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Window with Electrostatic Protection against Dust, Smoke, and Viruses

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***Abstract*—The article analyzes the effect of dangerous aerosols on the human body. In order to purify the air from aerosols, the effect of an electric field on them is considered. The electric and dielectrophoretic forces acting on submicron particles in an inhomogeneous electric field of two parallel wires are calculated. It is shown that part of this field is identical to the field between the wire and the grounded plate electrode located in the middle between the wires. This allows using a known formula for the electric field of a two-wire line to calculate the field gradient and the effect of dielectrophoresis on neutral particles. Smoke and dust particles already carry a negative charge, and a more or less uniform electric field is enough to move them. To filter neutral water droplets infected with the virus, you need either a field with a large gradient or a corona discharge. The paper shows that the polarization of particles in an electric field causes the particles to stick together, and larger particles settle faster on the electrodes of the filter. The design of a transparent electrostatic precipitator is proposed, which can be used to protect indoor air from external smoke, dust, or viruses.**

Keywords — electrostatic precipitators; dielectrophoresis; corona; particle charging; aerosols; breakdown voltage; public healthcare.

I. INTRODUCTION

In recent years, air quality, which determines human health, has periodically deteriorated. Global climate changes on the planet lead to frequent forest fires and dust storms. Added to these disasters is the unprecedented SARS-CoV-2 pandemic. In all these cases, aerosols carrying smoke, dust, or viruses are a risk factor for humans.

Air pollutants are gases and particles of inorganic and organic origin. The air of the premises in which a person spends most of his life significantly affects the quality and duration of life. Air pollution kills over 7 million people annually, with 3.8 million deaths (mainly women and children) associated with the burning of solid fuels and kerosene in domestic stoves [1]. In 2020, over 1.5 million people became victims of coronavirus infection.

More than four decades ago, it became known about the dangerous exposure of medical personnel to surgical smoke generated during electrosurgical and laser procedures [2]. The SARS-CoV-2 coronavirus pandemic has led to a surge in research aimed at studying the effect of nanoparticles on the human body. Aerosols have proven to be potential carriers of viruses, bacteria, and toxic organic compounds.

To protect the human respiratory system from hazardous aerosols, air filters are used - from the simplest cloth masks to complex multi-stage filtering systems. There are three main methods of air purification - mechanical, electrical, and chemical.

Mechanical air filtration is carried out through fibrous, membrane, cloth, and granular filters. Usually, the air is first pre-filtered from particles larger than 2.5 μm, and then the air is filtered from smaller particles. The best in this ratio are HEPA filters with 99.99% efficiency for 0.3 μm particles and ULPA filters capable of intercepting 99.999% of 0.1 μm particles [2]. These filters are folded "accordion" sheets of fibrous material (thin paper or fiberglass), through which air is pumped using fans. For nanoparticles, the electrostatic interaction of particles with the filter material plays a significant role.

In the most advanced systems, after mechanical air purification, chemical purification is also carried out by passing air through an activated carbon filter, which absorbs gases of high-molecular organic compounds with its pores. To filter low molecular weight compounds, chemisorbents (aluminum oxide and silicate, potassium permanganate) are used, which bind water molecules with gas molecules and decompose the latter into harmless substances. Another type of chemical filtration is the photocatalytic decomposition and oxidation of toxic aerosols on the catalyst surface under the action of ultraviolet radiation.

Electrical filtration usually involves the electrification of aerosols using a corona discharge (electrostatic or pulsed), ignited on wire or needle electrodes with a voltage of the order of ten kilovolts, and the subsequent deposition of charged particles on the plate electrodes. In synthetic air filters, electrostatically charged synthetic fibers with a diameter of 0.01–100 μm are used, on which

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a charge can be applied by a triboelectric or induction method, or using a corona discharge [3].

The high voltage of the corona electrodes in electrostatic filters leads to the generation of ozone, which at high concentrations causes inflammation of the airways. For electrostatic filters, the requirement for ozone generation is not higher than 0.05 ppm.

The airflow at the inlet surface of the filter usually has a velocity of the order of 0.1 m/s. The input stream can contain both electrically charged particles and uncharged ones. Charged particles appear in the atmospheric air near the Earth's surface due to their ionization by cosmic radiation, high-energy protons that appear during solar flares, and the decay products of radioactive radon contained in soil, granite, and water. During the period of calm Sun, the main ionizer of the surface air is radon-222, which has a half-life of 3.8 days. The rate of radon ionization strongly depends on weather conditions and terrain and can vary within wide limits, reaching values of the order of 10 ions$\cdot$cm$^{-3}\cdot$s^{-1} [4].

It has long been known that dust and smoke particles less than 2.5 μm in size have a detrimental effect on the human body. If larger particles are intercepted by the nasopharynx and bronchi and excreted from the body with a runny nose and cough, then smaller particles penetrate deep into the lungs, causing the release of reactive oxygen species by the cells of the alveoli and oxidative damage to the lungs. This provokes the development of severe forms of pneumonia and cardiovascular diseases [5].

