Наведено результати досліджень щодо нормалізації аероіонного режиму в приміщеннях за ультразвукової іонізації зволоженого повітря. Обґрунтовано підвищення концентрації негативних аероіонів у зазначених умовах шляхом комплексного впливу балоелектричного ефекту та ультразвукової кавітації. Встановлено, що при використанні дистильованої води як джерела аероіонів під дією ультразвукового генератора потужністю 10 Вт на відстані 0,5 м концентрація негативних аероіонів збільшується практично в шість разів. При цьому за рахунок спільного впливу ультразвукової кавітації у поверхневому шарі води та балоелектричного ефекту не спричиняється генерації озону і оксидів Нітрогену. Доведено, що зі зменшенням ступеня мінералізації води концентрації негативних і позитивних аероіонів збільшуються внаслідок зміни фізико-хімічних властивостей води та виникаючих механохімічних явищ. Запропоновано механізм утворення аероіонів у повітрі виробничих приміщень в умовах спільної дії балоелектричного ефекту та ультразвуку. Обґрунтовано, що поліпшення якості аероіонного складу повітря виробничих приміщень відбувається за температури демінералізованої води 20–25 °С і направленого повітряного потоку швидкістю 6 м/с у бік робочої зони зі сполучною дією ультразвуку та балоелектричного ефекту, що сприяє поліпшенню санітарно-гігієнічних умов праці. Запропоновано структуру автоматизованої системи керування аероіонним режимом робочої зони виробничих приміщень за штучної іонізації зволоженого повітря з використанням генератора аероіонів та вентиляційної системи. Це дозволить здійснювати моніторинг і обробку інформації стосовно технологічних, електричних і мікрокліматичних параметрів, налаштовувати, узгоджувати роботу та спільно керувати пристроями вентиляційної системи і ультразвуковим генератором аероіонів

Ключові слова: аероіонний режим, балоелектричний ефект, ультразвукова кавітація, робоча зона, виробниче приміщення

STUDYING AND SUBSTANTIATION OF THE METHOD FOR NORMALIZATION OF AIR-IONIC REGIME AT INDUSTRIAL PREMISES AT THE ULTRASONIC IONIZATION OF AIR

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1. Introduction

A concentration of air-ions of both polarities in the air is an important indicator of its quality. This is especially true for a production environment. There are factors of ionization and deionization of the air in many cases, such as electrical equipment, air conditioners, personal computers, etc. Presence of people can have a significant impact on these indicators. The concentration of air-ions may change unpredictably under these conditions.

Studies in the field of air-ionic effects on human body [1] showed that increased concentrations of negatively charged air-ions contribute to a reduction in fatigue at various types of work. We can observe normalization of the metabolism, facilitation of respiration and an increase in mental and physical capacity. The nervous system of a human body becomes stronger due to increased stress resistance.

We should note that we have sufficient body of research into formation of air-ions in the presence of carbon dioxide (CO_2) and development of mathematical models for moni-

toring concentrations of this substance in industrial agricultural premises on this basis [2]. However, now, there is no unambiguous idea of formation mechanisms of air-ions under conditions of humidified air of industrial premises in dependence on a degree of mineralization of water micro drops, which form humidity of air in the presence of dust particles of different nature. In addition, there is no data on content norms for specified production conditions. Only DBN No. 2152-80 (State construction specifications) defines norms for the content of negative air-ions in the air of industrial and public premises. The minimum content required is 600 air-ions/cm^3; the optimal level is 3,000–5,000 air-ions/cm^3.

Given the above, the relevance of this study is in determining the mechanisms of influence of humidity depending on a degree of water mineralization, a combined action of ultrasonic cavitation and the balloelectric effect on formation of air-ionic composition of the air in industrial premises to improve sanitary and hygienic working conditions.

2. Literature review and problem statement

Investigation of air-ion concentrations in the air of industrial premises relates directly to the study of an influence of technical means and presence of people for physiological and hygienic assessment of a microclimate of modern office premises and adaptive reactions of workers' bodies [3, 4]. In this regard, a base of working of modern automated microclimate support systems [5] is a use of computerized measuring instruments for collection of parameters of the microclimate of industrial premises. Modern systems of exhaust ventilation (*Displacement Ventilation*, *DV* and modifications *Cooled Beam*, *UFAD*, etc.) have these automated systems [6]. Two reasons determine such interest. One of the reasons is a certain "non-traditional" method of calculation. The second one is that we have no clear definition of the scope of DV application and design and regulation methods for now.

We have to note that it is possible to construct control systems of both ventilation complexes and separate systems of support of the air-ionic composition of the air according to different principles. The task of provision of the optimal level of air-ions is multifactorial. All parameters are closely interrelated [7]. There are intelligent systems, which use methods of fuzzy control or genetic algorithms, developed to solve such problems [8–10]. However, despite all the benefits of such approaches, there are no formal procedures for design of intelligent systems today. A base of the main ideas of design is an experience and knowledge of a developer obtained by trial and error. In recent years, there are systems with fractional controllers widely used to describe complex dynamic processes, as well as to improve a quality of regulation including multidimensional models [11–13]. But external air gets to a premise with unsatisfactory concentrations of air-ions of both polarities or of one polarity in many cases. This fact proves a complex mechanism of dynamics of air-ion concentrations in premises during a working day. Paper [14] defines the air-ionic mode of a working zone for artificial ionization of the air. The same authors carried out a modeling of propagation of air-ions in space under different conditions [15]. The advantages of these studies are suggestions of using scattering screens for uniform distribution of ionized air in the environment. But this does not remove the issue of control of levels of ionization of air and control of modes of an ionizer working. This necessitates the regulation of this parameter in the automatic mode with continuous or periodic determination of concentrations of air-ions of both polarities.

