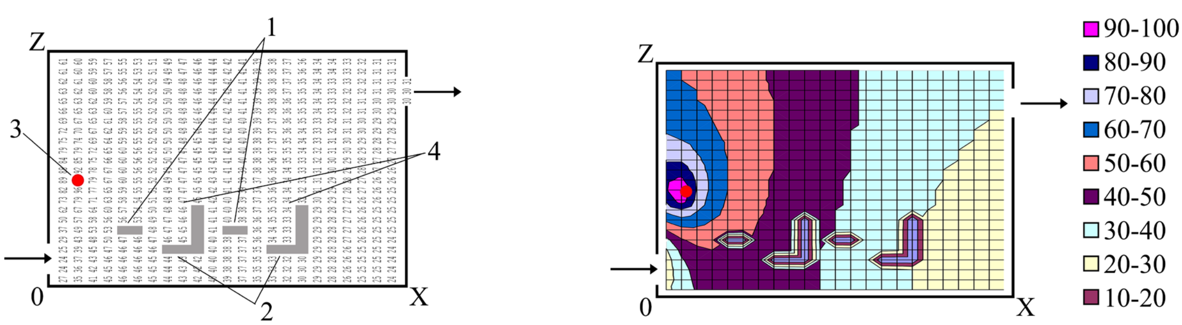
Next, Fig. 5, 6 show the distribution of the concentration of positive ions and dust in the room. This data is given for the first scenario of the ionizer in the room.

Fig. 5 shows a field of concentration of positive ions in the room for the first scenario of the ionizer.

Analysis of forecast data shown in Fig. 5, reveals that for the first employee in the area of his head, the value of the dimensionless concentration of positive ions is 90, and for the second employee this value is 84. The maximum value of the concentration of positive ions is 439 ion/cm^3. Thus, the forecast value of the concentration of positive ions in the breathing area of the first worker is 395 ion/cm^3. For the second employee – 368 ion/cm^3. These values are within the minimum required level of 400 ion/cm^3.

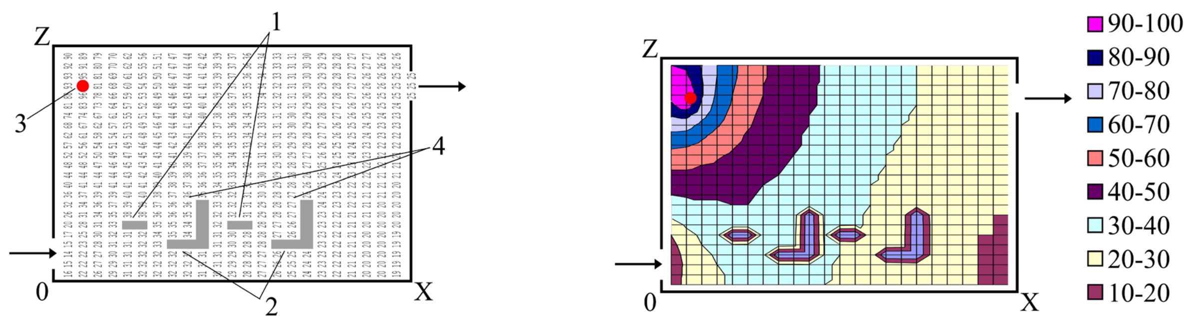
Fig. 6 shows a field of dust concentration in the room for the first scenario of the ionizer in the room.

Analysis of forecast data shown in Fig. 6 reveals that for the first employee in the area of his head, the value of the dimensionless concentration of dust is 44, and for the second employee this value is 45. The maximum value of the concentration of dust is 1.21 mg/m^3. Thus, the forecast value of the concentration of dust in the breathing area of the first employee is 0.53 mg/m^3. For the second employee – 0.54 mg/m^3. These values exceed the average daily MPC for dust – 0.02 mg/m^3. The time of the calculation of one scenario is 7 s.



