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STUDYING THE DYNAMICS AND OPTIMIZATION OF AIR IONS MOVEMENT IN LARGE STORAGE ROOMS

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This study presents the results of the study of the dynamics of movement of air ions in large storage rooms. The main forces acting on the ions in the ionization zone, in the storage volume of fruits, and on the surface of the processed product, are determined to establish the ionization regimes and design of the discharge gap of the ionizer. Based on technological requirements, the distribution of air ions in the room was studied at various distances between the ionizers. An analysis of the stability of the ionization process made it possible to determine the stationary conditions of the process in the ionization zone. Based on the research results, the location of the ionizers in the fruit storage volume was optimized, and the parameters of the indoor air ionization technology were calculated.

KEY WORDS: *ions, optimization, efficiency, fruit storage*

1. INTRODUCTION

The Government of the Republic of Uzbekistan pays special attention to the development of infrastructure for the storage and processing of fruits and vegetables for uninterrupted supply of the population with fresh fruits and vegetables. In 2017, more than 250 enterprises for processing agricultural products were created and more than 130 cooled fruit storage facilities with a total capacity of 85,700 tons were built and upgraded (Mirziyoev, 2018a,b). However, during the storage of fruits and vegetables, losses remain significant. The use of electrotechnological methods of storing fruits and vegetables allows better storing the products of plant raw materials for a long time. At the same time, a consumption of electric energy by one ionizer for the entire storage season does not exceed 4–5 kWh. Cool storage chambers with a capacity of 10, 30, 50, and 100 tons were used to study the possibilities of using electrotechnological methods during long-term storage of fruits and grapes. Grapes, apples, quince, and other fruits were stored in an ionized air environment via ozone and chemical treatment (sulfur and sulfur compounds); fruit storage in containers of different capacities were also used, and good results were obtained (Chizhevsky, 1960). Similar studies were conducted in Japan, the United States, Russia, Slovakia, Georgia, and Kazakhstan (But, 1977; Feodorov, 1981).

In Japan, air ionization was used for smoking and long-term storage of meat. In Russia, it was used for storing potatoes and vegetables. Grapes and apples were stored in Moldova. When apples and oranges are stored in an ionized environment, a physiological deterioration of the product is reduced by 40% and 30%, respectively. In Chelyabinsk, potatoes, apples, tangerine, and other foods were stored with air ionization, and positive results were obtained. Tomato and cucumber were treated once a day for 1 h with negative ions and stored fresh for 40 days. In Belarus, negative ions were also used, and positive results were obtained, while the microbiological damage decreased by 20% hectares and the mass loss by 25% hectares. At the same time, commodity indicators and nutrients of products were well preserved (Rakhmatov, 2015).

Nevertheless, all the preliminary studies, which have been carried out in this field, are related to the determination of the effective physical parameters of the ionizer. It should be noted that uniform distribution over the plates is a necessary way to ensure effective storage of fruits. The optimization of the ionizers' position in places to increase the efficiency of product storage was not performed in previous studies.

The aim of this study is to determine the effective physical and regime parameters and the optimal placement of ionizers in order to increase the efficiency of product storage. The following tasks are solved to achieve the above-mentioned goal:

- define the technological requirements for electrical ionizers of the fruit storage process;
- obtain the dynamics of the distribution of ions in the room from the ionization zone to the processed product;
- find the optimal location of ionizers in the room to improve the quality and efficiency of the product storage;
- to study the uniformity of ionization of the storage chamber at various distances from the electric ionizers and obtain the distribution curves of the volume concentration of ions in the room.

2. METHODS

A combination of physical and computational experiments was chosen as the research method. During the physical experiment, the features of the distribution of ions in the room of an existing storage were studied, taking into account the location of the goods being stored and the presence/absence of ventilation system. According to the results, distribution curves of the volume concentration of ions were obtained.

During the computational experiment, the obtained empirical distribution curves of the volume concentrations were used to determine the optimal location parameters of the ionizers.

We used the ionizers developed by us to conduct a physical experiment, the circuit diagram of which is shown in Fig. 1.

The electroionizer contains a 10-kV power supply and electrode systems (Rakhmatov, 1981). The first electrode is connected to the source, and the second electrode to the ground. The ionizer electrodes are blown by a fan.

In the storage room, the relative humidity is maintained within 90%. The potential electrode has a negative polarity, and air is ionized by negative ions. Negative unipolar ions on the surface of the product creates an ionic layer of negative polarity, preventing loss of moisture and nutrients from the surface of the fruit (Fig. 2).

When storing fruits in an ionized air, electric forces act directly on biological objects, electric field energy acts without conversion to other types of energy, and the technological process is carried out with minimal losses. The technological process can work automatically. Electric discharge products do not have a negative impact on

