UDC 628.5/8:614.7
DOI: 10.15587/1729-4061.2024.300909

STUDY OF AIR DEIONIZATION FACTORS

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The object of research is the dynamics in the concentration of air ions and suspended particles in atmospheric air and in supply-exhaust ventilation systems. An urgent task is to determine the factors and obtain quantitative data on the deionization of the atmospheric air that enters the environment where people live. Quantitative data on changes in the concentration of air ions depending on the time of day, temperature, and relative air humidity have been established. It was shown that even in the absence of significant man-made influence on the concentration of suspended particles, this indicator is at least 7000 cm^{-3}. In the presence of wind, this indicator reaches 30000 cm^{-3} and higher. Measurement of the spectrum of suspended particles in the range of 0.3–6.0 μm showed that the predominant fraction is particles with sizes of about 3 μm. Studies have been conducted on changes in the concentrations of air ions in supply-exhaust ventilation systems. It was established that in the air duct made of galvanized iron, which has a length of 16 m, the concentration of negative air ions is reduced by 67 %, and positive by 78 %. Laboratory studies of air deionization in air ducts made of different materials were carried out. There is significant air deionization in metal and cardboard ducts while it is absent in wooden ducts. This indicates the electrical nature of deionization. A calculation method for forecasting the aero-ionic mode of premises, taking into account the factors of air deionization, is proposed. For rooms with supply-exhaust ventilation, a calculation apparatus is proposed taking into account the air exchange rate (the number of complete air changes per unit of time). The results make it possible to choose the required performance of artificial air ionization devices for normalizing the aero-ionic regimes in the premises

Keywords: air ion concentration, aero-ionic mode, air deionization, concentration of suspended particles, forced ventilation

Received date 16.01.2024
Accepted date 25.03.2024
Published date 30.04.2024

How to Cite: *Tykhenko, O., Glyva, V., Levchenko, L., Burdeina, N., Biruk, Y., Zozulya, S., Krasnianskyi, G., Nikolaiev, K., Aznaurian, I., Zozulya, L. (2024). Study of air deionization factors. Eastern-European Journal of Enterprise Technologies, 2 (10 (128)), 26–33. https://doi.org/10.15587/1729-4061.2024.300909*

1. Introduction

Concentrations of air ions of both polarities are one of the indicators of air quality. Hygienic studies show that air deionization is harmful to the human body [1], therefore the minimum permissible concentrations of air ions are regulated by international and national standards [2]. The source of air ions is natural radioactivity, solar radiation, and partly atmospheric electricity. In the air, there is a continuous process of ion formation and disappearance of air ions as a result of their recombination. Usually, the concentrations of air ions are in a state of dynamic equilibrium. The fluctuation in this indicator (predominant concentration of air ions of one polarity) depends on the time of day and season. In the absence of outflows of air near the surface of the earth, positive air ions predominate (the charge of the Earth is negative). In the presence of such currents and wind, air ions of both signs are mixed. The concentration of air ions is affected by the presence of drops of moisture and snow in the air. But changes in air ion concentrations (air deionization) can occur as a result of man-made factors. In the atmospheric air of populated areas, these are dust and aerosols that are formed due to the operation of industrial enterprises, exhaust engines of motor vehicles, etc. Such air enters the premises and can be deionized to values lower than the normative ones. In addition, industrial and residential premises contain deionization factors that also negatively affect air quality. However, there are no data on the dynamics of concentrations of air ions and suspended particles in atmospheric air and air supplied to the room through air ducts. These data are necessary for calculating the concentration of air ions in indoor air. Currently, artificial air ionization devices are widely used, but a prerequisite for their use is the determination of the required performance depending on the state of the air entering the room. Therefore, determining the factors and obtaining quantitative data on the deionization of atmospheric air entering the environment of people are relevant tasks.