Authors of [16] showed that information technology equipment affects ionization of air (system blocks of personal computers, printers, etc.). In addition, there is a significant interaction between ionization of air and levels of fine dispersed dust and aerosol in air of production facilities and relative humidity of air. Studies in [17] worked out a system of aerosol pollution of premises and there is selection of methods of aerosol pollution control. However, it does not consider the issue of regulation of air-ionic composition of air in industrial premises for the purpose of integrated assessment of sanitary and hygienic working conditions. At present, we know only works devoted to research on improvement of the air-ionic composition of dwelling houses [18, 19] due to a use of new grades of primers and paints that contribute to increase in the concentration of negative air-ions during repairs.

A separate issue is that a use of artificial indoor air-ionizers leads to formation of harmful substances – ozone and oxides of Nitrogen, which have an adverse effect on the human body in significant quantities. Application of catalytic absorbers is very problematic, and there is no practice to use air-ionizers in such cases. Therefore, it is expedient to search for other means of air-ionization, which do not cause side effects. We know that the ionization factor is a balloelectrical effect [20, 21]; it is ionization of air during mechanical grinding of water. Therefore, we can observe the best by aeronautical composition natural air quality indicators on a seashore in areas of a surf and in waterfalls.

The experience of measuring near shower plants for generation of light air-ions indicates that water dispersion begins with formation of molecular complexes. Studies on the hygienic assessment of the "Ion" humidifier found that there was an intensive development of microorganisms, even at room temperature during the working of a device under conditions of water temperature thermostating [17].

Consequently, to eliminate this problem, there is a need for experimental studies changes in the concentration of air-ions in dependence on a degree of water mineralization. Based on physical considerations, we should expect that the most effective is grinding of water by a combined action of ultrasonic cavitation [22] and the balloelectrical effect. The given method of air-ionization is expedient for a use in premises with highly deionized air, where we need significant amounts of air-ions generation.

Paper [22] showed that the mechanism of formation of light air-ions is still unclear at destruction of a water surface. Results of the research carried out are opposite and contradictory. But most experiments showed that the balloelectric effect itself contributes to an increase of the concentration of negative air-ions only.

In view of the above, it is necessary to carry out a number of experimental studies with a use of water of varying degrees of mineralization, temperature, concentration of saline water solutions and changes in air velocity and ultrasound intensity in order to maintain the maximum amount of air-ions in an working area.

3. The aim and objectives of the study

The conducted research set the aim to raise a level of comfort and efficiency of workers by an increase in the con-

centration of negative air-ions in a working area of industrial premises.

We set the following tasks to achieve the objective:

– to conduct experimental study into changes in concentrations of air-ions to determine actual levels of air-ionization of premises of the same purpose type and to determine necessary limits of control of concentrations of air-ions;

– to experimentally investigate the dynamics of air-ionic concentrations in dependence on a change in physical factors due to ultrasonic ionization of air;

– to develop a structure of the automated system to control the air-ionic composition of air under conditions of a complex working environment of working premises in order to improve sanitary and hygienic working conditions.

4. Materials and methods to study the hydro-air-ionic composition of premises when using ultrasound energy

4. 1. Investigated aqueous solution and equipment used in the experiment

We carried out the research with a use of water of different temperature and different degrees of mineralization – 1.1; 2.2; 3.3 and 4.4 %, respectively (salt content in drinking water and natural waters).

We used a small-sized ultrasonic air-ions generator (UAG) with a power of 10 W, a voltage of 19–24 V DC, a current of 500 mA and a resonant frequency of 1.7 MHz for generation of air-ions. The submersible pump My 108 (Zamar, Indonesia) with a power of 2.5 W, a maximum flow rate of 180 dm^3/h and h_{max} of 0.48–0.55 m supplied water on UAG membrane. We used ROTEX RAT01- E fan (China) with a maximum power of 20 watts for dispersion of air-ions.

We measured air velocity by TM-4001 heat loss anemometer (TENMARS ELECTRONICS CO., LTD., Taiwan) with the following characteristics: air flow (volume) 0–9,999 mm^3, temperature 20–50 ºC, air velocity 0.01–25.00 m/s.

We used "Sapphire 3K" air-ions meter (produced in Russian Federation), equipped with a RS 232 port for connection with a personal computer to automate the control process.

We performed mathematical processing of the received data arrays of measurements of concentrations of air-ions of both polarities in accordance with a paper [16].

4. 2. Procedure for determining the concentration of air-ions

We used UAG with a supply voltage of 19 V to carry out tasks of the study. We supplied a thin water jet of water on a piezoelectric cell of UAG from a height of 0.2 m. Ultrasonic waves grinded a water jet completely. We carried out measurement of the concentration of air-ions according to the developed method [16] on the serial "Sapphire 3K" instrument with an error measurement of 20 %.

According to measurement results, the concentration of light air-ions (n_{meas}) is an arithmetic average of 24 device's measurements recorded continuously for two minutes of measurements [16]. In this case, a random error $\Delta\rho<\delta/3$. It satisfies conditions, under which the measurement error of air-ion concentrations Δ is equal to the systemic instrumental error δ. We carried out verification of adequacy of regression models with a use of built-in statistical functions and procedures in the Excel program for all measurement results.

5. Results of research and the formation of qualitative air-ionic composition of air at a working zone of industrial premises

A set of factors affects the number of air-ions in premises under artificially created working conditions. Physical factors among them include temperature, humidity and speed of its movement in a premise. A presence of people and concentrations of fine dispersed dust and gaseous impurities in air forms an effect of chemical factors.

For a general idea of a change in a concentration of air-ions during a day, we carried out actual measurements in the premises at the Kremenchug Mykhailo Ostrogradsky National University (Ukraine) of the same area with the same computer load for various internal and external factors (Table 1, 2).

The analysis of studies showed that the concentrations of air-ions of both polarities (both individually and together) change unpredictably in one or another premise in different months (January 2018 – Table 1, and February 2018 – Table 2).