II. ANALYSIS OF AEROSOLS AS POTENTIAL CARRIERS OF VIRUSES

Aerosols are predominantly solid or liquid dielectric particles. Airborne solid particles or water droplets are potential carriers of viruses. Aerosols that pose a threat to human health are submicron particles of smoke, dust, and water droplets with organic substances dissolved in them. Consider how viruses can spread in the air.

Infected water droplets. Research into the spread of respiratory droplets through the air is over 120 years old. Until the 40s of the last century, such parameters of respiratory droplets as size, velocity, times of evaporation and settling, as well as propagation distance were mainly investigated. The results of these studies were analyzed and summarized in [6]. According to these studies, 95% of respiratory droplets are in the range of 2–100 μm, with the most common droplets being 4–8 μm in diameter. In the process of settling, water evaporates, and droplet cores are formed, 97% of which are in the range of 0.25–12 μm, most often 1–2 μm. The settling time of 90% of the droplet nuclei ranges from 30 to 60 min, but the smallest nuclei can remain in the air for up to 30 hours [6].

Modern studies show that in a sick person the size of water droplets produced during breathing, talking and coughing varies within 0.05–10 μm, in a healthy person – in the range of 0.1–16 μm [7].

The droplet cores are 20–34% smaller than the original respiratory droplets. Droplet nuclei contain electrolytes, sugars, enzymes, DNA, epithelial debris, and white blood cells. The density of the nuclei is approximately 1.3 g/cm^3 [8].

Smoke particles. The main sources of smoke are thermal power plants, various industrial furnaces that burn fuel, internal combustion engines, forest fires and active volcanoes. The permissible level of particulate matter emissions from thermal power plants is 30 mg/m^3. In addition to solid particles, smoke also contains combustion gases. These gases are especially dangerous in indoor fires.

Dust particles. The most powerful source of dust is dust storms arising from soil erosion in desert and steppe regions and sometimes having global consequences. Coal dust appears in mines during coal mining, and has long been the cause of premature deaths of miners.

Pollen grains. Recent studies have shown that during the flowering period, pollen from plants can also carry the coronavirus. For example, willow pollen, which grains are about 30 μm in size, even at a wind speed of 1.1 m/s, will cover in 1 minute a group of about 100 people, located within 20 to 40 m from the willow [9]. Even with a social distancing distance of 2 m, the presence of people with coronavirus in a group can lead to infection of a significant part of the group. Note that the effect of pollen on the human body has been studied mainly from the point of view of allergic reactions (during the flowering period, only in the United States, hay fever affects 20 to 40 million people). Most grasses have pollen with a grain size of 20–30 μm, and the wind can also lift them into the air and turn them into potential carriers of the coronavirus.

Viruses and bacteria. Viruses and some types of bacteria are in the range of 10–300 nm [10]. Viruses are dielectric particles that can adhere to electrified particles of air pollutants. 1 m^3 of air can contain up to 10^5 such particles [11]. The density of many viruses is approximately 0.5 g/cm^3.

The viroid Covid-19 has a size of 125 nm and its carriers can be not only water droplets in the breath of a sick person but also nanoparticles of dust or smoke, including cigarette smoke.

III. ELECTRIZATION OF AEROSOLS

Electrostatic air filtration requires the electrization of uncharged particles using ionizers. Some aerosols already carry a positive charge and do not need ionization. These include aerosols such as dust, cigarette smoke, pollen, mold spores, and bacteria.

In good weather, 1 cm^3 of air at sea level contains 2000–3000 ions of both polarities. During a thunderstorm, the number of negative ions can increase up to 14000, and positive – up to 7000. Smoking one cigarette indoors can reduce the number of negative ions to 10–100 [12].

There are several mechanisms for the electrization of aerosols. Let's analyze their natural and artificial sources.

Radioactive decay. The decay products of radioactive radon-222 are the main ionizer of the near-surface air during the quiet Sun period. Radon-222 has a half-life of 3.8 days and is found in soil, granite, and water. The rate

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of radon ionization strongly depends on weather conditions and terrain and can vary within wide limits, reaching values of the order of 10 ions·cm^{-3}·s^{-1} [4].

Solar flares and cosmic radiation. Charged particles appear in the atmospheric air near the Earth's surface due to their ionization by cosmic radiation and high-energy protons that appear during solar flares.

IV. CORONA DISCHARGE

One of the methods for transferring charge to neutral dielectric particles is the excitation of a corona discharge in air. For a corona discharge to occur in air, the electric field near the electrode must be inhomogeneous and exceed the value of the dielectric strength of air under normal conditions, i.e. 3 kV/mm. To create such a field, electrodes in the form of a thin wire or a tip are usually used. In electrostatic air filters, a corona discharge is usually ignited between the wire cathode and plate anodes by applying a potential difference in excess of 10 kV across them. Primary ions located near the cathode are accelerated by a strong electric field and cause the impact ionization of air molecules and particles, contributing to the development of electrical breakdown of air near the cathode. In this case, the generation of ozone is an undesirable effect.

To determine the electric field between the wire and plate electrodes, we first consider a symmetric electrode system of two parallel wires of diameter w, separated by a gap $2D$. The electric field of a single wire of length L carrying a charge Q decreases in inverse proportion to the distance z [13]:

$$E_w = \frac{Q}{2\pi\varepsilon_a\varepsilon_0 L z},$$

where ε_a and ε_0 are the dielectric constant of the air and the electric constant.