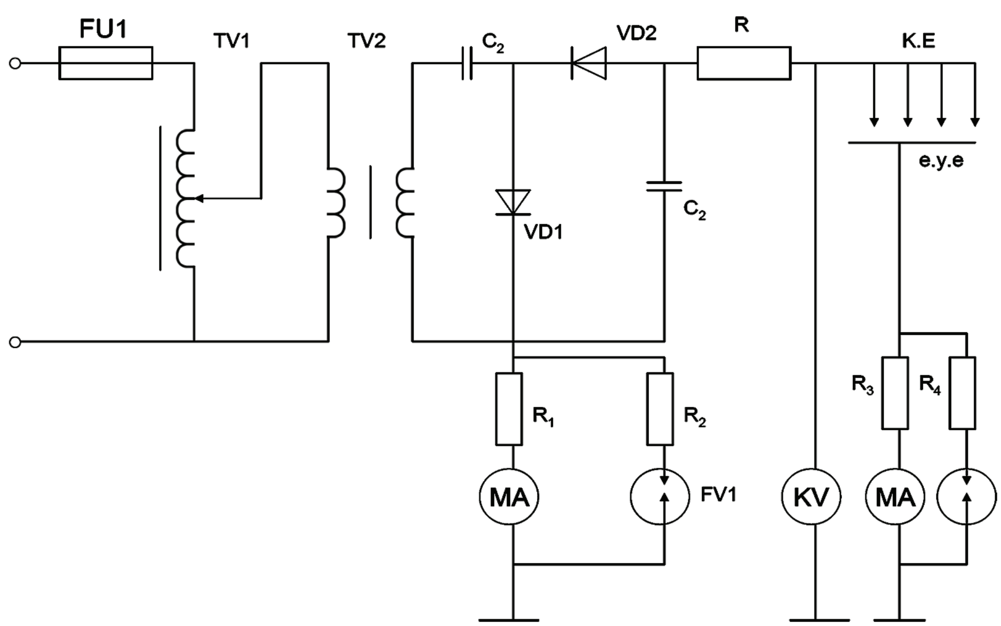

FIG. 1: Schematic diagram of the air ionizer: KE) discharge electrodes; e.y.e) grounded electrode; R) voltage divider; TV2) step-up transformer; TV1) autotransformer; FV) dischargers; mA — milliammeters, and kV — kilovoltmeter

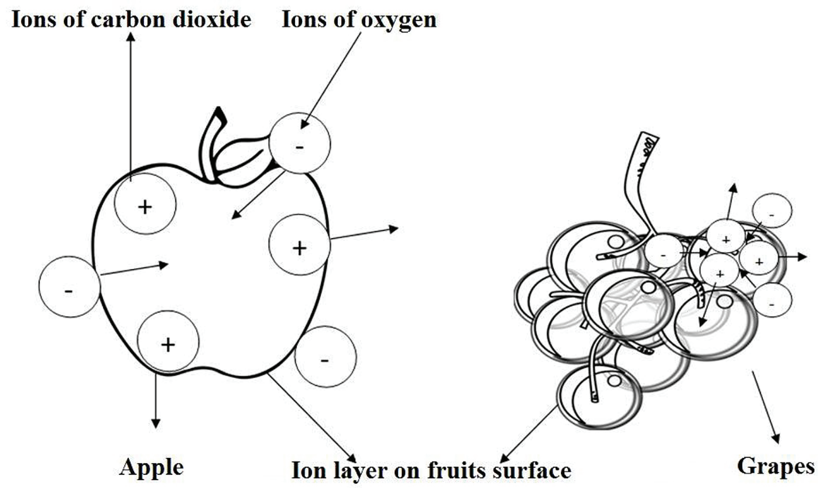

FIG. 2: Fruits of apples and grapes coated with negative ions from the surface

the environment; the stored product does not lose dietary and commercial qualities. In this case, the loss of moisture and nutrients of the fruits will be minimal (Muzafarov, 2016).

We used corona-discharge electric ionizers, which operate on the basis of ionization of neutral molecules of gases contained in air with a sufficient potential of electrodes with a strongly inhomogeneous field. Corona-discharge air ionizers can be successfully used when storing plant materials. They are distinguished by the simplicity of technology, low cost, are convenient to operate and can be implemented in various versions.

Muzafarov and Isakov (2017) and Popkov (1949) dealt with the questions of determining the design parameters of needle corona-discharge electrodes and their arrangement. They used ionizers to clean the air from pollution and to produce ozone. It is proved that corona-discharge electroionizers are most effective for air purification and for processing plant materials.

Discharge electrodes in a storage room can be located on top of stacks of boxes in the form of an antenna or can be hung in the form of garlands. At the same time, the product which is located at different levels is processed differently; ions are distributed unevenly throughout the room. For uniform ionization of air in large rooms, it is advisable to install ionizers in the ventilation system (Rakhmatov, 2017). In this case, the ions will be distributed in the room not only by the forces of the electric field, but also by the ventilation forces. Ions are distributed in the volume evenly and the processing of products is performed efficiently. In fruit storage, the ventilation system can be centralized, with one fan or distributed fans. The duct which is installed in the upper part of the room provides a uniform distribution of ions and does not interfere with the placement of the product. To increase the efficiency of the ionizers, they are installed on the ventilation holes of the duct (Fig. 3).

Ionization of air in the field of a corona discharge occurs at a sufficient voltage at the corona electrodes. A critical value of the corona-discharge electric field strength (i.e., when the air ionization process begins in the discharge gap) is determined by empirical expression depending on the electrode surface (Rakhmatov, 1981):

$$E_0 = 30.3\rho\left(1 + \frac{0.298}{\sqrt{\rho r}}\right), \quad 10^6\ \text{V/m} \tag{1}$$

where ρ is the relative air density, kg/m^3, and r is the radius of corona-discharge electrode, m.

The design and dimensions of the ionizer depend on technological requirements and parameters. The discharge electrode may be in the form of thin wires or needles. The best effect can be obtained with needle-shaped discharge electrodes. Needle electrodes have better mechanical properties and a less surface curvature.

When using needle electrodes, the degree of air ionization increases with increase in the number of electrodes; however, the number of needles is limited by the effect of mutual shielding (Vereshchagin, 1974). A mutual screening of the electric field of needle electrodes, besides weakening the ionization process, affects the dynamics of ions movement.

The physics of the formation of ions and their propagation between the electrodes of the ionizers are studied in detail and described by Leb (1950) and Deutch (1933). The basic equations for calculation are also given there.