Table 1

Dynamics of air-ionic composition of air in the computer class in the absence of personnel

Characteristics		Time of measurements					
		15 h 15 min		17 h 22 min		Outdoors	
Polarity of air-ions		n^-	n^+	n^-	n^+	n^-	n^+
Concentration of air-ions, cm^{-3}	n_{aver}	840	790	750	785	250	220
	n_{min}	440	355	355	340	155	130
	n_{max}	1,015	970	980	1,005	490	485

Note: 16 turned on personal computers (air temperature +20 °C, humidity 60 %, radiation background of 8 µR/h, outside temperature –3 °C)

Table 2

Dynamics of air-ionic composition of air in the computer class in the presence of personnel

Characteristics		Time of measurements							
		7 h 15 min		8 h 52 min		10 h 25 min		Outdoors	
Polarity of air-ions		n^-	n^+	n^-	n^+	n^-	n^+	n^-	n^+
Concentration of air-ions, cm^{-3}	n_{aver}	340	450	245	260	445	590	60	85
	n_{min}	15	290	25	50	65	150	10	15
	n_{max}	470	550	380	380	640	695	110	135

Note: 16 turned on personal computers (air temperature +19 °C, humidity 65 %, radiation background 6 µR/h, outside temperature –5 °C)

An analysis of many measurement series (Tables 1, 2) did not reveal direct concentration of air-ions with some prevailing factor of ionization (deionization) of air. This is obviously due to the combined effect of a number of factors, each of which affects the quality of characteristics on the verge of an error of the measuring instrument. It is advisable to control the concentrations of air-ions continuously or with the required periodicity under such conditions.

We performed the first studies with a use of UAG determine the dependence of changes in the concentration of air-ions on the degree of water mineralization – distilled water, weakly mineralized water (tap water) and mineral water (Fig. 1, *a, b*).
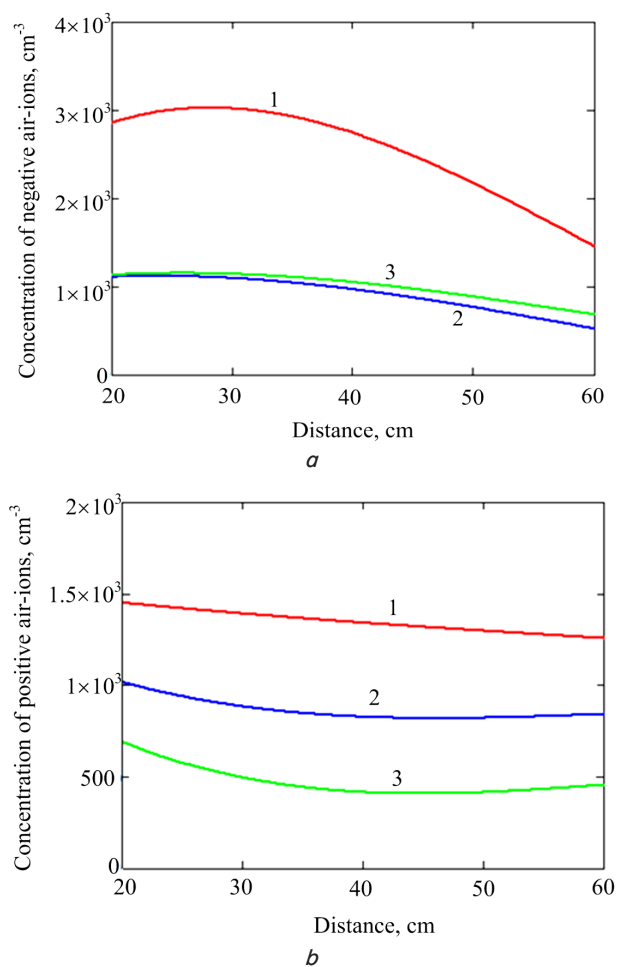
Fig. 1. Dynamics of the concentration of air-ions from the distance to the source of ultrasound taking into account the degree of water mineralization: 1 — distilled water; 2 — mineral water; 3 — tap water; *a* — negative (background — n^-=651 cm^{-3}); *b* — positive (background — n^+=1,611 cm^{-3})

water molecules change; and this reduces activation energy of formation of air-ions with the participation of these atoms. In addition, we should bear in mind that water molecules are dipoles interconnected by electrostatic interaction and intermolecular hydrogen bonds. And there are bonds breakdown and a release of certain water molecules in the form of a steam under the action of ultrasonic cavitation. An influence of energy of deformation oscillations of chemical bonds in water molecules increases under the influence of ultrasonic cavitation. This affects a rate of formation of hydrated protons (H$^+$·H$_2$O) and ions of hydroxyl (OH$^-$·H$_2$O). Proceeding from the above, we can state that water forms a mixture of clusters nH$_3$O$^+$ and m (OH$^-$·H$_2$O) under the action of ultrasonic cavitation. In this case, Oxygen, as an electron donor, forms a significant number of compounds with relatively weak bonds between the molecules easily. Unpaired electrons form a charge transfer complexes and this facilitates formation of hydro-air-ionic radicals.

Table 3

Functional dependences of air-ionic change on the degree of water mineralization

Air-ions	Approximation functions
distilled water	
n^-	$y=-1,965x^2+8,266x-5,650$; R^2=0.99
n^+	$y=41.5x^2-341.5x+1911$; R^2=0.98
mineral water	
n^-	$y=-573x^2+2,292x-1,194$; R^2=0.97
n^+	$y=34x^2-210.5x+1,173$; R^2=0.98
tap water	
n^-	$y=-540.2x^2+2,241x-1,176$; R^2=0.99
n^+	$y=230.5x^2-1,192x+1,958$; R^2=0.98

An analysis of the dynamics of the concentration of air-ions showed that results of experimental measurements of the content of negative and positive ions obey a dependence. We can describe the dependence with a polynomial of the second degree with the accuracy of approximation R^2=0.98−0.99 (Table 3). A nature of the dependences has an opposite relationship: for negative air-ions $C_{n-}=-al^2+bl-c$; and for positive ones – $C_{n+}=al^2-bl+c$. This is due to the presence of components of inorganic nature with different content such as sulfates (SO$_4^{2-}$), chlorides (Cl$^-$), carbonates (CO$_3^{2-}$), hydro carbonates (HCO$_3^-$), calcium ions (Ca^{2+}), magnesium ions (Mg^{2+}), sodium ions (Na$^+$) in water. In addition, hydroxyl ions (OH$^-$) and ions of hydrated water molecules (ions of hydroxonium - H$_3$O$^+$) appear under the action of ultrasound.