The field between two parallel wires at a distance $2D$ at a constant voltage U is the vector sum of the fields of the individual wires. Taking into account that, we have

$$\begin{aligned} E &= E_{l1} - E_{l2} = \\ &= \frac{Q}{2\pi\varepsilon_a\varepsilon_0 L(z+D)} - \frac{-Q}{2\pi\varepsilon_a\varepsilon_0 L(z-D)} = \\ &= \frac{CUz}{\pi\varepsilon_a\varepsilon_0 L\left(z^2-D^2\right)}. \end{aligned} \qquad (1)$$

Such a system of electrodes has a capacitance [13]

$$C = \frac{\pi\varepsilon_a\varepsilon_0 L}{\ln(2D/w)}.$$

Substituting this expression into formula (1), we obtain

$$E(z) = \frac{Uz}{\ln(2D/w)\left(z^2-D^2\right)}. \qquad (2)$$

The distribution of the electric field between wires with a diameter of w = 0.05 mm at a distance between them $2D$ = 20 mm and at different voltages U on them is shown in Fig. 1. The choice of voltages for determining the electric field near the wires will become clear from the subsequent analysis.

In the middle between the wires, at the point z = 0, the field strength takes on a zero value. If you place a grounded plate electrode at this point, then the type of field will not change, and the potential difference between the wire and the electrode will become equal to $U/2$.

Fig. 2 shows the distribution of the same electric field as in Fig. 1, but in this case, it is the field between the wire and plate electrodes, in the immediate vicinity of the corona wire. The plate electrode is placed in the plane of the zero potential of the electric field shown in Fig. 1.

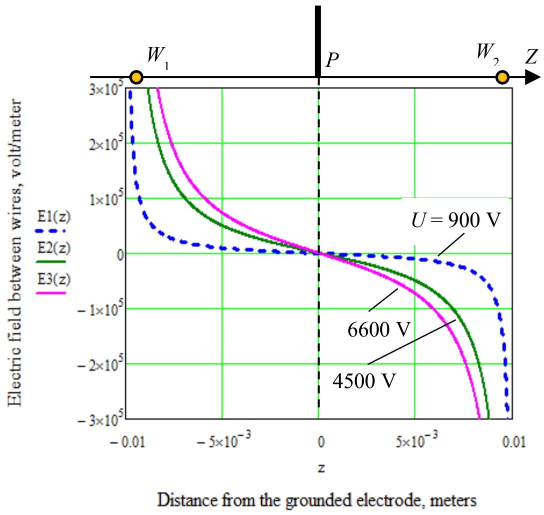

Fig. 1. The electric field between parallel wires $W1$ and $W2$ with a diameter of 50 µm, located at a distance of 20 mm, with different voltages on them. Grounded plate P, located in the middle between electrodes, does not distort the field.

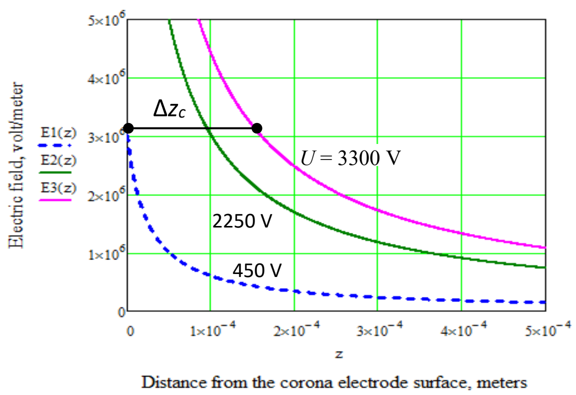

Fig. 2. The electric field near a 50-µm wire electrode at different voltages between it and a 10 mm wide plate electrode spaced 10 mm apart; Δz_c – the corona discharge length

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The dotted line in Fig. 2 is constructed for an interelectrode voltage of 450 V, at which the breakdown field strength is achieved only at the surface of the corona wire electrode. According to the average curve plotted for a voltage of 4500 V, the breakdown field strength exists in the near-surface layer of the corona electrode with a thickness of 100 µm. The upper curve is plotted for an initial corona voltage of 3300 V, calculated using the Peak formula [14]:

$$U_c = 3.1 \cdot 10^6 \delta r\left(1+\frac{0.0308}{\sqrt{\delta r}}\right)\ln\left(\frac{D}{\delta r}\right),$$

where δ is the relative density of air (for normal conditions δ = 1); r is the radius of the wire electrode (in meters); D is the distance between the wire and plate electrodes (in meters). This curve shows that the breakdown field strength extends up to a distance of 160 µm from the surface of the corona electrode. This is probably the distance at which the avalanche process of multiplication of charge carriers due to impact ionization leads to the ignition of a corona discharge. Note that Peak called the initial corona field strength "visual critical voltage gradient" and noted that this field strength was much higher than the breakdown one.

According to formula (2), the field strength on the surface of the wire electrode at the initial corona voltage is $2.2 \cdot 10^7$ V/m.