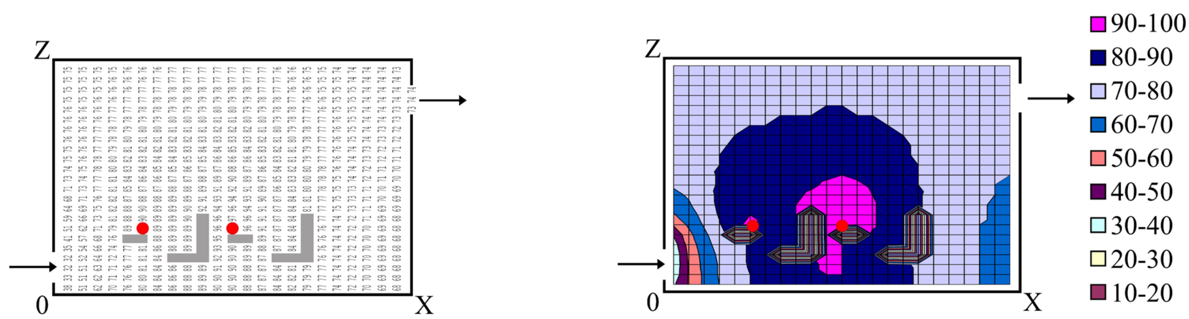
a *b*

Fig. 3. The results of modeling the propagation of negative ions in the room; cross-section y=2 m (first scenario: the ionizer is located at a height Z=1.8 m): *a* — a matrix of distribution of dimensionless concentration of negative ions in the room; 1 — table; 2 — chair; 3 — ionizer; 4 — position of the head of the employee; *b* — isolines of dimensionless concentration of negative ions in the room



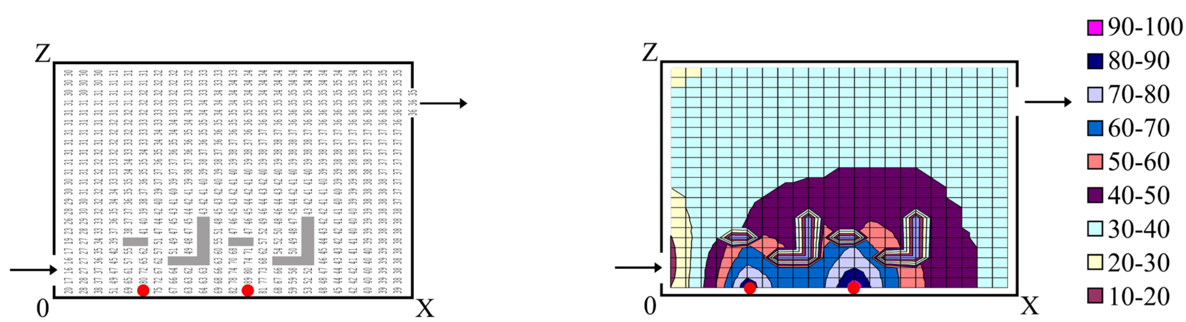
a *b*

Fig. 4. The results of modeling the propagation of negative ions in the room; cross-section y=2 m (second scenario: the ionizer is located at a height Z=3 m):
a – a matrix of distribution of dimensionless concentration of negative ions in the room;
1 – table; 2 – chair; 3 – ionizer; 4 – position of the head of the employee;
b – isolines of dimensionless concentration of negative ions in the room



a *b*

Fig. 5. The results of modeling the propagation of positive ions in the room, cross-section y=2 m;
a – matrix of distribution of the dimensionless concentration of positive ions in the room, C_{max}=439 ion/cm^3;
b – isolines of dimensionless concentration of positive ions in the room



a *b*

Fig. 6. The results of simulation of dust distribution in the room; cross-section y=2 m:
a – a matrix of distribution of a dimensionless concentration of dust in the room, C_{max}=1.21 mg/m^3;
b – isolines of dimensionless dust concentration in the room