Such a phenomenon occurs due to the mechanical action on water molecules located on a surface of liquid as a double electric layer under the action of the ultrasonic wave – cavitation – due to the applied mechanical stress. On our opinion, there are mechanical-and-chemical reactions followed by turbulization of a water flow due to the action of ultrasonic cavitation. Because of this, distances between atoms and geometric parameters of individual

We performed the next study to determine dynamics of changes in the concentration of air-ions in dependence on a level of water salinity (from 1.1 to 4.4 %, Fig. 2, *a, b*).

An analysis of the experimental data obtained (Fig. 2, *a, b*) shows that the concentration of negative and positive air-ions with an increase in water mineralization from 1.1 to 4.4 % at a distance of 0.3 m from UAG decreases almost twice compared with the background concentration (without ultrasound treatment - the "0" point). Unlike the data shown in Fig. 1, the concentration of positive air-ions increases gradually to almost background values with an increase of the distance to 0.6 m. The picture of a change in concentrations for negative air-ions is slightly different. There is a rapid decrease in concentrations – from 650 to 250–350 cm^{-3}, with a change in the mineralization of water from 1.1 to 3.3 %, but the curves are almost the same both for negative and for positive air-ions for the concentration of the aqueous solution of 4.4 %. Statistical processing of the data obtained showed a reliable correlation between the Pearson correlation coefficient between changes in concentrations of air-ions of both polarities on a distance to UAG (n^- – 0.98 and n^+ – 0.95) and on a degree of water mineralization (n$^-$ – 0.99 and n$^+$ – 0.93).

Nest, we conducted a study to determine the dependence of a change in the concentration of air-ions under an influence of airflow at a speed of 1 to 8 m/s (Fig. 3, *a, b*).
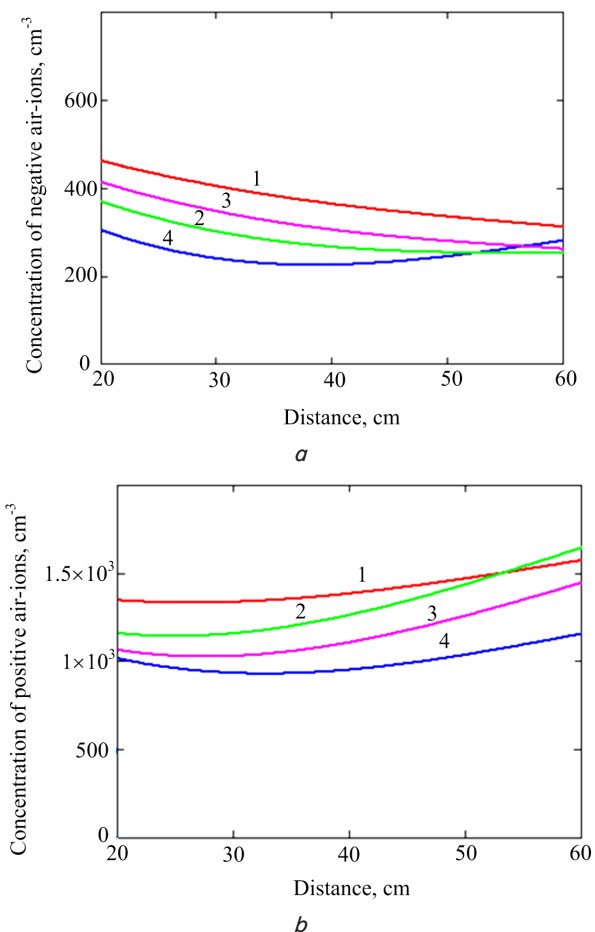
a

b

Fig. 2. Change in the concentration of air-ions with a distance at ultrasonic treatment of water of varying degrees of mineralization: a — negative (background — $n^-=651$ cm^{-3}); b — positive (background — $n^+=1,611$ cm^{-3}). Concentration of saline water solutions: 1 − 1.1 %; 2 − 2.2 %; 3 − 3.3 %; 4 − 4.4 %
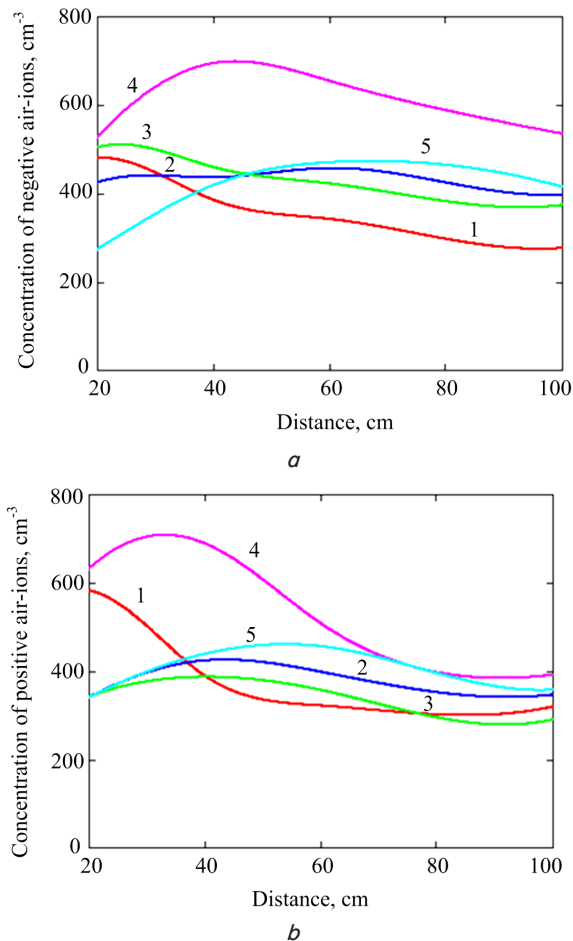

a

b

Fig. 3. Dynamics of the concentration of air-ions after ultrasonic treatment of distilled water with distance from the air flow rate: 1 − 1 m/s; 2 − 2 m/s; 3 − 4 m/s; 4 − 6 m/s; 5 − 8 m/s: a — negative (background — $n^-=147$ cm^{-3}); b — positive (background — $n^+=170$ cm^{-3})