The mean free path of air molecules under normal conditions is 68 nm [15], and electrons, according to the kinetic theory of gases, have a long free path, that is, 385 nm. According to the distribution of the electric field near the corona electrode, shown in Fig. 2, the field strength at such a distance changes by only 1.6%, which makes it possible to find the potential difference along this path for the upper curve as

$$(2.2 \cdot 10^7 \text{ V/m})(3.85 \cdot 10^{-7} \text{ m}) = 8.5 \text{ V}.$$

When accelerating in a field with such a potential difference, an electron gains energy of 8.5 eV, but this energy is not enough to ionize gas atoms, which all have ionization energy above 13 eV. However, particles carrying two or more elementary charges have sufficient energy to ionize.

Consider the forces acting not only on the electron but also on other particles located near the corona electrode.

V. *ANALYSIS OF FORCES ACTING ON AEROSOLS*

The movement of aerosols occurs in a field of forces of various natures arising from the presence of gravity, pressure, and temperature gradients, as well as electric and magnetic fields.

In the absence of an electric field gradient, the stationary sedimentation rate of an electrically neutral spherical particle of diameter d_p and density ρ can be found from the equation $F_g - F_{St} = 0$, where $F_g = \pi d_p^3 \rho g/6$ is the gravitational force and $F_{St} = 3\pi d_p \eta V_0$ is the Stokes force (here g is the acceleration of gravity, η is the viscosity of air). From these relations we find

$$V_0 = \frac{\rho d_p^2 g}{18\eta}. \tag{3}$$

Let us find the settling rates of water droplets of different sizes. For the calculation, we will use the following parameter values: air temperature $T = 293$ K, gravitational acceleration $g = 9.81$ m/s², water density $\rho_w = 10^3$ kg/m³, and air viscosity $\eta = 1.82 \cdot 10^{-5}$ kg /(m·s). Substituting these data into formula (3), we find that the sedimentation rates of droplets with a diameter of 0.1, 1.0, and 10 µm are $3 \cdot 10^{-7}$, $3 \cdot 10^{-5}$ and $3 \cdot 10^{-3}$ m/s, respectively.

Nanoparticles about 100 nm in size can float in indoor air for up to several days, participating in the Brownian motion of air molecules. In models of air exchange in rooms, the authors often take for particles 1 µm in size, the settling rate equal to 10^{-4} m/s [16]. These circumstances should be taken into account when analyzing the migration of viruses, such as Covid-19, indoors.

When a sick person speaks loudly, several thousand virus-infected droplets up to 20 µm in size appear in the air in 1 sec. After dehydration, they form nuclei with a diameter of about 4 µm [17]. Effective means of combating them are frequent ventilation of the room, electrostatic air filtration, and ultraviolet irradiation of the room.

The electric field E between parallel plate electrodes of the same size, located at a distance D from each other, is determined by the potential difference U applied to them, namely $E = U/D$, the magnitude of the charge Q on the electrodes depends on a given potential difference U on the capacitance of this pair of electrodes $C = \varepsilon_a \varepsilon_0 wL/D$. The field between the electrodes can be considered uniform and depends only on the distance between the electrodes.

In the case of a decrease in the width of one of the electrodes from w_1 to w_2, for the law of conservation of charge to be fulfilled, the equality

$$\beta = \frac{U}{E_0 D} = \frac{w_1}{w_2}.$$

It follows from the last relation that it is possible to achieve a breakdown field strength of 3 kV/mm in air under normal conditions even at a potential difference of 100 V, if in a system of two parallel plate electrodes located, for example, at a distance of 10 mm, one of the electrodes has a width 10 mm and the other is less than 30 microns. If w_1 = 10 mm and w_2 = 10 microns, we get β = 1000.

An electric field of strength $E(z)$ near the corona electrode determines the electric force F_{el} and dielectrophoretic force F_{DEP} acting on the particle.

The electrical force is determined by the expression

$$F_L(z) = MeE(z), \tag{4}$$

where e is the elementary charge and M is the relative charge of the particle (expressed in e). This force acts only on charged particles, and it does not matter whether the field is uniform or non-uniform. A homogeneous field practically does not act on a neutral particle of a spherical shape, since electric forces balance each other on the same volume charges of the opposite sign, which appeared in the particle due to polarization. This equilibrium will obviously be violated for particles of an asymmetric shape. Fig. 3 shows the dependence of the electric force on the distance to the corona electrode for particles with different charges.

In an inhomogeneous field near the corona electrode, a dielectrophoretic force acts on the particle, directed towards an increase in the field strength [18],

$$F_{DEP} = \frac{\pi d_p^3 \varepsilon_a \varepsilon_0}{4}\left(\frac{\varepsilon_p - \varepsilon_a}{\varepsilon_p + 2\varepsilon_a}\right)\nabla E^2, \qquad (5)$$

where ε_p and ε_a are the dielectric constants of the particle material and air, ε_0 is the electric constant, ∇E^2 is the gradient of the square of the electric field strength.