When using ionizers in enclosed spaces, a processed product is at different distances from the ionizer. A processing efficiency depends on the uniformity and on the de-

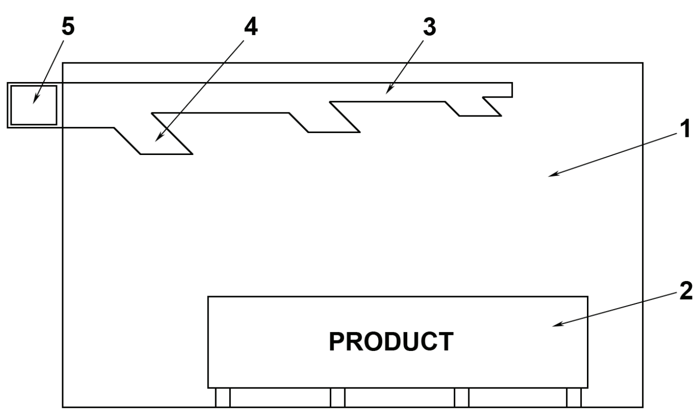

FIG. 3: The arrangement of ionizers in the fruit storage: 1) storage room; 2) stored product; 3) air duct; 4) air duct vents where ionizers are installed; 5) power supply for ionizers

gree of air ionization. A sufficient concentration of air ions should be created at each level of the product stackpiles.

When air is ionized in enclosed spaces, each air ion passes through three characteristic zones: ionization zone, dispersion field of bulk ions, and a processed product's surface area covered by an ionic layer. The nature of ions movement will be different in each zone. A highly inhomogeneous electric field exists in the ionization zone, the electric field strength will be higher than the critical one, and air molecules acquire a charge of a certain polarity and fly out to the outer zone. In this zone, the ions move mainly under the influence of electric forces. The dynamics of the ions movement will be sharply unstable. An electric wind is formed along the electric field force lines, which determines a direction of air ion movement. The electric field's force effect value on the ions (the Coulomb force) depends on the electric field intensity and the air ion's charge value and is determined from the following expression (Deutch, 1931):

$$F_k = Eg\ . \tag{2}$$

The ion is also affected by its own gravity:

$$F_q = mg\ . \tag{3}$$

Due to the nonuniform distribution of ions in rooms, a charged particle with a dielectric constant ε_0 is affected by the electric field force of a space charge with intensity E:

$$F_e = 2\tau\varepsilon_0 a^2 \frac{\mathrm{c} - 1}{\mathrm{c} + 2} \text{ grad } \mathrm{E}^2 . \tag{4}$$

The ions are influenced by the medium resistance force depending on the shape and dimension. If a form of the particle is taken as spherical, this force is determined from the following expression:

$$F_m = -6\pi\mu\vartheta\alpha^2 . \tag{5}$$

The medium resistance force, also called ventilating, occupies a significant place in the movement and distribution of charged particles in the storage room volumes. Herewith, a force value depends on the medium Reynolds number. This number is determined from the expression below:

$$R_n = vl/\gamma\ , \tag{6}$$

where v is the velocity of charged particles, l is the characteristic size of a charged particle, and γ is the kinematic viscosity of the medium.

A kinematic viscosity of the medium has a value of $0.136 \cdot 10^{-4}$ m^2/s at the air pressure $P = 1.013 \cdot 10^5$ Pa and temperature 0°.

For small air particles, if they are not taken as balls, the Reynolds number is assumed to be Re < 0.5. In this case, more accurate results can be obtained from the following expression:

$$F_e = -6\pi\mu\alpha\gamma \frac{1}{1 + A_k l_m / a}, \quad (7)$$

where l_m is the charged particle's free path determined from the kinematic viscosity of the medium.

The length of the charged particle's free path will be $0.942 \cdot 10^{-5}$ cm at the air pressure $P = 1.013 \cdot 10^5$ Pa and temperature 20°C. The value of A_k depends on the state of the particle surface; for a smooth surface $A_k = 0.86$.

With a large range of Reynolds number variation, the formula for the medium resistance force to the movement of a particle is expressed as follows (Vereshagin, 2008):

$$F_e = -6\pi\mu\alpha\gamma \left(1 + \frac{3}{16}\,\text{Re}\right). \quad (8)$$

With this expression, with Reynolds numbers Re ≅ 0.5–1, it is possible to obtain results with minimal errors ($\delta \leq 5\%$). If Re increases, the errors will grow. Therefore, the last expression will be acceptable when the Reynolds numbers Re < 1.

The dynamics of the ions movement is determined from the following expression:

$$v = \frac{E_q \left(1 + A_k \dfrac{l_m}{a}\right)}{6\mu\alpha\pi}. \quad (9)$$

3. RESULTS AND DISCUSSION

The use of ionized air in various technological processes is predetermined by the fact that the process is easy, with low energy costs and ease of operation. The operational parameters of air ionization are determined by the design of the ionizers and the power supply features of the electric ionizer. A variety of power sources were used in this study: positive, negative, industrial frequency current, pulsed and increased frequency current. Optimal discharge parameters were determined for each type of current (Vasyaev and Vereshagin, 2001). When processing live plant raw materials and when it is necessary to create unipolar ions, the best results are obtained with negative ionization of the electric ionizer for fruit storage facilities (Vereshagin, 2008).

Figure 4 presents the experimental and analytical results of the potential distribution in the outer zone of the corona discharge and the space charge density in the room. The deviation of the analytical and experimentally obtained results from the electric field parameters of the corona discharge does not exceed 3–5%. When the space charge density in the electric field's outer zone of the corona discharge is