Table 4

Functional dependences of a change of air-ions on the concentration of saline water solutions

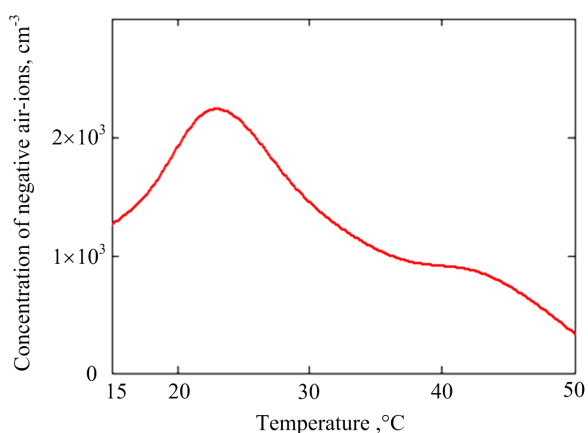| Air-ions	Approximation functions
Concentration of saline water solutions – 1.1 %	
n^-	$y=77x^2-477x+1,050;\ R^2=0.99$
n^+	$y=253.5x^2-1,032x+2,389;\ R^2=0.98$
Concentration of saline water solutions – 2.2 %	
n^-	$y=225x^2-1,084x+1,510;\ R^2=0.97$
n^+	$y=446.7x^2-2,013x+3,177;\ R^2=0.98$
Concentration of saline water solutions – 3.3 %	
n^-	$y=150.2x^2-799.2x+1,299;\ R^2=0.99$
n^+	$y=466.7x^2-1,849x+2,994;\ R^2=0.97$
Concentration of saline water solutions – 4.4 %	
n^-	$y=109x^2-630x+1,171;\ R^2=0.98$
n^+	$y=496x^2-2,065x+3,180;\ R^2=0.99$

Table 5

Functional dependences of a change in air-ions on air velocity

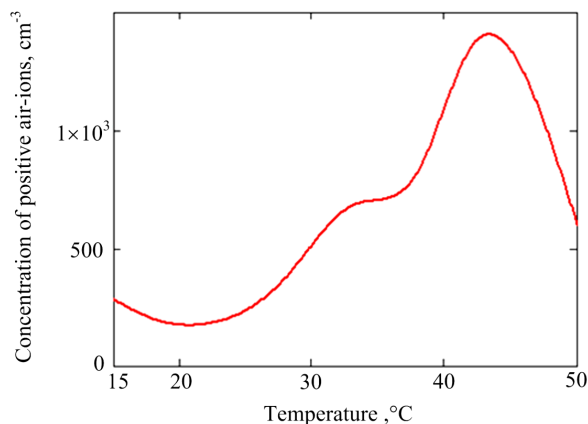| Air-ions	Approximation functions
v, 1 m/s	
n^-	$y=-27.35x^2+244,5x-151,5;\ R^2=0.88$
n^+	$y=-22.84x^2+201.2x-27.86;\ R^2=0.85$
v, 2 m/s	
n^-	$y=-32.42x^2+329.0x-343.1;\ R^2=0.87$
n^+	$y=-24.89x^2+249.7x-207.4;\ R^2=0.87$
v, 4 m/s	
n^-	$y=-32.35x^2+312.3x-273.5;\ R^2=0.79$
n^+	$y=-23.49x^2+223.9x-155.1;\ R^2=0.78$
v, 6 m/s	
n^-	$y=-55.38x^2+557.8x-702.8;\ R^2=0.82$
n^+	$y=-53.57x^2+488.7x-492.8;\ R^2=0.76$
v, 8 m/s	
n^-	$y=-11.62x^2+166.7x-150.9;\ R^2=0.758$
n^+	$y=-18.00x^2+198.9x-145.5;\ R^2=0.718$

An analysis of the graphic dependences obtained (Fig. 3, *a, b*, Table 5) showed the identity of changes in concentrations of negative and positive air-ions with changes in

velocity of the airflow, which falls under the atmospheric air of industrial premises. Because there is a change in surface tension, which contributes to a purely mechanical breakdown of intermolecular hydrogen bonds due to ultrasonic cavitation, during application of a water jet of ~5 mm thickness to the ultrasonic membrane. A dynamic equilibrium appears. A number of formed air-ions is equal to a number of recombined air-ions. This is especially noticeable at a distance of 40 cm and above from a source of airflow.

We conducted a study where we applied a thin stream of distilled water with a temperature of 15 to 50 °C to the working membrane of the ultrasonic generator to determine the dependence of a change in the concentration of air-ions on temperature of the aqueous solution. The distance from UAG to "Sapphire 3K" was 0.5 m. Fig. 4, *a, b* shows the graphs of dependences.

An analysis of the experimental data obtained (Fig. 4, *a, b,* Table 6) shows that we can achieve the highest concentration of negative air-ions by maintenance of the temperature from 20 to 25 °C. The concentration of positive air-ions acquires the greatest value at 42–45 °C, but falls again after 45 °C again. In addition, we can observe establishment of a mechanical-and-chemical equilibrium in the temperature range of 35–37 °C: the concentrations of negative and positive air-ions are almost the same. In this case, a rate of formation of air-ions of both signs is equal to rates of recombination.