The gradient of the square of the electric field strength between the wires (along the Z-axis), based on formula (1), can be represented as

$$\frac{\partial}{\partial z}\left(E^2\right) = \frac{-2U^2}{\ln^2(2D/w)}\frac{z\left(z^2+D^2\right)}{\left(z^2-D^2\right)^3}.$$

The dielectrophoretic force, taking into account formulas (1) and (5), takes the form

$$F_{DEP} = \frac{-\pi d_p^3 \varepsilon_a \varepsilon_0 U^2}{2\ln^2(2D/w)}\left(\frac{\varepsilon_p - \varepsilon_a}{\varepsilon_p + 2\varepsilon_a}\right)\frac{z\left(z^2+D^2\right)}{\left(z^2-D^2\right)^3}. \qquad (6)$$

Fig. 4 shows the dependences of the dielectrophoretic force acting on particles of different diameters on the distance to the corona electrode.

Fig. 5 shows the dependences of the ratio of dielectrophoretic and electric forces acting near the corona electrode on water droplets with a diameter of 1 μm with different charges on the distance to the corona electrode.

The dielectrophoretic force is directed towards a higher field strength, i.e. towards the corona electrode, and the magnitude of the dielectrophoretic force does not depend on the particle charge. On a particle with a diameter of 1 μm, the action of the electric force at the electrode surface is 75 times weaker than the dielectrophoretic force, and the forces are compared either at M = 75 or at M = 1 at a distance of 80 μm, where the dielectrophoretic force becomes 2 orders of magnitude less than that of the electrode surface. This follows from the analysis of formulas (4) and (6).

Let us consider the motion of positively charged particles with a diameter of 0.5, 1.0, and 1.5 μm near a corona electrode. within 1 μ from its surface, where the dielectrophoretic force changes by 11% and it can be considered constant with average values of 31, 245, and 829 pN, respectively. The electrical force in this segment can be neglected. When the particle moves, the dielectrophoretic force will be counteracted by the inertia force F_{ma} and the air resistance force (Stokes force) F_{St}. At any time along the Z-axis, the condition of the dynamic balance of forces will be maintained:

$$F_{DEP} - F_{ma} - F_{St} = 0.$$

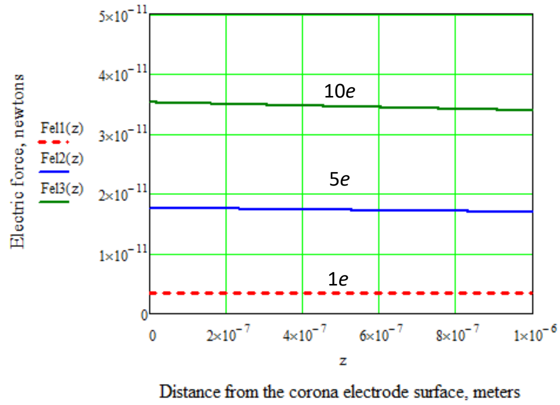

Fig. 3. The dependence of electrical force on distance to the corona electrode at different particle charges (parameters of the electrode system are the same as in Fig. 2)

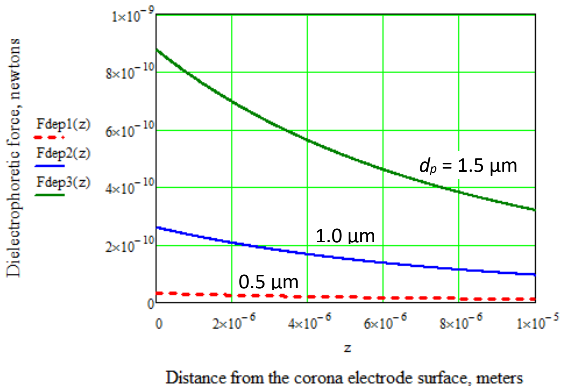

Fig. 4. Dependence of dielectrophoretic force on the distance to the corona electrode for particles of different diameters (parameters of the electrode system are the same as in Fig. 2)

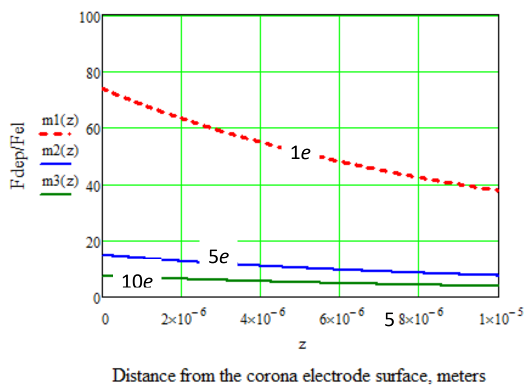

Fig. 5. Dependence of the ratio of dielectrophoretic and electrical forces acting on differently charged micron droplets from the distance to the corona electrode surface

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Let's rewrite this condition as

$$\frac{\pi d_p^3 \rho}{6}\frac{dV_z}{dt} + 3\pi\eta d_p V_z + F_{DEP} = 0.$$

We obtain an ordinary differential equation of the first order of the form

$$Ay'(x) + By(x) + F_{DEP} = 0.$$

The solution of this equation, provided that $y(0) = 0$, is the function

$$y(x) = \frac{F_L}{B}\left[\exp\left(-\frac{B}{A}x\right) - 1\right],$$

which, after substituting the expressions for the coefficients A, B and F_{DEP} gives the dependence of the particle velocity along the direction of the force action on time:

$$V_z(t) = \frac{F_{DEP}}{3\pi\eta d_p}\left[1 - \exp\left(-\frac{18\eta}{\rho d_p^2}t\right)\right]. \quad (7)$$

The plots of this dependence for different particle sizes are shown in Fig. 6, where the density of water is taken for the density of particles (ρ = 1000 kg/m^3). The densities of other aerosols can be either less than the density of water (for smoke particles 500–600 kg/m^3, for soil particles 800–900 kg/m^3) or higher (for sand grains 1450–1550 kg /m^3).