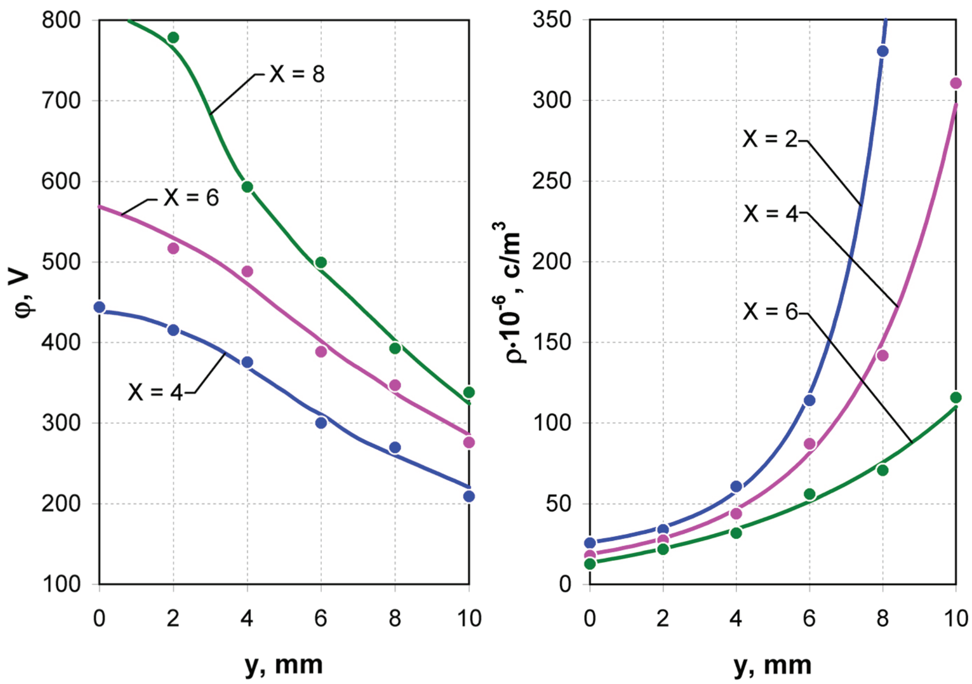

FIG. 4: Distribution of electric field potential and space charge density in the outer zone of a corona discharge, *x*, *y*) coordinates of the electric field

10^{-6} k/m^3, air ions volume concentration was in the range of 10^{14} ion/m^3 (Figs. 4 and 5) which is enough for the fruits storage technologies in an ionized air environment in the conditions of fruit storage facilities of the Republic of Uzbekistan. The results correspond to the calculated values of the electric field parameters of the corona discharge (Vereshagin, 2008; Rakhmatov, 2015). Thus, the potential distribution and the electric field strength were obtained.

The distribution of the electric field strength with distance from the ionizer was also determined experimentally and calculated analytically (Fig. 5).

A preliminary evaluation study of the optimal location of the ionizers made it possible to determine that the distance between them is recommended within 2.0–2.5 m. It is also seen from Fig. 6 that the installation of ionizers in the ventilation system is more effective to achieve greater uniformity of air ionization in large rooms.

However, it was necessary to perform more accurate studies to find the optimal location of the ionizers in the room.

Since the electrical characteristics of the ionization system obtained in the experimental study satisfied the basic requirements for the design parameters, optimization of the ionizers' location should be performed by the value of the concentration of ions at different points in the room.

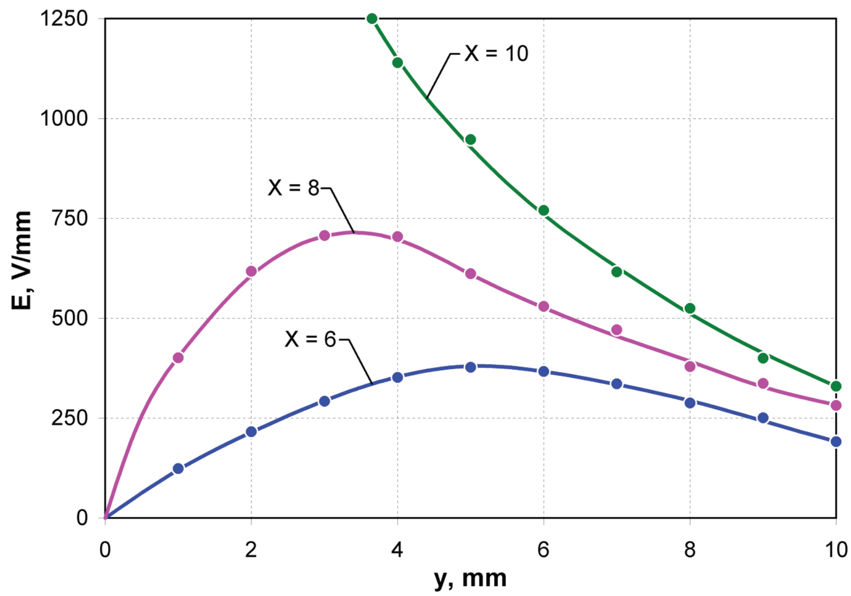

FIG. 5: The distribution of the electric field in the outer zone of the corona; *x*, *y*) coordinates of the electric field

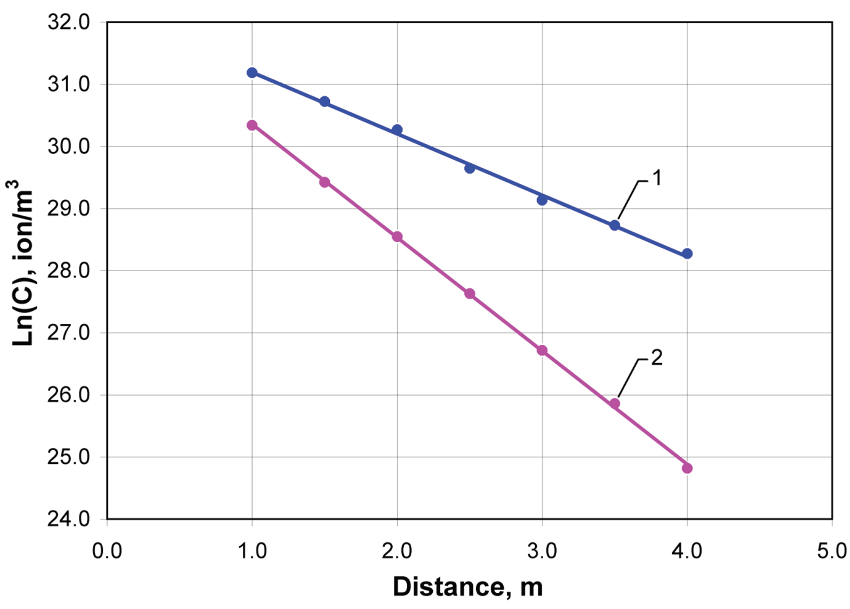

FIG. 6: The distribution of the concentration of the space charge of ions in the room: *n*-concentration of space charges: 1) with ventilation, 2) without ventilation

The main requirements for the space charge concentration parameter are:

- exceeding the minimum acceptable value — 10^{12} ions in 1 m^3 of air volume;
- the maximum uniformity of the distribution of ions in the volume of the room.