2. Literature review and problem statement

Most research on the state of atmospheric air concerns its pollution by dust and aerosols. In [3], the effect of particles with sizes of 0.1–100 μm on atmospheric chemistry and biogeochemistry was investigated. Their interaction with atmospheric moisture and influence on the distribution of clouds and precipitation are shown. However, no information was provided on the effect of particles on the concentration of air ions. In study [4] it was shown that an increase in the concentration of dust in the atmosphere leads to a decrease in temperature and counteracts the greenhouse effect. The paper analyzes the emissions of enterprises but does not show how this dust interacts with aerosols and air ions. A significant body of research considers the physics of the atmosphere. The interaction of atmospheric air ions with suspended particles was studied in [5], and with secondary organic aerosols in [6]. In all these studies, air ions are considered as factors affecting the dynamics of suspended particles. Deposition of aero-ions on suspended particles leads to air deionization, but there are no quantitative data on the fluctuations of aero-ion concentrations. There are practically no studies on temporal changes in concentrations of air ions in atmospheric air. Available works relate to the modeling of the spread of air ions in the air [7]. But modeling without reliable initial data (concentrations of air ions under different conditions) cannot be used in practical work. In fact, there are no data on the concentrations of air ions in atmospheric air, which enters the room naturally or through ventilation systems. More attention is paid to ionization and deionization of air in buildings and premises. In work [8] it is shown that there are factors of air deionization (system units of personal computers) and ionization (laser printers, photocopiers) in the premises for the operation of computer equipment. But these data refer to the air quality that is already present in the room. It has not been investigated whether the concentrations of air ions change during the entry of air into the room. Paper [9] shows that air cooling systems (split systems) and electrostatic charges accumulating on polymer surfaces due to the triboelectric effect are factors of air deionization in rooms of any purpose. The advantage of the work is taking into account the aero-ionic composition of atmospheric air, which enters the room due to infiltration and ventilation. At the same time, the actual state of the air and its redistribution in the room are considered. Air cooling systems distribute the air in the room with its partial deionization. Paper [10] substantiates the use of LED sources of ultraviolet radiation for indoor air ionization. However, there are no criteria for the need to use sources of artificial air ionization. Without data on the dynamics of the aero-ionic composition of the air, the automatic application of artificial ionization may be inappropriate. Study [11] reports the results of modeling the spread of air ions in rooms taking into account all critical factors affecting the concentration of air ions: sources of air ionization and deionization, directional air movement, location of forced ventilation holes, etc. However, both sources of air ionization and sources of air deionization are taken abstractly in the work. The output quantitative data does not correspond to any real conditions. The availability of experimental data could provide an opportunity to rationalize the placement of workplaces with the provision of regulatory concentrations of air ions of both signs.

Currently, the dynamics of the aero-ionic composition of atmospheric air, taking into account the factors of deionization, which are suspended particles, as well as changes in the concentrations of air ions depending on the time of day, have not been studied. Possible changes in the aero-ionic composition of the air entering the premises through the channels of ventilation systems are not taken into account. Obtaining such data will make it possible to determine the need for artificial air ionization in rooms of various purposes and the required performance of air ionization devices. The results of research on determining the factors of air deionization are necessary for choosing the required performance of artificial air ionization devices and normalizing aero-ionic regimes in rooms.

3. The aim and objectives of the study

The purpose of our work is to determine the factors of deionization of atmospheric air and air in public and industrial buildings. These results are necessary for choosing the desired performance of artificial air ionization devices and normalizing aero-ionic modes in rooms.

To achieve the goal, the following research tasks are defined:

– to conduct experimental studies into the dynamics of the aero-ionic composition of atmospheric air;

– to conduct experimental studies on changes in the aero-ionic composition of air in forced ventilation channels of premises;

– to suggest a calculated forecast of the aero-ionic composition of the air, taking into account the factors of deionization.

4. The study materials and methods

The object of our study is the dynamics of the concentration of air ions of both polarities and suspended particles in atmospheric air and in supply-exhaust ventilation systems.

The main hypothesis of the research assumes that the concentrations of air ions of both polarities in atmospheric air change depending on the time of day. The main cause of air deionization in standard ventilation systems is electrical interactions with the walls of air ducts.

The study of the dynamics of concentrations of air ions and concentrations of suspended particles was carried out by the method of field measurements.

Air ion concentrations of both polarities were measured with a small-sized MAS-01 air ion counter according to the operating instructions. The measurement results were processed according to the procedure given in [12]. The concentration of suspended particles in atmospheric air was measured by the ORS-2 device (Estonia) with automatic display of results on the screen of a personal computer. The concentrations of all suspended particles with sizes from 300 to 6000 nm were measured. The generation of air ions in the air was determined by calculation based on the value of the radioactive background. The radioactive background was measured by a professional dosimeter SRP-88 (Russian Federation). The temperature and relative humidity of the air were measured by a combined instrument CX601Д (China). The study of changes in the concentration of air ions of both polarities was carried out in ventilation channels made of galvanized iron.

The forecasting of the aero-ionic composition of the air, taking into account the deionization factors, was carried out on the basis of the ratios of transport phenomena, continuity of the flow, and using the classical ratios given in [13].