The kinetic energy acquired by the particles under consideration near the corona electrode under the action of the dielectrophoretic force is sufficient to ionize atoms in molecules of any gases. For example, if a particle with a water density and a diameter of 0.5 μm acquires energy of 26.4 eV near the corona electrode (in a field of $2.2\cdot10^7$ V/m), then the energy of a particle with a diameter of 1 μm becomes already equal to 3346 eV, which makes multiple ionization possible.

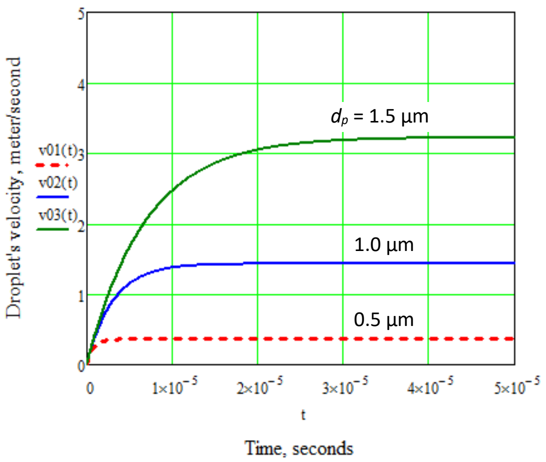

Fig. 6. Time dependencies of the velocity of singly ionized particles of different diameters in an electric field $2.2\cdot10^7$ V/m near the corona electrode

VI. AEROZOLS MOVEMENT NEAR THE CORONA ELECTRODE

Let us find the stabilization time t_{st} of the velocity at the level of 0.99 from the stationary value. This means that the expression in square brackets in formula (7) must satisfy the condition $1-\exp\left(-18\eta t_{st}/\rho d_p^2\right) = 0.99$, whence we get

$$t_{st} = \frac{0.26\rho d_p^2}{\eta}. \quad (8)$$

For particles with a water density and a diameter of 0.5, 1.0, and 1.5 μm, the velocity stabilization times are 3.6, 14.3, and 32.1 μs, respectively.

From formula (8) it can be seen that the time of stabilization of the particle velocity is not affected by the force F applied to it, unless, of course, the force changes too quickly in space. Let us estimate how far the particle will travel in time t_{st} with an average velocity equal to half the stationary velocity $V_{st} = F_{DEP}/3\pi\eta d_p$:

$$L_{st} = \frac{1.4\cdot10^{-2} F_{DEP}\rho d_p}{\eta^2}. \quad (9)$$

As can be seen from formula (9), this path is proportional to the size of the particle, its density, and the force applied to it. For singly ionized particles with a water density of 0.5, 1.0, and 1.5 μm in diameter and in a field of $2.2\cdot10^7$ V/m near the corona electrode, the particle path L_{st} will be 0.66, 1.31, and 1.97 μm, respectively. These values can be regarded as a rather rough estimate of the distance at which the particle velocity stabilizes, because, for example, in the case of a particle with a diameter of 1.5 μm, the dielectrophoretic force at a distance of 2 μm from the electrode surface decreases by 21%.

Note that the polarization of dielectric particles in an electric field can lead to the attraction of electric dipoles induced in them and the fusion of particles, for example, the fusion of water nanodroplets with each other, as well as with nanoparticles of dust, smoke, and viruses. As it follows from formulas (6) and (7), enlarged drops settle faster on the electrodes.

In modern designs of electrostatic filters, needle-shaped corona electrodes are mainly used, which is due to the fact that the tip provides a higher field amplification factor β than a wire of extremely small diameter. The magnitude of the field at the electrode surface increases with an increase in the curvature of the surface, and the radius of curvature of the tip can be several orders of magnitude smaller than the radius of the thinnest wire.

If the shape of the tip is approximated by a half of an ellipsoid (Fig. 7), then for a separate such electrode located on a flat conducting surface, the field amplification factor is determined by the relation [8]

$$\beta = \frac{2h/r}{\log(4h/r) - 2}, \quad (10)$$

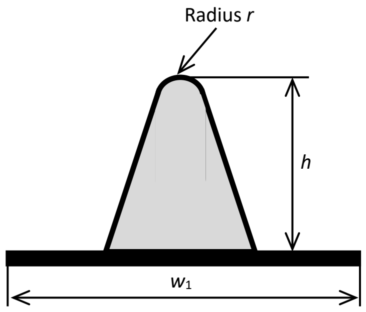

Fig. 7. Side view of the corona electrode

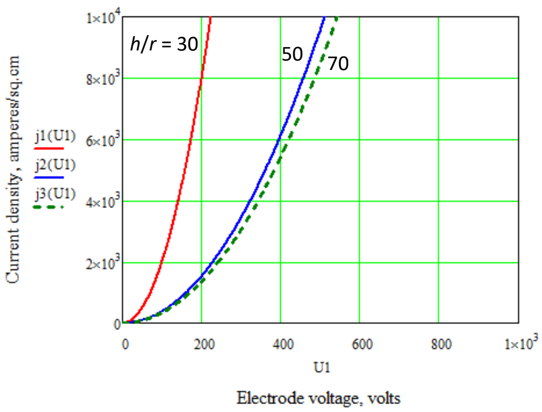

Fig. 8. Dependences of the corona discharge current on interelectrode voltage for different ratios the height of the pointed cathode to the radius of the tip