We carried out the last research was to determine the dependence of a change in the concentration of air-ions. We supplied a thin stream of distilled water to a working piezo element of an ultrasonic generator whose voltage varied in the range from 16 to 24 V. The distance from UAG to "Sapphire 3K" was 0.5 m. Fig. 5, *a, b* shows the dependences.

Fig. 4. Dynamics of the concentration of air-ions under ultrasound treatment in dependence on temperature of distilled water: *a* — negative (background — n^-=371 cm^{-3}); *b* — positive (background — n^+=394 cm^{-3})

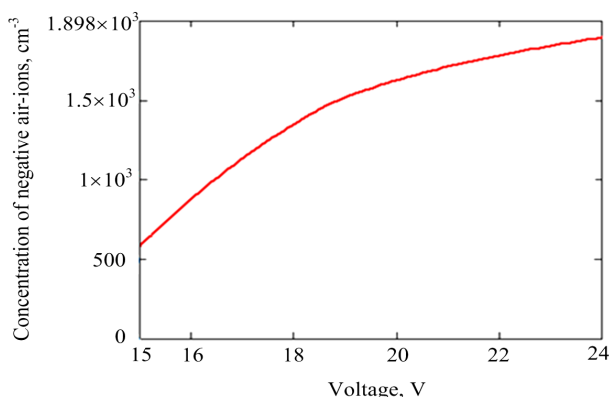Fig. 5. Dynamics of the concentration of air-ions after ultrasonic treatment of distilled water by voltage to UAG: *a* — negative (background — n^-=371 cm^{-3}); *b* — positive (background — n^+=394 cm^{-3})

Table 6

Functional dependences of change in air-ions on temperature of distilled water

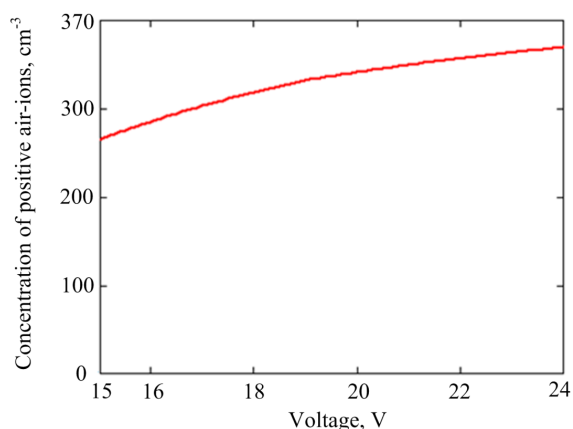| Air-ions	Approximation functions
n^-	$y=18.782x^3-362.8x^2+1931.1x-1{,}258.1$; $R^2=0.89$
n^+	$y=-12.633x^3+197.92x^2-784.73x+1{,}067.7$; $R^2=0.79$

Table 7

Functional dependences of change in air-ions change on voltage to UAG

Air-ions	Approximation functions
n^-	$y=-134.7x^2+1{,}088x-153.7$; $R^2=0.98$
n^+	$y=-3.958x^2+60.62x+223.3$; $R^2=0.99$

There was a combined influence of the balloelectric effect and ultrasonic cavitation at ionization of air in the preceding studies (Fig. 1–4). However, in this case (Fig. 5, Table 7), there is a predominant influence of the cavitation processes due to transformation of low density of ultrasound energy into high energy density near and inside a gas bubble. With an increase in voltage on a resonant membrane from 16 to 24 V, there is an increase in intensity of ultrasound and, therefore, cavitation processes, which causes an increase in the content of hydro ionic particles in the air.

The experimental researches gave possibility to develop a structure of an automated system for control of the air-ionic mode of a working area of industrial premises by artificial ionization of air with a use of a generator of air-ions and a ventilation system (Fig. 6).

n^-_{set} (a required concentration of air-ions) and current values of a pump speed and water temperature determine a working mode of the system. The main element is a control system that manages a certain set of subordinate devices in dependence on a given working mode and a signal of discrepancy from a comparison block. They include a ventilation installation, a pump unit (a drive unit) and an ultrasonic air-ions generator (a voltage regulator).

A temperature regulator receives a signal from U_{cot} system and manages working of a tubular electric heater by sending t_w control to it. In addition, the system controls working of a pump by a control signal of rotation speed v_p. A fan controlled by a frequency converter, which in turn receives the setting v_w – a control signal of the speed of a fan rotation, controls the airflow rate.
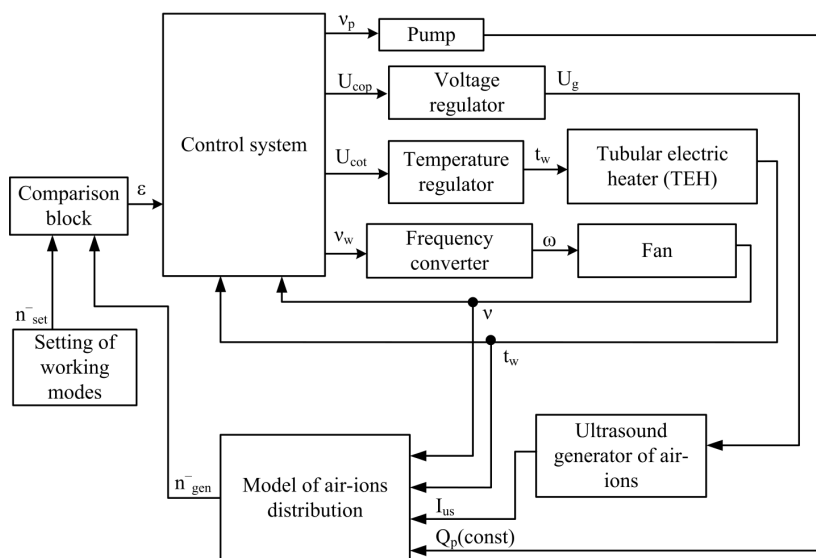

Fig. 6. Block scheme of the system for enabling the high-quality air-ionic mode at production premises with ultrasonic ionization of air

We should mark an ultrasonic air-ionic generator (UAG), which receives control influences U_g from a voltage regulator in this system of control of the quality of internal air. A voltage generator, in turn, receives U_{cop} setting from the control system. A value of a control signal depends on a task of a required number of air-ions in a task block.