5. Results of research into processes of deionization of atmospheric air and air in public and industrial buildings

5. 1. Experimental studies of the dynamics of the aero-ionic composition of atmospheric air

Air ion concentrations in atmospheric air were measured. Measurements were carried out at different hours of the day Kyiv time. The weather was cloudy, there was no wind (Table 1).

Table 1

Changes in air ion concentrations depending on the time of day and climatic conditions

T, hour	t, °C	ϕ, %	Air ion concentration	
			n^-, cm^{-3}	n^+, cm^{-3}
8.00	20–22	60–62	600–700	750–850
13.00	24–25	40–45	550–650	550–600
19.00	22–23	50–55	600–650	700–750
8.00	–4–(–5)	35–40	200–300	300–350
13.00	1–2	60–65	300–400	350–450
19.00	–1–(–2)	50–55	300–400	350–400

The results given in Table 1 show that the concentrations of air ions change during the day. The predominant polarity of air ions also changes. In the morning, the predominant positive polarity of air ions is explained by the negative charge of the Earth. In the absence of directed air movement, positive ions drift to the earth's surface. Despite the cloudy weather, an upward movement of air begins in the middle of the day, which in a certain way moves the air ions of both polarities. Such a phenomenon can be considered firmly established as a result of numerous measurements both in the city and in suburban areas. Despite the fact that all measurements were performed at great distances from possible sources of anthropogenic influence on air ion concentrations, they decreased during the day in the warm season. Most likely, this is due to the appearance of suspended particles in the air, on which air ions settle. There are fluctuations in relative humidity, but the temperature is far from the dew point, that is, condensate that absorbs air ions does not form. During the cold season, concentrations of air ions increase slightly during the day. This can be explained by the fact that the air is cleaner, and the influence of solar radiation becomes noticeable. Ultraviolet radiation slightly increases the concentration of air ions.

Information on the concentration of suspended particles is necessary to determine the factors of air deionization intensity. Most of them are aerosols, which become heavy ions due to the deposition of light air ions on them.

The conditions given in Table 1 correspond to the concentration of suspended particles A=7500–8000 cm^{-3}. But this indicator changes even for areas far from man-made sources of dust and aerosols. The change in the concentration of suspended particles over several days in the place where the concentration of light air ions is measured is given in Table 2.

Table 2

Concentrations of suspended particles in atmospheric air

No.	1	2	3	4	5	6	7
A, cm^{-3}	7500–8000	12400–12800	8100–8400	18900–19100	15300–15500	24200–24600	32300–32500

Table 2 demonstrates that the change in the concentration of suspended particles is very large, this indicator affects the ionization of the air. The cause of such fluctuations can be the transfer of particles by the wind, even at low speeds. It was established that the predominant fraction of suspended particles in the size spectrum of 0.3–6.0 µm are particles with a size of about 3 µm. Such particles are easily transported due to even slight movements of atmospheric air and can contribute to the deionization of the air that enters the premises of buildings due to natural or forced ventilation.

5. 2. Experimental studies of changes in the aero-ionic composition of air in systems of forced ventilation of premises

In all high-rise residential and industrial buildings, ventilation of premises is carried out by supply and exhaust systems. That is, atmospheric air is pumped through ventilation channels. Most of these channels are metal. In Ukraine, they are made of galvanized iron.

Measurements were made of changes in the concentration of air ions in a standard supply-exhaust ventilation system. Ducts are made of galvanized iron. The ventilation system was 16 m long. Air velocity υ=2.6–2.8 m/s. The air temperature was 22 °C, the relative humidity was 65–66 % (Table 3).

The data in Table 3 demonstrate that significant air deionization takes place in the ventilation channel in both polarities.

To clarify the causes of deionization, laboratory studies were performed on changes in the concentration of air ions in air ducts made of different materials. The conditions of the experiment were air temperature 24 °C, relative humidity 50–52 %. The length of the ducts was 1.65 m. The speed of air movement was 0.6 m/s. Ducts were made of galvanized iron and pressed cardboard with a diameter of 0.12 m. The duct of dry wood had a square cross-section of 0.12×0.12 m.

The results of measurements are given in Table 4.