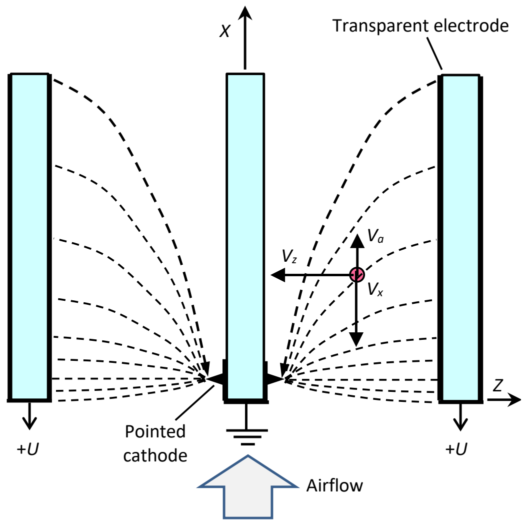

Fig. 9. Distribution of the electric field in the section of the window with electrostatic filtration (top view). Velocity components are shown for the positively charged particle moving under the influence of airflow (V_a) and electric field (V_x and V_z)

where h is the height of the needle electrode, r is the radius of curvature of the surface at the top of the electrode. When $h/r = 50$ formula (10) gives $\beta = 332$.

The current density from the tip can be found using the Fowler-Nordheim formula [8]

$$j = \frac{k_1 \beta^2 U^2}{\Phi D^2} \exp\left(-\frac{k_2 \Phi^{3/2} D}{\beta U}\right),$$

where k_1 and k_2 are the Fowler-Nordheim coefficients, Φ is the work function of the tip material, D is the distance between the electrodes. In this formula, the coefficients have the following values: k_1=1.56·10^{-6} A·eV·V^{-2}, k_2=6.83·10^{-7} V·eV$^{-3/2}$·cm^{-1}. Fig. 8 shows the dependence of the current density on the interelectrode voltage for different ratios h/r. The work function of the material of the pointed electrode is taken to be 4.5 eV, which is close to the values of Φ for such metals as Cu, Al, Fe, Zn, and W.

Note that the Fowler-Nordheim formula describes the current density only from the very top of the tip, i.e. at the point where the surface has a minimum radius of curvature. This current density is a kind of maximum value in the dependence of the current density on the radius of curvature of the surface. With distance from the top, the local electric field strength near the tip electrode decreases, and the corona discharge current decreases.

Let us estimate the magnitude of the electric charge of the droplets since it determines the rate of deposition on the electrodes of droplets carrying viruses and, ultimately, the efficiency of filtration.

The maximum drop charge qR (the so-called Rayleigh limit) is determined from the equilibrium of surface compression forces (surface tension) and surface tensile forces (due to repulsion of the same surface charges), which leads to the expression [19]

$$q_R = \pi\sqrt{8\varepsilon_0 \gamma d_p^3},$$

where γ - surface tension; for water γ = 0.0727 N/m at a temperature $T = 293$ K.

Let us express the Rayleigh limit in units of elementary charge, i.e. in the form of a relationship

$$q_{R/e} = \frac{q_R}{e} = \frac{\pi}{e}\sqrt{8\varepsilon_0 \gamma d_p^3}.$$

Hence, we find that the maximum charge of a water droplet with a diameter of 1 micron is 4.5·10^4 e. When this charge is exceeded, droplet fission occurs.

VII. WINDOW CONSTRUCTION WITH ELECTROSTATIC AIR FILTRATION

In the design of the window electrostatic filter, it is proposed to use a lattice of narrow plates made of transparent plastic, for example, PMMA or polycarbonate, on which wide strip transparent indium tin oxide (ITO) electrodes and narrow metal strips with pointed cathodes are applied, as shown in Fig. 9.

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The choice of materials and geometry of electrodes requires further research. The main mechanisms for the destruction of a pointed cathode are overheating and melting of the tip, as well as its ion bombardment. Currently, pointed cathodes are made mainly of tungsten, which is able to withstand the high temperatures of the cathode tip. A possible replacement for metal cathodes can be silicon carbide, which has high hardness and temperature resistance. Pointed cathodes made of carbon nanotubes and silicon nanowires are also promising.

The fundamental difference between the proposed window filter design and existing electrostatic filters is that the filter is transparent to light and sound, which allows it to be used both in the windows of premises and in the client windows of various institutions that separate employees and visitors.

Note that attempts have already been made to create a transparent window filter. In particular, a design of a transparent window filter based on a mesh of polyacrylonitrile fibers with a diameter of 200 nm and approximately the same mesh size was proposed. The filter had a transparency of 77% and removed 98.7% of particles larger than 2.5 μm from the airflow [20].