We should note that the exact measurement of the amount of air-ions in real time shows significant technical difficulties. The system provides a model for the propagation of air-ions with corresponding parameters of measurement. These are an airflow rate, water temperature and voltage on UAG. An output of a model is actually a reverse signal. If, according to the experiments, to provide stabilization of some parameters (water supply, voltage to UAG, etc.), we will be able to simplify the control greatly and to use given rigid and/or flexible reverse bonds.

6. Discussion of results of studying the changes in a concentration of air-ions under the action of the balloelectrical effect and ultrasound

A change in the concentration of air-ions with a degree of mineralization of water (Fig. 1, a, b) occurs because, firstly, dipoles of water molecules create their own electric field, which contributes to a convective transfer of charges. In this case, a hydrated proton at the expense of the action of cavitation leaves its shell and gets to adjacent water molecules with formation of a new hydrated shell. Secondly, there is ionization of water molecules with absorption of heat due fluctuations of the electromagnetic field generated by oscillatory movements of water dipoles under the action of ultrasonic cavitation.

We should note that tap water contains components of weak and strong electrolytes, which is reflected on the oxidation-reduction potential of such a solution, especially on superficial films formed by the action of an ultrasonic wave. In this connection, a spatial transfer of H_3O^+ positive charge occurs in the electric field due to participation of associated molecular complexes in this process. Simultaneously with a use of ultrasound, the balloelectrical effect increases significantly.

In this case, electrical conductivity of water increases due to appearance of charged bubbles of oxygen, which creates conditions for formation of the electric-kinetic potential near a double electric layer, which consists of gaseous oxygen and hydrogen with surrounding H_3O^+ and OH^- ions.

Analysis of dynamics of changes in the concentration of air-ions in dependence on the salinity of water (Fig. 2, a, b), showed that the concentration of hydrated forms of both positive and negative ions, which forms the chemical composition of water, $-Me^{n+} \cdot nH_2O$, $A^{n-} \cdot nH_2O$, increases with an increase in water mineralization. It does give possibility for water molecules to be released to a surface and to atmospheric air due to the electrostatic interaction of positive and negative ions of dissolved salts and dipoles of water molecules. This, in turn, influences the mechanism of action of ultrasound on surface layers of the aqueous solution – we observe ultrasonic cavitation due to the dissolved gases, for example, oxygen, in the aqueous solution. Oxygen can transform as follows under given experimental conditions under the action of ultrasound energy:

$$O_2 \leftrightarrow O_2^+ + O_2^-. \qquad (1)$$

In turn, each of components forms an Oxygen radical and positively and negatively charged ion radicals with activation energies of 5.76 and 4.32 eV, respectively, which is quite realistic for ultrasonic cavitation conditions:

$$O_2^+ \rightarrow O^{\cdot} + O^+, \qquad (2)$$

$$O_2^- \rightarrow O^{\cdot} + O^-. \qquad (3)$$
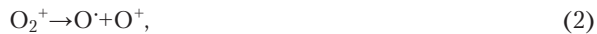
Obviously, a rapid decrease in the concentrations of negative and positive air-ions occurs according to the scheme at a distance up to 0.3 m (Fig. 3, *a, b*):

$$n^- + O^{+\cdot} \rightarrow n^o + O, \qquad (4)$$

$$n^+ + O^{-\cdot} \rightarrow n^o + O, \qquad (5)$$

$$O^{\cdot} + O^{\cdot} \rightarrow O_2. \qquad (6)$$

With an increase in a distance from a source of ultrasound, atmospheric oxygen promotes formation of negative and positive air-ions, not the oxygen contained in the aqueous solution. An increase in mineralization of water reduces a degree of formation of ion-radicals of oxygen because presence of salt ions at the cost of presence of hydrated complexes blocks the release of ion-radicals of oxygen.

In addition, the concentration of ultrasound energy occurs due to a small amount of aqueous solution, but its power is not enough to break chemical bonds in hydrated complexes and intermolecular hydrogen bonds in water molecules. Second, a number of unbound air-ions of both polarities increases in air with an increase in a distance from a source of ultrasound and mineralization of water. In this case, we fixed a change in electrical conductivity of solutions from 2.5 mS/cm for the concentration of 1.1 % to 7.5–8 mS/cm for a concentration of 4.4 % [23].

The analysis of studies on a change in the concentration of air-ions under the influence of air flow proved that the main effect is dynamic pressure of the air flow, therefore, water experiences a greater dynamic pressure at higher air velocity, that is a value of dynamic pressure is more than the force of tension of water, or external forces work against forces of adhesion of molecules. In this case, the surface layer molecules have a higher potential energy compared to inner layers ones. The action of ultrasound adds sound pressure. It contributes to the creation of areas, which alternate with discharge and increased pressure, on a surface of water. Then the condition for formation of air-ions in an air stream by the combined action of ultrasonic cavitation is

$$P_{ap} + P_{sp} > P_{tw}, \qquad (7)$$

where P_{ap} is the dynamic air pressure ($\rho v^2 / 2$); ρ is air density, kg/m^3; v is air velocity, m/s; P_{sp} is the effective sound pressure ($Z \cdot v_{\pm}$); Z is acoustic water resistance, Pa·s/m; $v_{\pm}$ is the mobility of water molecules, m/s; P_{tw} is the force of surface tension of water ($\sigma \cdot l$); σ is the coefficient of surface tension of water

$$\sigma = \frac{\rho \lambda^2}{4\pi^2} \left(2\pi v^2 - g \right);$$

λ is the wavelength of ultrasound; g is the acceleration of free fall; v is the frequency of a source of ultrasound. Then we can record the mathematical expression (7) in the general case as

$$\frac{\rho v^2}{2} + Z \cdot v_{\pm} > \frac{\rho \lambda^2}{4\pi^2} \left(2\pi v^2 \lambda - g \right) \cdot l. \qquad (8)$$

Consequently, we can state that formation of air-ions of both signs has a physical and mechanical nature for distilled water (without mineral impurities).