Table 3

Change in the concentration of air ions in the supply and exhaust ventilation system with a length of 16 m

Place of measurement	Air ion concentrations	
	n^-, cm^{-3}	n^+, cm^{-3}
Inlet to the supply and exhaust ventilation duct	730–750	1600–1700
Outlet from the supply and exhaust ventilation duct	230–250	340–380

Table 4

Changes in the concentrations of air ions in air ducts made of different materials

No.	Date and location of measurements	Air ion concentrations	
		n^-, cm^{-3}	n^+, cm^{-3}
1	Inlet to the air duct made of galvanized iron	320–330	600–640
2	Outlet from an air duct made of galvanized iron	190–200	280–290
3	Inlet to the duct made of cardboard	310–320	580–600
4	Outlet from an air duct made of cardboard	230–240	360–370
5	Inlet to an air duct made of wood	700–710	890–900
6	Outlet from an air duct made of wood	690–700	880–890

The data above indicate that deionization is absent only in the duct made of dry wood. This can be explained by the lack of electrification of the wood surface. At the same time, significant electrification is inherent in the paper surface as a result of the triboelectric effect when dry air is pumped through the duct. That is, deionization in real metal boxes occurs due to the presence of electrical interactions between the duct surface and air ions.

Our result requires an acceptable interpretation from the point of view of determining the physical mechanism of air deionization in metal air ducts, which are widely used in Ukraine and throughout the world.

In addition to recombination, a possible and prevailing mechanism of deionization is the neutralization of air ion charges upon contact with the inner surface of the air duct. In order for this to happen, the inner surface of the channel must have a charge, which, in addition to electrification due to the triboelectric effect, can arise due to the adsorption of air molecules on this surface.

Currently, the most common are ducts made of galvanized iron. Zinc is a transition metal, an element found in the d-block of the periodic table. Approaching the galvanized surface of the duct, gas molecules that are part of the air, first of all, undergo van der Waal attraction, which is then replaced by Pauli repulsion due to the overlap of the wave functions of the metal and the filled orbitals of the molecule. These two interactions form a potential hole (minimum on the curve of the system's energy dependence on the distance between the adsorbent surface and the adsorbate molecule), which corresponds to physical adsorption. As the molecule approaches the surface, this adsorption is replaced by a deep chemisorption pit.

In the air, zinc is covered with a thin film of ZnO oxide, which is an n-type semiconductor by its electrical properties, the electrical conductivity of which is due mainly to the transfer of electrons in the conduction band. Changes in the charge state of the galvanized surface occur as a result of the adsorption of gas medium molecules. As a result, a region of space charge is formed and the conductivity changes in the near-surface region of the semiconductor, the depth of which is equal to the Debye length of the shielding. Thus, adsorbed oxygen molecules create local energy levels in the band gap on the semiconductor surface. The new surface centers formed at the same time can capture both free electrons of the conduction band and electrons that were previously located on the donor center of the semiconductor. As a result, the electrical conductivity and electronic charge density in the near-surface region of the oxide film changes.

In addition to molecules and molecular ions of the gas phase, water molecules are present in the moist air passing through the air duct, which can also be adsorbed by the galvanized surface. Adsorbate molecules, falling on the surface of the semiconductor oxide film, tend to capture or give away an electron, depending on their physical and chemical properties. Oxygen molecules, due to their high electronegativity, localize an electron near them. At the same time, water molecules, falling on the surface of ZnO, donate their electron to the conduction zone or center on the surface, which tends to form a chemical bond with H_2O. Note that the appearance of a surface charge can also be caused by the physical adsorption of polar water molecules, which have a significant dipole moment.

Thus, as a result of the adsorption of atmospheric air molecules, the inner surface of the galvanized duct is charged. It should be noted that the thermal fluctuations of the lattice of the solid body and the adsorbed molecule stimulate desorption – breaking the bond of the adsorbed molecule with the surface of the oxide film and its subsequent transition into the gas phase. The steady-state value of the surface density of adsorbed molecules $N_{ad.}$, which was established as a result of competing adsorption-desorption processes, at low adsorbate concentrations should decrease with increasing temperature T:

$$N_{ad} \sim \exp\left(\Delta E / kT\right), \tag{1}$$

where ΔE is the heat of adsorption (bonding energy of the adsorbed gas molecule with the adsorption center); k is the Boltzmann constant.

Accordingly, the charge density created by molecules on the surface of the oxide film should also decrease. This, in turn, should lead to a decrease in deionization associated with the neutralization of air ion charges by the galvanized surface of the duct.

It is known that zinc oxide ZnO has piezoelectric properties. Due to this, the polarization that occurs under the action of mechanical stresses in the air duct can make a certain contribution to the appearance of a charge on the surface of the oxide film.

