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Possible applications of the electron source with a wide-grid plasma cathode and the output beam into the atmosphere

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Abstract. Possible applications of a wide-aperture (750×150 mm) electron source with a grid plasma cathode based on a low-pressure arc discharge and the output of a large cross section beam through an output foil window are given. The mesh (layer) stabilization of the emission plasma boundary in such cathode makes it possible to generate an electron beam in a wide range of its parameters with weak dependence on each other (beam energy up to 200 keV, beam current in the atmosphere up to 30 A, pulse duration up to 100 μ s, frequency pulse repetition up to 50 s⁻¹). In particular, preliminary experiments were conducted on the use of such a beam in the processes of radiation cross-linking of natural latex without any chemical additives accelerating the vulcanization process; the principal possibility of the formation of carbon structures in polyvinyl chloride films is shown; preliminary experiments were conducted on electron-beam disinfection of agricultural products in the atmosphere. The promise of using such an electron source confirms the unconditional need for the further development of such technologies for the possibility of applying them both for scientific and industrial purposes.

1. Introduction

Electron sources or accelerators capable of producing broad beams with their extraction into the atmosphere hold undeniable promise for research and technological applications [1-7]. At present, several types of such electron sources are known, most notably the type of cathode used (thermionic cathodes, plasma cathodes, explosive-emission cathodes, cathodes based on ion-electron emission, etc.). Each of these electron sources has its advantages, however, in the case of using sources based on the plasma cathode with mesh (layer) stabilization of the emission plasma boundary, it is possible to generate an electron beam with a wide range of parameters, which also depend weakly on each other [8–10], which greatly simplifies the search for the optimal irradiation regime for the samples.

This paper presents the results of using an electron source with a grid plasma cathode based on a low-pressure arc discharge with the output of a generated beam to the atmosphere through a thin metal foil in experiments on an electron beam modification of natural latex, the formation of carbon structures from polyvinyl chloride films, as well as preliminary results on the disinfestation of agricultural products (barley) by a low-energy electron beam into the atmosphere.

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2. Experimental procedure

A schematic of the electron source used in the study is shown in figure 1 [9–10]. The source is based on a plasma cathode (1) being a hollow stainless steel semicylinder with two low-pressure arc units (2, 3) at both of its ends [11]. The anode for the arc is an emission grid (4) of dimensions 750×150 mm covered with a stainless steel mask (5) 200 µm thick in which 344 round holes of diameter 8–12 mm are made. The holes are individual plasma emitter units to form beamlets whose superposition results in a broad electron beam with a grid-stabilized plasma boundary. The emission grid (4) is connected to a hollow anode (6) via a resistor to assist the discharge ignition, switching, and operation in the emission grid region. For electron extraction from the plasma produced by the emitter units, a dc accelerating voltage of up to 200 kV is applied to the 120-mm gap between the plasma cathode (1) and a support grid with foil windows (7, 8). The number of holes in the support grid (7), having a total geometric transparency of 56%, are the same as that in the mask (5) but their diameter is larger (15 mm). The holes in the mask (5) and in the support grid (7) are aligned, thus providing the acceleration gap with coaxial plane-parallel geometry and minimizing the loss of electrons through the grid with foil windows. The foil covering the support grid (7) is 30 µm thick and is made of AlMg–2n alloy [10].



Figure 1. Schematic of the electron source with a wide-aperture plasma cathode: 1 – plasma cathode; 2 – cathode; 3 – igniter; 4 – emission grid; 5 – mask; 6 – hollow anode; 7 – support grid with output foil windows; 8 – output foil; 9 – discharge power supply;10 – source power supply; 11 – high-voltage power supply; 12 – collector or substrate.