This requirement is important, because with an uneven distribution of ions, an increase in the intensity of respiration and metabolism of fruits is possible, where the concentration of ions is insufficient according to the requirements of the technology of storage of fruits. The movement of ions is always accompanied by collisions with gas molecules and loss of charge, as a result of which, the total ion concentration decreases during the movement.

To conduct a computational experiment, the data obtained from the physical experiment on the distribution of ion concentrations were approximated by empirical dependences. The dependences for curves 1 and 2 in Fig. 6 are represented by the following empirical equations:

$$C = e^{32.1803 - l \cdot 0.9888} \text{ – in the presence of ventilation,} \quad (10)$$

$$C = e^{32.1803 - l \cdot 1.8244} \text{ – in the absence of ventilation.} \quad (11)$$

For approximation, exponential distributions were used, which are in good agreement with the physical meaning of this distribution. In this case, it is allowed to use empirical equations outside the range of experimental data in which they were obtained. In our case, it is necessary to calculate the ion concentration at distances significantly exceeding 4 m (Fig. 6), which limited the conditions of the physical experiment.

The obtained empirical dependences were incorporated into the calculation of ion concentrations.

When installing several concentration ionizers at a given point in space, the simultaneous operation of all ionizers is determined. In the first approximation, the assumption was made that the concentration of ions during the simultaneous operation of several ionizers can obey the law of superposition—summation. This assumption is physically explainable, since identically charged air ions do not enter into interaction reactions between themselves and, thus, do not change their quantity as a result of the reaction.

The one-dimensional approximation was used to calculate ion concentrations. Since ionizers in real conditions are installed on the same line along the power cable (Fig. 3), in this case, the calculation can be performed according to the scheme presented in Fig. 7.

Using this scheme, dependences (10) and (11) and the assumption of superposition of concentration, the field of ion concentration was calculated for rooms of different lengths and at different heights from the floor. The data were selected as close as possible to the actual storage parameters: room length 14–22 m, the height of the ionizers from the floor is 3 m, the calculated points were located at a height of 0.2 m from the floor — 2.5 m.

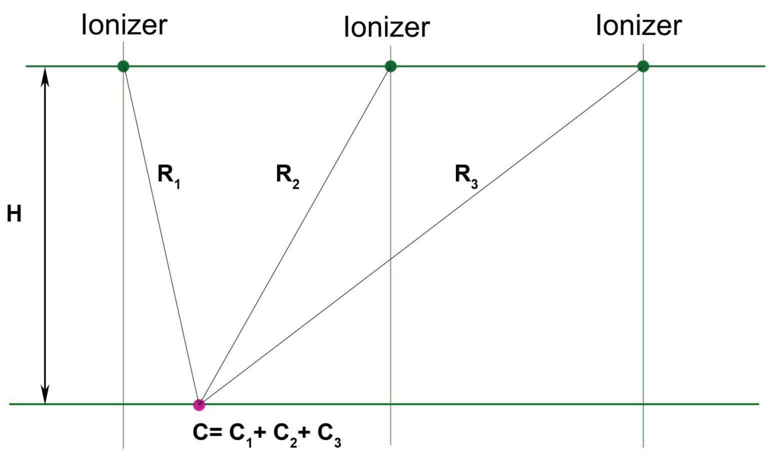

FIG. 7: The scheme for calculating ion concentrations: H, height from the calculated point to the line of location of the ionizers; R_i, the distance from the calculated point to the corresponding ionizer

During the calculation, the number of ionizers and the distance between them were changed taking into account the room size as well. In this case, distribution of ionizers along the length of the room was chosen to be uniform.

The level of ion concentrations was insufficient for the storage conditions due to the absence of ventilation; hence, we consider only the cases of arrangement of ionizers in the ventilation ducts.

The calculation results are shown in the figures below.

A significant nonuniformity of concentration is clearly seen when approaching the line of location of the ionizers (3 m) (Fig. 8). The greatest volume concentration of ions is at the exit from the ventilation openings (Fig. 8). The uniformity of ionization is also quite high. With distance, the ion concentration gradually decreases. However, under the influence of ionizers in the volume of the room, a cloud of space charges is formed which penetrates to each processed product. The uniformity of fruit processing with an increase in the distance between the ionizers of more than 2.5 m does not meet the requirements of the fruit storage technology. With increase in ionizers, the distance between them decreases, the processing of the storage product is more uniform. However, when the distance between the ionizers is less than 2.0 m, the change in the volume concentration of ions becomes insignificant (three lower curves). This is due to the effect of mutual screening of air ions.

The comparison shows a significant dependence of the level and uniformity of the concentration field on the distance between the ionizers (Fig. 9). The uniformity parameter was chosen to determine the uniformity, which is the ratio of the minimum concentration level at a given height along the length of the room to the maximum concentration value at the same height along the length of the room.