The increase in air deionization with increasing humidity observed in the experiment is due, apparently, to an increase in electrification of the duct surface both due to the triboelectric effect and due to an increase in surface charge due to an increase in the number of adsorbed H_2O molecules. In addition, with an increase in the relative humidity of the air, the number of light air ions can decrease due to settling on microscopic water droplets.

Adsorption of molecules occurs in a thin layer of air adjacent to the surface of the air duct. The significant deionization observed in this case can be associated with the eddy movements of the air in the turbulent flow inside the channel. In this case, one of the ways to reduce deionization can be laminarization of the flow due to the selection of the optimal diameter of the air duct and the flow speed, which ensure the minimum value of the Reynolds number. An alternative way to reduce deionization can be the propagation of the laminar regime to large Reynolds numbers (increasing the critical Reynolds number for a given channel). This is realized by reducing disturbances at the duct entrance, increasing the degree of smoothness of its inner surface, reducing the number of joints, etc.

The results indicate that in the process of determining the conditions for maintaining the standard concentrations of air ions in residential and industrial conditions, all factors affecting the quality of the air entering the building should be taken into account. Monitoring concentrations of air ions in the air and concentrations of suspended particles require large volumes of work, which is due to the complex dynamics of these factors. To carry out project work on the development of organizational and technical measures for the normalization of air ion concentrations in premises, it is advisable to implement a calculation method based on experimental data previously obtained for this environment.

5. 3. Estimated forecasting of the aero-ionic composition of air taking into account deionization factors

As a basis for forecasting the dynamics of the aero-ionic composition of the air, it is advisable to choose the ratios introduced in [13]:

$$\frac{dn}{dt}=g_n-\gamma np-\beta nA, \tag{2}$$

$$\frac{dp}{dt}=g_p-\gamma np-\beta pA,$$

where g_n, g_p are the productivity of negative and positive ion sources,

γ is the recombination coefficient of air ions,

β is the deposition coefficient of ions on suspended particles,

n, p – concentrations of negative and positive ions (air ions),

A is the concentration of suspended particles.

The possibility of practical application of these ratios is feasible because data on ion generation can be obtained by calculation based on the radiation background and the ionizing action of radioactive radiation (1P=2.6×10^{-4} Kl/kg). Data on concentrations of air ions and suspended particles are taken from the results of field measurements. The values of the coefficients are also known. The recombination coefficient γ is 1.67×10^{-6} cm^3/s. Deposition coefficient of air ions on neutral suspended particles $\beta^-=1.67\times10^{-6}$ cm^3/s, $\beta^+=1.2\times10^{-6}$ cm^3/s.

Calculations were performed of changes in air ion concentrations using the example of negative air ions. Calculations were carried out with a radioactive background of 12 μR/h, which corresponds to the generation of 120 pairs of ions in cm^3 of air per second. The initial concentration of air ions is 60 cm^{-3} (Table 1), and the concentration of suspended particles is 7500 cm^{-3} (Table 2). Under such conditions, the concentration of air ions decreases with time ($dn/dt>0$). The dynamic equilibrium of the ionization and deionization processes ($dn/dt=0$) occurs at air ion concentrations of 450–470 cm^{-3}. The process is similar for positive air ions. At initial concentrations of 750 cm^{-3}, the dynamic equilibrium occurs at the level of 680–690 cm^{-3}. The processes of the state of dynamic equilibrium for positive and negative air ions differ somewhat due to different values of the coefficients of deposition of air ions on suspended particles β.

For concentrations of air ions and suspended particles typical of atmospheric air and the air of most rooms, the deposition of light air ions on charged suspended particles can be ignored. But this is necessary for high concentrations of fine dust and aerosols under specific production conditions, or the presence of intense corona discharges.

The above ratios are convenient for determining the dynamics of air ion concentrations in atmospheric air and in the absence of directed air movement in rooms. But under conditions of forced ventilation of premises, it is necessary to take into account the constant supply of outside air. Productivity of supply-exhaust ventilation – air speed in air ducts and their cross-sections (usually known from technical documentation). Therefore, for individual rooms, it is advisable to use such an indicator as the air exchange rate, that is, the number of air changes per unit of time:

$$\frac{dn}{dt}=g_n-\gamma np-\beta nA+n_0B-nB, \tag{3}$$

$$\frac{dp}{dt}=g_p-\gamma np-\beta pA+p_0B-pB,$$

where n_0, p_0 are the concentrations of negative and positive air ions entering the room,

B is the number of changes in the room per unit of time.