A nature of curves of a change in the concentration of air-ions by temperature of the aqueous solution (Fig. 4, *a, b*) is the same on the one hand, and on the other, the graph of changes in the concentrations of positive air-ions is a reflection of the graph of changes of negative air-ions. It differs in intensity of peaks only. We should emphasize also that an increase in temperature of the environment decreases viscosity of water and increases mobility of water molecules. As a result, intermolecular and internally molecular hydrogen bonds ....H–OH....OH–H...... weaken simultaneously. This facilitates formation of hydrogen-air-ions (H$^+$), hydroxonium-air-ions (H$_3$O$^+$ - hydrated form of hydrogen-air-ion) and hydroxyl-air-ion (HO$^-$).

Since the molecular weight of hydrogen-air-ion is 1 a.u. only, it is easier for it to reach a surface from interior layers of water. In connection with this, there is an increase in concentration at 20–25 $^{\circ}$C. The molecular mass of hydroxyl-air-ion is 17 a.u. It is necessary to spend more energy to release it from water. And we achieve this at the temperature of 42–45 $^{\circ}$C only.

Simultaneously, in the temperature range of 20–42 °C, we observe a gradual decrease in the concentration of hydrogen-air-ions and an increase in hydroxyl-air-ions. This is because with an increase in the temperature of water on its surface, actual molecules of H$_2$O appear on its surface and the process of "decomposition-recombination" begins.

$$H_2O + H^+ \rightarrow H_3O^+, \qquad (9)$$

$$H_3O^+ + OH^- \rightarrow 2H_2O, \qquad (10)$$

$$H^+ + OH^- \rightarrow H_2O. \qquad (11)$$

Consequently, temperature increases air-ionization of air in the production environment, and we achieve additional humidity of premises in conjunction with the phenomenon of ultrasonic cavitation, which contributes to an increase in the level of comfort for workers.

Analysis of the graphs of the concentration of air-ions at ultrasound treatment of distilled water by voltage on UAG (Fig. 5, *a, b*) showed that the concentration of negative air-ions increases almost in three times; in turn, the concentration of positive air-ions almost does not change. This is due to the mechanical-and-chemical nature of the occurring phenomena.

In this case, we can assume that there is a reorientation of water dipoles in a field of influence of voltage from UAG and mechanical disruption a at the same time – a breakdown of chemical bonds with formation of corresponding negative and positive air-ions. We can equate the effect of ultrasound to mechanical impact, since there is sound pressure on water medium and on chemical bonds simultaneously. In the field of application of mechanical forces – sound pressure – an airflow velocity (Fig. 3, *a, b*) and a level of energy output of molecules on a surface (an influence of temperature of the medium – Fig. 4, *a, b*) with the subsequent formation of negative and positive air-ions gain value. An increase in the value of UAG voltage is a counteraction to the processes of recombination of formed air-ions. Due to this, concentrations of negative and positive air-ions increase. After removal of pressure, the concentration of air-ions will be reduced

due to recombination and processes of chemical interaction with impurities contained in the air of industrial premises.

We should note separately that we performed the research in the absence of people and in the absence of technological equipment, which may affect a number and direction of distribution of air-ions in a working space of industrial premises. We can consider as a disadvantage a fact that we did not take into account changes in temperature and humidity conditions, which could affect concentrations of air-ions generated by UAG in a working area during performance of physical measurements. It is necessary to create a more powerful UAG to increase an air-ionic zone of comfort. The experimental research of the air-ionic mode in premises with ultrasonic air-ionization proved the expediency of synthesis of the mathematical model of interdependence of the considered physical factors and development of a holistic control system for their combined effect.

The development of the software and hardware complex of the automated control system of a ventilation system and an ultrasonic air-ionic generator will make possible monitoring and processing of information on technological, electrical and microclimatic parameters, adjusting, coordination of work and joint managing of devices of a ventilation system and an ultrasonic air-ionic generator.

7. Conclusions

1. An analysis of experimental data proved that the level of formation of air-ions decreases with an increase in water mineralization, as well as with an increase of a distance from a source of ultrasound. There is a simultaneous occurrence of the balloelectrical effect and ultrasonic cavitation due to the dissolved gases in mineralized water.

2. The study proved that the concentration of negative and positive air-ions increases with a decrease of the concentration of salts in water. Thus, we proposed to use demineralized water at a temperature of 20 to 25 °C and directed airflow at a speed of 6 m/s towards a working zone with a coupling effect of ultrasound and the balloelectrical effect to improve the quality of air in industrial premises, since formation of negative air-ions occurs more intensively under such conditions. This contributes to improvement of sanitary and hygienic working conditions.

3. Application of a small ultrasonic air-ions generator with a power of 10 W at a distance of 0.5 m with a use of distilled water increases the concentration of negative air-ions almost by six times. There is no generation of ozone and nitrogen oxides Due to the combined effect of ultrasonic cavitation on a surface layer of water and the balloelectrical effect. This creates a comfortable air-ionic composition of the air in a working area of industrial premises.

4. We proposed a structure of the system for provision of a high-quality air-ionic mode in a working area of industrial premises by ultrasonic air-ionization. It implements a combined change in fan speed and pump speed, a temperature mode of the aqueous solution and power of an ultrasonic air-ions generator.

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