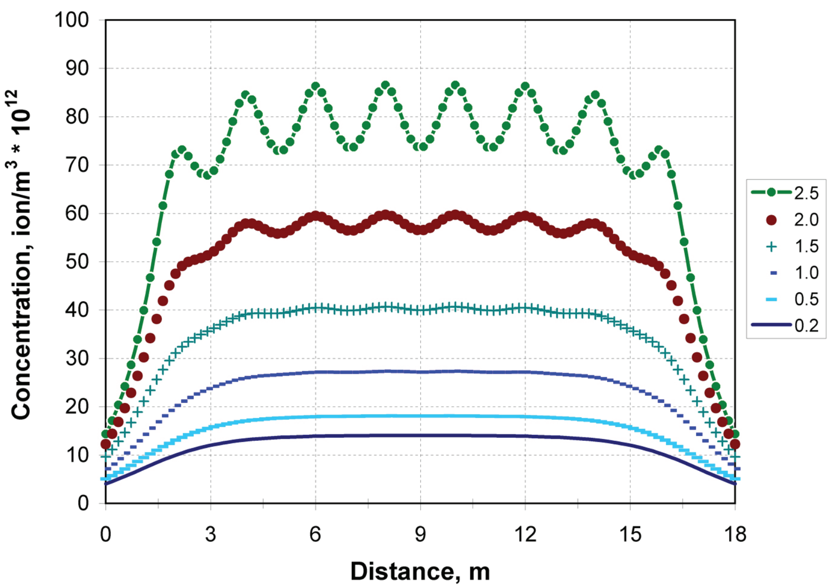

FIG. 8: The concentration distribution for the room with a length of 18 m with a distance between the ionizers of 2 m; designations 0.2–2.5 refer to the height in meters above the floor (the number of ionizers 8 pcs)

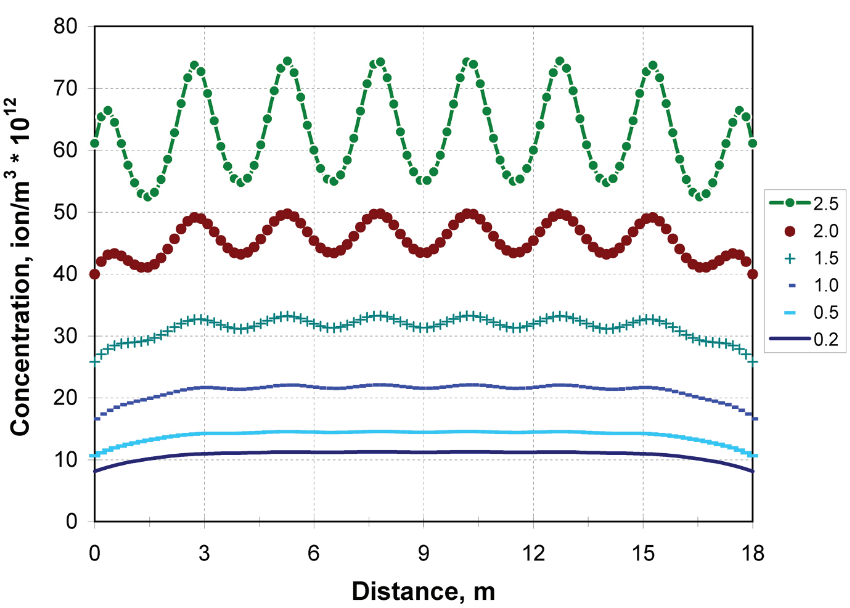

FIG. 9: The concentration distribution for a room with a length of 18 m with a distance between ionizers of 2.5 m, designations 0.2–2.5 refer to the height in meters above the floor (the number of ionizers 8 pcs)

The results of a computational study of the uniformity dependence on the distance between the ionizers with the same number of ionizers are shown on the example of a room which is 18-m-long.

Figure 10 shows that with increasing distance between the ionizers, the uniformity increases. However, for a given number of ionizers, it is impossible to increase the distance between them more than the upper limit, which is determined by the length of the room.

Studies have also been performed on the effect of the number of ionizers at the same distance between them, taking into account the uniformity of the field of the volume concentration of ions in that the electric and ventilation forces on the surface of the product are inferior to the forces of dispersion of the space and surface charges.

Thus, in a fruit storage room with a certain length, the number and distance between the ionizers are simultaneously influencing factors. For instance, with increase in the number of ionizers, uniformity increases, but with correct selection of distance one can do with a smaller amount—a comparison of 10 ionizers and 2.0-m step between them, and 8 ionizers and 2.5-m step. It is important to note that the ionization zone of one ionizer is about 2.0–2.5 m (Fig. 11). Therefore, when the ionizers are located less than 2.0 m, the space charge of the ionizer covers the ionization zone of adjacent ionizers and does not give an additional effect of the uniform distribution of air ions in the volume and the safety of the fruit.

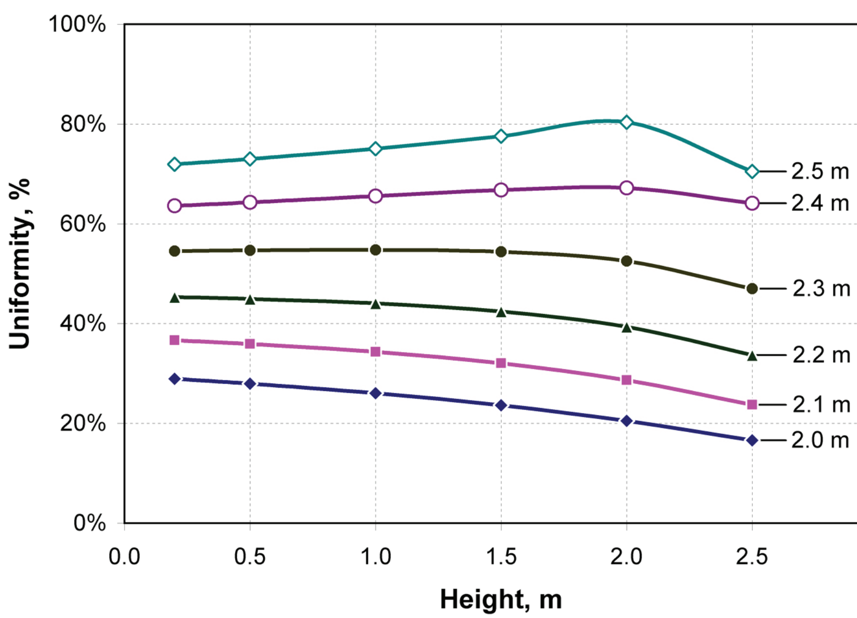

FIG. 10: The length of the room is 18 m, the number of ionizers is 8, the distance between the ionizers is indicated near the curves, *X* axis, height from the floor