The growth of air ion concentrations of both signs in the room is proportional to the amount of air exchange in the room. Dynamic equilibrium occurs when the concentration of air ions in the room becomes equal to the concentration in the air supplied to the room by natural or artificial ventilation systems.

The above ratios (2) and (3) make it possible to predict the air-ion mode of premises of any purpose, taking into account all critical influencing factors, and in case of non-compliance of air-ion concentrations with normative values, to determine the required performance of the artificial air ionization source.

The process of deposition of air ions on suspended particles can be described based on the provisions of the molecular kinetic theory. Collision of air ions with suspended particles occurs as a result of chaotic thermal movement of air ions, i.e., diffusion processes. After an air ion collides with an aerosol particle, it remains on it. As a result of such collisions, a charge accumulates on the particle. This charge creates an electric field that repels air ions of this polarity. That is, the rate of charge accumulation decreases.

The number of air ions that collide with a suspended particle per unit of time can be described by the ratio:

$$\frac{dN}{dT}=\frac{\pi d^2}{4}N\upsilon, \tag{4}$$

where N is the number of air ions that are near the particle,

υ is the root-mean-square velocity of air ions,

d is the diameter of the suspended particle.

According to the kinetic theory, the density of air ions in the potential field changes according to the law:

$$N=N_0\exp {W}/{kT}, \tag{5}$$

N_0 is the average concentration of air ions,

W is the potential energy of the air ion,

k is the Boltzmann constant,

T is air temperature.

The potential energy of an air ion at a distance R from the center of a particle on which there are n elementary charges e of the same sign is defined as:

$$W = {-ne^2}/{R}. \tag{6}$$

In this case, the concentration of air ions on the surface of the particle ($R=d/2$) is defined as:

$$N = N_0 \exp\frac{-2\pi e^2}{dkT}. \tag{7}$$

That is, the rate of change in the number of air ions can be defined as:

$$\frac{dN}{dT} = \frac{\pi d^2}{4} \upsilon N_0 \exp\frac{-2\pi e^2}{dkT}. \tag{8}$$

The above ratio (8) makes it possible to estimate air deionization depending on the content of suspended particles. It is more convenient for practical use than ratio (2) and takes into account both the size of suspended particles and the speed of air ions, which depends on the air temperature.

Diffusion charging of suspended particles occurs mainly in the absence of an electric field or its insignificant influence on this process. But in the absence of air movement in the surface layer, positive air ions drift towards the surface due to the negative charge of the Earth. Indoors, the movement of air ions is observed towards polymer surfaces (for example, floor coverings), which receive a surface electrostatic charge due to the triboelectric effect [11]. To quantify the charging of suspended particles in the presence of an electric field, the ion current to the particle is determined. This electric current depends on the number of air ions that can reach the particle, and, on its surface, which can accept air ions:

$$i = \frac{dq}{dt} = \frac{d(en)}{dt} = jA(n), \tag{9}$$

where j is the ion current density in an undisturbed electric field;

$A(n)$ is the cross-sectional area of the undisturbed ion flow that reaches the particle when it contains n ions:

$$A(n) = \frac{\psi(n)}{E_0}, \tag{10}$$

where $\psi(n)$ is the flow of the electric field intensity vector entering the particle;

E_0 is the intensity of the undisturbed electric field near the particle.

The flow of the intensity vector is equal to the product of the field intensity $\psi(n)$ on the surface of the particle E and the surface area dA perpendicular to the field intensity vector:

$$\psi(n) = EdA. \tag{11}$$

The electric field E_1 in a more accurate surface of a sphere placed in a uniform electric field can be represented as:

$$E_1 = \delta E_0 \cos\theta, \tag{12}$$

where $\delta = {3\varepsilon}/{\varepsilon + 2}$, ε is the dielectric constant of the sphere, θ is the angle between the normal to the sphere and the tangent to the lines of the electric field curved by the particle.

Accumulated charges on the sphere generate an electric field of repulsion, which prevents the deposition of air ions of the same polarity. The intensity of such a field can be defined as:

$$E_2 = \frac{-4\pi ne}{d^2}. \tag{13}$$

As a result, the total electric field is equal to:

$$E = E_1 + E_2 = \delta E_0 \cos\theta - \frac{4\pi ne}{d^2}. \tag{14}$$

At $E=0$ $\theta=\pi/2$.