6. Discussion of results of modeling the propagation of air ions in rooms with artificial ionization of air

The determination of the regularities of the propagation of air ion makes it possible to regulate the productivity of the ionizer to obtain the desired concentrations of air ions in any area of the room (Fig. 3 for negative air ions, Fig. 5 for positive air ions). It was found that the increase in the location of the ionizer from a height of 1.8 m (Fig. 3) to a height of 3.0 m (Fig. 4) leads to an increase in the concentration of air ion in the working area by only 2 %–4 %. That is, the height of the ionizer does not significantly affect the concentrations of air ions in the workplace. Also taking into account the interaction of air ions with suspended particles (3) makes it possible to determine the spatial distribution of dust particles (Fig. 4).

It is possible to provide optimal concentrations of air ions in the areas of permanent stay of people

($3–5\times10^3$ cm^{-3}) and the minimum permissible (more than 500 cm^{-3}) in other places.

The advantage of the method of scattering of air ions from the source of ionization by air flow is the ability to neutralize surface electrostatic charges by ions of opposite signs. Considering the presence of electrostatic field (1), (2) makes it possible to neutralize surface electrostatic charges. This can be provided with additional generation of air ions of the proper sign.

It is known that electrostatic charges are formed on polymer surfaces due to the tribolectric effect [3]. These are the surfaces of furniture, equipment, flooring, etc. The accumulation of such charges is regulated by the international standard [11]. The electrostatic potential should not exceed 0.5 kV. But under real operating conditions of computer equipment, it reaches from several to several tens of kilovolts. Neutralization of surface electrostatic charges reduces the concentration of air ions in the air, and unpredictable. This determines a certain limitations of this study.

The main disadvantage of the study is the lack of accounting for air viscosity in its directional movement.

It is advisable to determine the need for increased generation of air ions of the required polarity for simultaneous provision of normative concentrations of air ions in the air and neutralization of surface charges. For this purpose, on the basis of full-time measurements of electrostatic charges and their predominant signs, it is necessary to determine the boundary conditions and build dynamic models of electrostatic charges distribution on surfaces. This could help adjust the generation of air ions of both polarities by sources of artificial ionization of air with the values of the physical factors of the environment in the process of designing buildings and premises and the placement of equipment in them.

7. Conclusions

1. The mathematical model of air ion scattering in the room has been improved. The impact of the electrostatic field and the interaction of air ions with suspended particles was taken into account, which increases the compliance of calculations with actual conditions. The model of air ion propagation in rooms with artificial air ionization and the principles of its numerical modeling were built. The use of Laplace equation in the aerodynamic model instead of the Navier-Stokes equation for the potential of the flow rate has made it possible to design an "Ion 3D" tool, which reduces the time of implementation of one scenario from several hours to 7 seconds.

2. A three–dimensional model of air ion propagation in the room was developed, provided there are different air ionization sources of both polarities, the location of the openings of the opening and exhaust ventilation, the speed of the directional air flow, the arrangement of flow obstacles (furniture, equipment, etc.). According to the results of numerical modeling, it was established that in the area of respiration of humans the generation of ions and regulation of directional air flow can ensure the concentration of ions of both signs close to the optimal – 3000–5000 cm^{-3}. In the case of excessive generation of air ions of one polarity (9774–12770 cm^{-3}), there is a decrease in the concentration of positive air ions (to 395–368 cm^{-3}). Reducing the generation of air ions of one polarity leads to an increase in the concentration of the opposite polarity, which is a way of regulating their concentration. The designed tool makes it possible to quickly select the scenarios to get the result. Visualization of modeling results allows us in the design process of premises to place workplaces in the intended areas with regulatory concentrations of air ions of both polarities. This approach makes it possible to provide in the places of permanent stay of people the concentration of air ions close to optimal ($3–5\times10^3$ cm^{-3}) and the minimum permissible one (more than 500 cm^{-3}) in other places.

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.

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