The selection of the operating voltage of the filter largely depends on the shape of the corona electrode and the distance between the electrodes. The curvature of the surface of the corona electrode determines the field amplification factor and the magnitude of the dielectrophoretic force, and the distance between the electrodes determines the magnitude of the electrical one. At distances, less than 30 μm, a dependence of the field gain on the distance appears . [21]

CONCLUSIONS

Currently produced electrostatic air filters provide protection against dangerous submicron particles, but their design does not allow direct visual and audio contact, for example, between visitors and employees of various institutions. Protective masks used today make breathing difficult, and replacing mechanical filtration with electrostatic filtration would solve this problem. Note that individual respirators with electrostatic filtration solve the problem in part, as there remains the possibility of particles getting on the mucous membrane of the eyes.

The influence of electric and dielectrophoresis forces on the motion of submicron particles near the corona electrode is considered in the article. The corona discharge, on the one hand, is necessary for the electrification of neutral particles for the purpose of their electrostatic filtration, and on the other hand, at the voltage on a corona electrode over 10 kV, the electrostatic filter becomes the ozone generator. It is known that the accumulation of ozone in the room can cause inflammation of the respiratory system and act as a carcinogen on the human body.

Dust and smoke particles carry a positive charge and can settle on the electrodes without the participation of the corona discharge. Neutral water droplets carrying viruses are electrified by the corona discharge and also settle on the electrodes. Polarization of dielectric aerosols can lead to their attraction and enlargement, and the enlarged particles settle faster on the electrodes.

Although the principle of electrostatic air filtration has been known for almost two centuries, its design solutions are constantly being improved and are far from optimal. New materials, new technologies, new areas of application open up a wide field of activity for researchers and designers, which, in the end, will allow a person to breathe clean air even in adverse conditions.

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Вікно з електростатичним захистом від пилу, диму та вірусів

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Анотація—У статті розглянуто аерозолі природного та штучного походження, які можуть бути небезпечні для здоров'я людини або безпосередньо, або як носії вірусів. Проаналізовано вплив таких аерозолів на організм людини. Відмічено, що найбільш небезпечними для людини є частинки субмікронних розмірів, оскільки вони не затримуються верхніми дихальними шляхами і потрапляють у легені. Є певна схожість у дії наночастинок диму і коронавірусу на легені. Ця схожість проявляється у тому, що альвеоли у відповідь починають виділяти окиснювачі, які пошкоджують легені і викликають важкі форми пневмонії та серцево-судинних захворювань.

Для очищення повітря приміщень використовують механічні, електричні (електростатичні) та хімічні фільтри, причому найкращу фільтрацію забезпечують системи з поєднанням усіх трьох типів фільтрів.

Аналіз процесів, які протікають в електростатичному фільтрі, показує, що використовувані електродні напруги (більше 10 кВ) призводять до генерації озону, який за накопичення у приміщенні негативно впливає на організм людини. У статті проаналізовано, за яких умов можливе використання менших напруг для підтримання коронного розряду, необхідного для електризації аерозолів та їх осадження на електродах. Для цього розглянуто дію на аерозолі електричного поля електродів різної конфігурації.

Розраховано електричну та діелектрофорезну сили, які діють на субмікронні частинки в неоднорідному електричному полі двох паралельних проводів. Продемонстровано, що частина цього поля є ідентичною полю між проводом та заземленим пластинчатим електродом, розташованим посередині між проводами. Це дозволяє за допомогою відомого співвідношення для електричного поля двопровідної лінії розрахувати градієнт поля та дію діелектрофорезної сили на нейтральні частинки.

Частинки диму та пилу вже несуть негативний заряд і для їх переміщення достатньо більш-менш однорідного електричного поля. Для фільтрації нейтральних крапельок води, інфікованих вірусом, потрібне або поле з великим градієнтом, або коронний розряд. У статті показано, що поляризація частинок в електричному полі викликає злипання частинок, причому більш крупні частинки швидше осідають на електродах фільтра.

Для створення електричного поля з потрібним градієнтом запропоновано використовувати електродну систему у вигляді пар пластинчатих та загострених електродів. Використання для пластинчатого електроду оксиду індію-олова забезпечить його прозорість. Загострені електроди традиційно виготовляють з вольфраму, що убезпечує вістря електрода від оплавлення, але високу твердість та теплостійкість мають і більш сучасні матеріали, такі як карбід кремнію, вуглецеві нанотрубки та кремнієві нановолокна.

Повітряні фільтри, які використовують для очищення повітря приміщень, зазвичай непрозорі ні для світла, ні для звуку. У статті запропоновано конструкцію прозорого електростатичного фільтру, який може бути використаний для захисту повітря приміщень від зовнішнього диму, пилу або вірусів. Такий фільтр може бути вбудований у вікно приміщення для очищення повітря, яке надходить ззовні, або використаний у тих закладах, де потрібно розділити простір відвідувачів і простір персоналу, залишаючи можливість візуального та аудіо контакту.

Ключові слова — електростатичні фільтри; діелектрофорезис; коронний розряд; заряджання частинок; аерозолі; напруга пробою; охорона здоров'я.