The modification has made possible an automated wide-aperture plasma cathode electron source capable of providing the beam parameters presented in table 1.

| Table 1. | Main | beam | parameters. |
|----------|------|------|-------------|
|----------|------|------|-------------|

| Electron energy, keV | 100-200 |
|----------------------------------|----------|
| Beam current, A | 5-30 |
| Pulse duration, µs | 10-100 |
| Pulse frequency, Hz | 1–50 |
| Beam dimensions, mm | 750×150 |
| Current density nonuniformity, % | ± 10 |
| Average beam power, kW | 5 |
| | |

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3. Radiation modification of natural latex

To solve this problem, a pumping system was developed and fabricated for multiple passage of latex under the electron beam, described in detail in [11]. The uniformity of irradiation in such system is achieved by providing a laminar motion of the latex in the treatment zone at a given rate, and further mixing the treated latex with the original and partially treated. This system was installed at a distance of ≈ 30 mm from the beam output window. Taking into account the parameters of the latex pumping system and beam parameters, the processing of natural latex by the electron beam was carried out in the following mode: accelerating voltage $U_0 = 160$ kV, beam current into the atmosphere $I_b \approx 20$ A, pulse duration t = 35 µs, repetition rate f = 10 s⁻¹. The training regimes in this study differed in the dose invested in latex, which was regulated by changing the number of pulses of the beam current.

After latex irradiating, samples measuring $150 \times 100 \times 0.5$ mm were made from it, which were held for 24 hours in an air atmosphere at room temperature, and then after soaking in a 1% solution of ammonia, they were heated in an oven at a temperature of 70° C to full vulcanization. Samples in the form of a "blade" were cut from the obtained rubber cloth for clamping them in a universal testing machine "Zwick-2.5", by means of which these samples were torn in a standard way to determine their tensile strength.

Experiments have shown that when the irradiation dose is increased, the strength of the samples made from the treated latex increases linearly (figure 2), which is most likely due to a change in the network structure of the polymer, which becomes more frequent. The maximum tensile strength of the rubber samples, which was 21 MPa, was obtained by introducing into the natural latex the irradiation dose equal to 27 Mrad. According to the literature data this value of tensile strength is a record among the chemically pure processes of obtaining natural rubber.





4. Radiation modification of polyvinyl chloride (PVC) films

Experiments on the irradiation of PVC films by an electron beam, described in detail in [12], were carried out on samples of thickness $\approx 200 \ \mu\text{m}$, with a diameter of 50-60 mm, which were placed on a copper substrate located at a distance $\approx 40 \ \text{mm}$ from the output foil in atmospheric pressure air with the following beam parameters: $U_0 = 160 \ \text{kV}$, $I_b \approx 5 \ \text{A}$, $t = 40 \ \mu\text{s}$, $f = 2 \ \text{s}^{-1}$, pulse number N = 2100, the maximum pulse power of the beam (in the atmosphere) was $P_m \approx 800 \ \text{kW}$, the average power of the extracted beam into the atmosphere did not exceed $P_{av} \leq 100 \ \text{W}$. In this mode, the electron beam with an energy of $E_l \approx 25 \ \text{J}$ for 1 beam current pulse was output into the atmosphere. The total beam energy for 2100 pulses was $E_{av} \approx 50 \ \text{kJ}$. Since the processing area of each PVC sample is $\approx 25 \ \text{cm}^2$, the total energy and total dose introduced into each sample did not exceed $E_{avl} \leq 1.5 \ \text{kJ}$ and $D_{avl} \leq 1.5 \ \text{MGy}$, respectively. The total time of processing of PVC by an electron beam did not exceed 5 minutes. The average temperature of the samples during the irradiation time increased from room temperature by no more than $\approx 50 \ \text{°C}$. At the same time, initially transparent colorless samples of the films acquired black color without violating their integrity and geometric shape.

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Suspension PVC with a mean molecular mass of 47000 (PVC-S-SI-70, TU 2212-012-46696320-2008, produced by SAYANSKKHIMPLAST, Sayansk) was used as the initial polymer material in the work. It did not contain fillers, dyes, stabilizers, and so on. Polymer films were produced from 10% PVC solution in tetrahydrofuran via solvent evaporation for 24 h at room temperature. The same procedure was used for production of samples of PVC films modified by 5-mass % ferrocene [Fe(C_5H_5)₂], the estimated amount of which was introduced in the polymer solution.