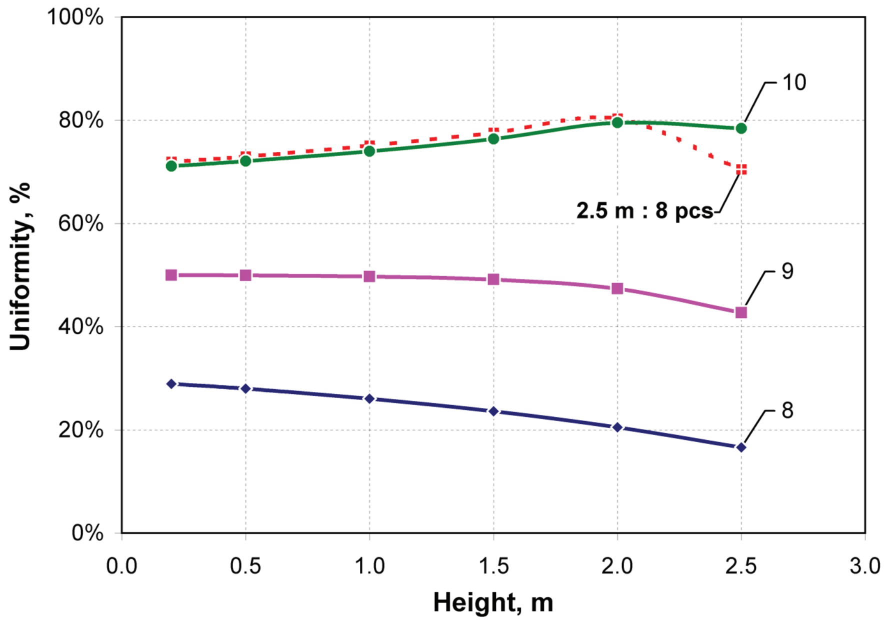

FIG. 11: The length is 18 m, the distance between the ionizers — solid curves 2 m, the dashed curve 2.5 m, the number of ionizers 8, 9, and 10 is indicated near the curves

Since this fact was discovered, a search was made for the optimal values of the number of ionizers and the distance between them for rooms of different lengths. As can be seen from the two previous figures, the level of uniformity also changes for different heights from the floor: uniformity = *f* (height, *D*, number). Here, *D* is the distance between the ionizers, number is the number of ionizers. Since the minimum level of uniformity is a critical parameter, optimization was reduced to finding such *D* for a given length of the room and the number of ionizers at which the highest value of uniformity was achieved among all the calculated heights from the floor.

Figure 12 shows the dependences (for each case) of the uniform distribution of ions in different rooms with different numbers of ionizers at an optimum distance between them.

It can be seen from Fig. 12 that the number of ionizers should also be optimal. With a change in the number of ionizers from 6–7 to 8–10, the intensity of ionization and uniformity of processing of the product increases, and a further increase in the number of ionizers does not significantly change the uniformity of ionization.

Figure 13 shows the dependence of uniformity on the distance between the ionizers for different rooms. There is an optimal distance (everywhere there are inflection points). In the Republic of Uzbekistan, fruit storages are being built with a small

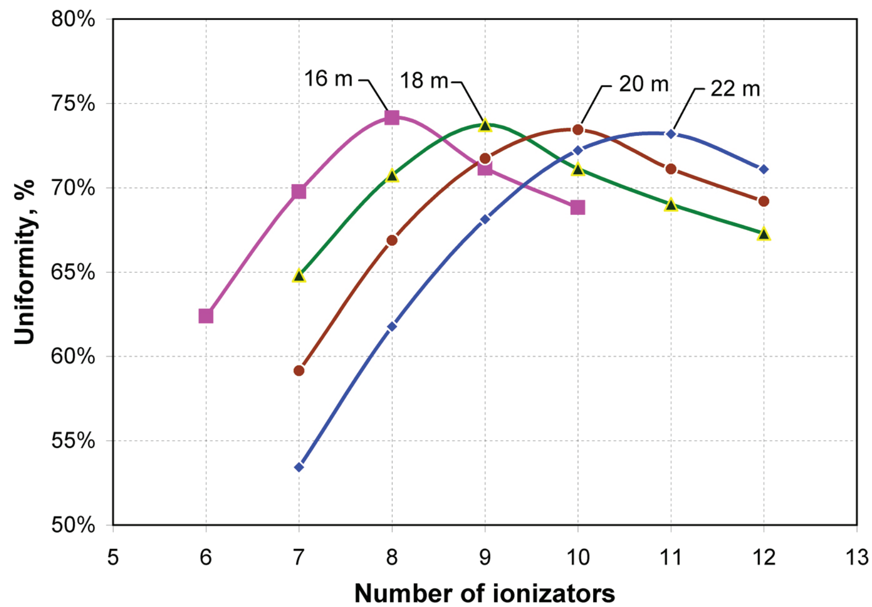

FIG. 12: The dependence of uniformity on the number of ionizers for different rooms