Thus, the total flux of the electric field strength vector that enters the particle is:

$$\psi(n) = 2\int_0^{\varepsilon_0} \left(\delta E_0 \cos\theta - \frac{4\pi e}{d^2}\right) \times \left(\frac{\pi}{2}\right) d^2 \sin\theta d\theta. \tag{15}$$

After integration, the following was obtained:

$$\psi(n) = \delta \frac{\pi d^2}{4} E_0 \left(1 - \frac{4\pi e}{\delta E_0 d^2}\right)^2. \tag{16}$$

The charge saturation of the particle occurs when $\psi(n)$ is equal to zero. That is:

$$n_e = \frac{\delta E_0 d^2}{4e}, \tag{17}$$

where n_e is the largest charge acquired by particles with an average diameter d in an electric field with an intensity E_0.

The above ratio (17) will allow determining the drift speed of suspended particles in natural and man-made electric fields. In particular, it can be used to evaluate the cleaning of indoor air from suspended particles due to their settling on the surface. This can be done by artificially ionizing indoor air with air ions of the required polarity, depending on the charge sign of the surface electrostatic charges. At the same time, the air is cleaned of suspended particles and surface electrostatic charges are neutralized.

The results of calculations regarding changes in concentrations of suspended particles under conditions of artificial air ionization and the presence of people were compared (Fig. 1).

As can be seen from Fig. 1, in the zone with no air exchange, the concentration of suspended particles increases, but this increase slows down. Concentrations of suspended particles increase as a result of breathing and the presence of people. The slow growth of this indicator can be explained by the deposition of ions on suspended particles and the deposition of particles on the surface. In zones II and III, there is a significant decrease in the concentration of suspended particles due to their removal by the ventilation system. At the same time, the initial concentration of air ions in the room was 600–700 cm^{-3} of each polarity, and after 1.5 hours this indicator was 650–750 cm^{-3}. That is, a significant part of the ions of the ionization source (1800 cm^{-3}) is spent on settling on suspended particles. This fact must be taken into account in practical work.

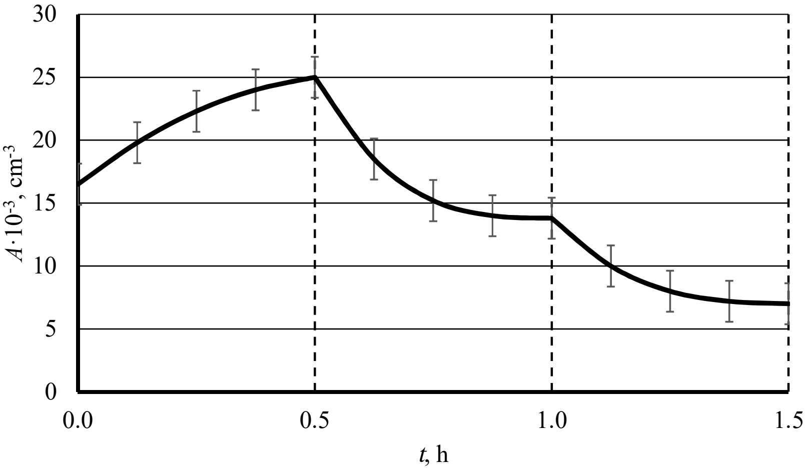

Fig. 1. Change in the concentration of suspended particles in a room with artificial air ionization and the presence of forced air exchange (the productivity of the ionization source is 1800 cm^{-3}, zone I corresponds to the conditions of the absence of air exchange, II, III – two and four complete air exchanges per hour)

6. Discussion of the results of research into the processes of deionization of atmospheric air and air in public and industrial buildings

Field measurements of concentrations of air ions and suspended particles in atmospheric air are highly variable. The data in Table 1 demonstrate that concentrations of air ions, even in the absence of wind, change depending on the time of day. Taking into account the negative charge of the Earth, in the absence of upward air flows in the morning and evening in the near-surface layer of the earth, the number of positive air ions is much greater. During the day, due to air mixing, the concentrations of air ions of both polarities are approximately the same within the measurement error. Suspended particles are the deionizing factor of atmospheric air [6]. Even with the remoteness of the measurement zone from the sources of dust and aerosol production (in this case, the nearest highway is located at a distance of 300–400 m), the concentration of suspended particles was at least 7000 cm^{-3}. And in the presence of wind, they reached 30,000 cm^{-3} and more (Table 2). The mutual relationship between the concentrations of air ions and suspended particles cannot be considered linear due to the dependence of the degrees of their interaction on concentrations, air humidity, and temperature, which follows from the fundamental relations of the molecular kinetic theory. The dynamics of these air parameters should be taken into account in the process of organizing forced ventilation of buildings. It has been established that atmospheric air is deionized in standard metal air ducts.