According to TEM results (figure 3), geometrically irregular particle aggregates are observed in PVC film samples after electron-beam irradiation. The electronograms of these particles have the forms of diffuse rings, this being characteristic for the amorphous state of matter. According to semiquantitative X-ray microanalysis results, the content of carbon in the irradiated film is 92%, of oxygen is 6%, and of chlorine is 2% (mass). The presence of oxygen in the irradiated material is explained by its partial oxidation during irradiation in air with formation of oxygenated groups. Thus, irradiated PVC is an amorphous carbon material. Carbon structures are formed due to dehydrochlorination of chloropolymer macro-molecules stimulated by the electron irradiation and subsequent interchain condensation of the resulting polyene chains.



Figure 3. (a) EM image of the amorphous structure of a PVC film with ferrocene after electron irradiation; (b) X-ray spectrum of this region.

5. Electron-beam disinfection of barley seeds in the atmosphere

Insect pests of grain are ubiquitous and cause great damage to agricultural products during storage. They cause not only large losses of grain, but also its spoilage, reduce quality of flour and the feed value of grain fodder, mixed fodder [13-14].

Radiation disinfestation of grain is an alternative to chemical disinfestation, the main advantage of which is the absence of environmental pollution. However, usually high-energy electron beams (more than 1 MeV) are used to disinfect grains from diseases, which leads to the death of its embryo, and, consequently, to zero germination of irradiated grain. That is why these experiments, which were preliminary, were aimed at investigating the possibility of disinfecting grain at an electron beam energy of up to 200 keV, which allows processing only the surface of the grain without killing its embryo.

As a research object, barley was selected, the grains of which were placed under the beam output foil window at a distance of 20 mm.

Studies on presowing seed irradiation on the electron source with accelerating voltage 160 kV at doses of 1, 5, and 8 kGy, dose rates of 100 and 500 Gy per impulse, made it possible to establish that presowing irradiation of barley seeds at doses of 5 and 8 kGy (dose rate 100 Gy per impulse) and doses of 1 and 5 kGy (a power of 500 Gy per impulse) reduced its incidence of helminthosporiosis

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(Helminthosporium sativum P., K. et B) of barley by 3.2 and 2.1 times, and the prevalence of the disease was 3.0 and 1.4-2.3 times, respectively (table 2).

| Dose, kGy | Dose rate, Gy/imp. | Damage | Prevalence |
|-------------------|-----------------------|--------|------------|
| 0 (control) | - | 17.00 | 36.33 |
| 1.0 | 100 | 14.00 | 29.33 |
| 5.0 | 100 | 5.33 | 12.00 |
| 8.0 | 100 | 5.33 | 12.00 |
| 1.0 | 500 | 8.0 | 26.00 |
| 5.0 | 500 | 8.17 | 16.00 |
| 8.0 | 500 | 16.00 | 34.00 |
| HCP ₀₅ | | 5.82 | 11.11 |

Table 2. The results of grain irradiation by a lowenergy electron beam.

6. Conclusion

The possibilities of using a pulse-periodic source of electrons with a grid plasma cathode with the output of a low-energy large cross-section beam to the atmosphere are demonstrated, confirming the prospects for further development of such technologies both for scientific and technological purposes.

As a result of experiments on the modification of natural latex, the possibility of efficient use of such an electron source in the processes of preliminary radiation crosslinking of natural latex without additional substances accelerating the vulcanization process is shown, which is promising for the organization of chemically pure production of natural latex products.

The use of the effect of the formation of carbon structures in the electron irradiation of PVC significantly enhances the possibilities of controlled synthesis of carbon materials, in particular, by incorporating into their structure modifying additives and giving the final product a given morphology and geometry at the stage of preparation of the polymer precursor. In addition, the developed approach can serve as a basis for the development of non-dioxin methods for utilization of chlorine polymer waste, allowing for their dechlorination under mild conditions without the use of high-temperature influences (including incineration) leading to the release of chlorodioxins.

As a result of preliminary experiments on the disinfection of barley grains, the possibility of reducing grain contamination with helminthosporium at its absolute germination was demonstrated, which, first of all, is promising for preplant processing, including other agricultural products.

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