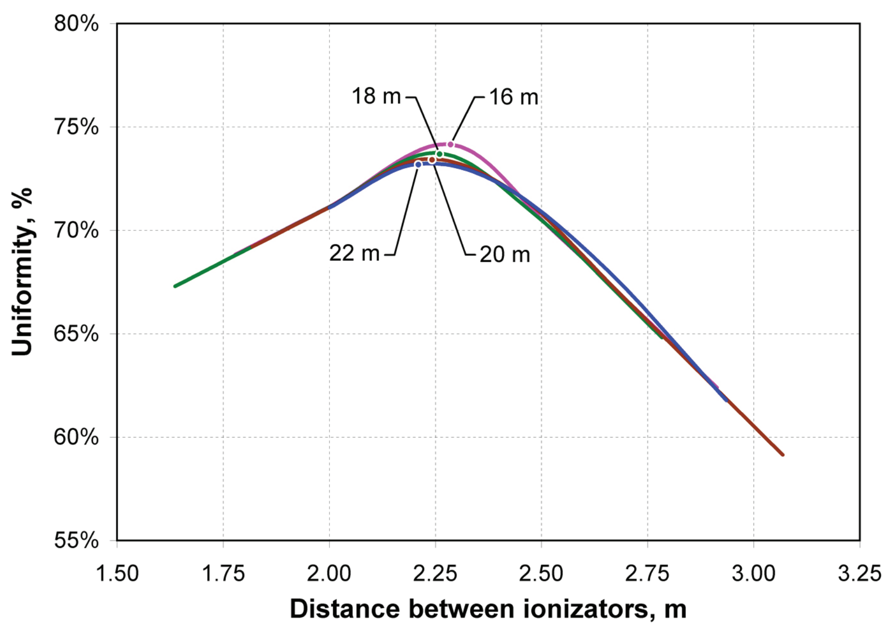

FIG. 13: The dependence of the concentration field uniformity on the distance between the ionizers for rooms of different lengths

volume of 10 to 100 tons of capacity. The length of storages in the study varied from 12 to 24 m. With this length of premises, the number of ionizers varies from 6–8 to 12 pcs. In each case, the optimal number of ionizers corresponds to a distance between ionizers of 2.0–2.5 m.

The obtained data can be generalized by the dependence of the optimal distance between the ionizers on the length of the room in the range from 14 to 22 m when installing ionizers at a height of 3 m from the floor in the supply ventilation ducts. In this case, the number of ionizers should also be chosen optimal. Thus, the selected ionizers are located at distances from each other within 2.0–2.5 m, while the uniformity of the ionization of the storage chamber within 75%.

The dependence of the optimal distance between the ionizers on the length of the room is presented in Fig. 14. The longer the length of the room, the smaller the distance between the ionizers. For example, if the room length is 12 m the distance between the ionizers is 2.5 m, with a length of 24 m, the optimal distance between the ionizers becomes 2.15 m. This is due to the increase in the storage volume. It becomes more difficult to obtain the effect of uniformity of volume ionization and the distance between the ionizers is reduced.

This result is in good agreement with the data of a physical experiment in which it was found that the optimal distance between the ionizers is in the range from 2.0 to 2.5 m. However, numerical calculation allowed more accurately determining the value of this quantity.

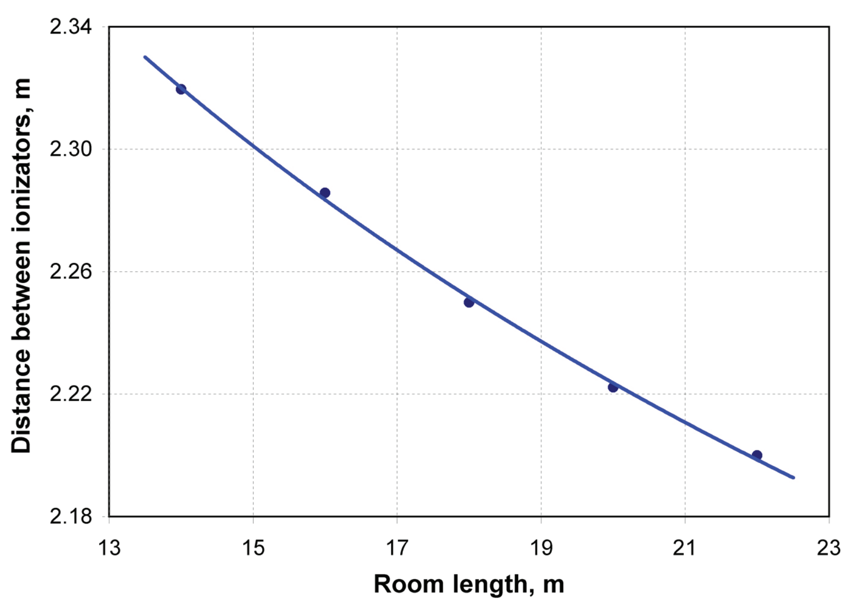

FIG. 14: The dependence of the optimal distance between the ionizers on the length of the room

4. CONCLUSIONS AND RECOMMENDATIONS

1. During the air ionization process of fruit storage by electrical ionizers, the air ions (on the way from the ionizer to the processed product) pass through three characteristic zones: ionization zone, scattering field of volume charges inside the room, and a covered zone by an ionic layer of the product surface. These zones differ sharply from each other, have different dynamics parameters of their alteration, and it is required to study them separately.

2. In the ionization process, air ions are affected by the forces that determine the nature of ions movement: electric field force of a corona discharge, force of gravity, electric field force of the volume charge, medium resistance force to the ion movement and electric field force of the ionic layer on the fruit surface.

3. Thus, in a fruit storage plant with a certain length, the number and distance between the ionizers are simultaneously influencing factors.

4. The greater the length of the room, the smaller the distance between the ionizers. This is because with an increase in the storage volume, it becomes more difficult to obtain the effect of uniformity in the ionization of the volume and the distance between the ionizers is reduced.

5. According to the results from studying dynamics of ions movement in large storage rooms and taking into account the technological requirements of the air ionization of fruit storage facilities, the electric ionizers' design and operating parameters for fruit storage facilities in the Republic of Uzbekistan were developed.

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