According to laboratory studies, the mechanism of deionization in both polarities has an electrical nature. At the same time, non-conductive materials (in this case – cardboard and wood) showed different results (Table 4). Due to the electrification of the surface due to the triboelectric effect, the cardboard deionizes the air. And dry wood does not affect the concentration of air ions. It can be concluded that the use of polymer materials for the manufacture of air ducts does not solve the problem. All polymers, except fluoroplastic and polyamide, accumulate surface electrostatic charges that absorb air ions.

To devise organizational and technical measures to normalize and maintain the concentrations of air ions at a normative level, it is advisable to use calculation methods for determining the degree of air deionization. A feature of the application of the relevant ratios to determine the air quality in the premises is the need to use data on the concentrations of the air entering the premises through air ducts as a parameter of the outside air. In ventilation rooms, the multiplicity of air exchange in the rooms should be taken into account, based on the speed of the air flow in the air duct, its cross-section, and the volume of the room [12]. Our research has certain limitations. The paper considers only the conditions of small concentrations of suspended particles and concentrations of air ions of normative values, or those when these concentrations are close to normative values. Under real production conditions, there can be large concentrations of suspended particles that completely deionize the air. And in such a situation, even a powerful air ionizer may not provide purification and normative air ionization.

The disadvantage of our study is that the linear deionization of the air (deionization per unit length of the duct) was not determined. But in the long run it can be fixed. Such a study is possible in the presence of identical supply-exhaust ventilation systems of different lengths. Further development of this research is possible to find out the effect of dust deposition on the inner surfaces of air ducts, as well as polymer filters on the concentration of air ions. It is appropriate to study the degree of air deionization depending on the value of the Reynolds criterion. This criterion depends on the speed of the air flow and the cross-section of the duct and determines the border between laminarity and turbulence of the flow. It should be expected that ensuring laminar flow will reduce the degree of interaction of air ions with the walls of air ducts. An effective method of designing ventilation systems with the required parameters is the modeling of the distribution of air flows that carry air ions. The application of approaches to modeling the propagation of particles with air flow is given in [14]. Using velocity-potential ratios instead of the Navier-Stokes equation provides an acceptable error and speeds up the calculation process. This will make it possible to quickly calculate the optimal option for ensuring standard air parameters in the premises.

7. Conclusions

1. It was established that the concentrations of air ions of both polarities in atmospheric air, even in the absence of significant man-made influences, change depending on the time of day. This is due to the absence or presence of upward air currents due to solar radiation. This indicator also depends on relative humidity and air temperature. The differences in concentrations of air ions of both polarities are up to three times. Concentrations of suspended particles, which are the main factor in air deionization, are at least 7000 cm^{-3}. In the presence of wind, this indicator reaches a value of 30,000 cm^{-3} and higher. Such phenomena must be taken into account when organizing the supply of atmospheric air to buildings.

2. It has been established that in standard forced ventilation systems made of galvanized iron significant deionization of air

occurs in both polarities. In the 16-m long ventilation system, at standard temperatures, relative humidity and air movement speed, the concentration of negative air ions decreased by 67 %, and positive ones by 78 %. Laboratory studies of air deionization in air ducts made of various materials have shown that the cause of deionization is electrical interactions with the walls of the air ducts. This is confirmed by significant deionization of the air in the air duct made of pressed cardboard due to the electrification of the paper due to the triboelectric effect and the lack of deionization in the air duct made of dry wood.

3. The possibility of forecasting the aero-ionic mode of premises by calculation methods has been shown. The output data are the results of monitoring the composition of atmospheric air and air deionization in forced ventilation channels. Under the conditions of the use of supply-exhaust ventilation systems, it is advisable to take into account the frequency of air exchange in the room in the calculations, based on the volume of the room and the speed of the air flow in the air duct and its cross-sectional area. It was determined that with double air exchange, the concentration of aerosols in the room is sharply reduced by 50 %. At the same time, the initial concentration of air ions in the room was 600–700 cm^{-3} of each polarity, and after 1.5 hours this indicator was 650–750 cm^{-3}. That is, a significant part of the ions of the ionization source (1800 cm^{-3}) is spent on settling on suspended particles.

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.

Funding

The study was conducted without financial support.

Data availability

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

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