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Electron beam generation efficiency in a high-voltage abnormal DC glow discharge in helium, neon, and argon

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The aim of this work was to carry out a comparative study of the current-voltage characteristics and the energy efficiency of electron beam generation in a high-voltage abnormal DC glow discharge in helium, neon, and argon at voltages above 1000 V. It is shown that, under ultraclean conditions and with thorough degassing of the cathode material, the current-voltage characteristics acquire a nonmonotonic form, while the total efficiency of electron beam generation reaches approximately 80 % in helium, approximately 90 % in neon, and 40 % in argon. The results of this work open up prospects for increasing the efficiency of electron beam generation in existing high-voltage discharge generators for applications in plasma technologies.

Keywords: gas discharge, helium, neon, argon, electron beam, efficiency.

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Introduction

Gas-discharge electron beam (EB) generators are of interest as compact sources of fast electron fluxes formed directly in a gas medium due to the acceleration of charged particles in strong electric fields [1–3]. The generation of EBs directly in a gas medium is a promising direction for the development of electron-beam and plasma technologies, since it makes it possible to dispense with the differential pumping systems and foil windows characteristic of vacuum accelerators. At the same time, considering both pulsed and stationary generators based on various types of gas discharges indicates the relevance of a comparative study of the mechanisms of beam formation, its energy efficiency, and the operating pressure ranges for discharges of different types. The simplest

representative of discharge types – the abnormal glow discharge (AGD) of direct current in inert gases – is characterized by a monotonically increasing current-voltage characteristic [4–6]. Works [7, 8] showed that, in high-voltage AGD in helium at pressures of 2–10 Torr, under conditions of minimized controlled and uncontrolled impurities in both the working medium and the cathode material, the current-voltage characteristics develop regions of negative differential resistance as the pressure increases. The electron-beam generation efficiency (EB) reaches about 80% [7].

Understanding the features and processes occurring in such fairly simple types of discharges is relevant for the development of plasma technologies. The current-voltage characteristics of the AGD depend to a large extent on the realized experimental conditions

[8]. Under uncontrolled conditions where the gas medium contains molecular components and the cathode surface is insufficiently cleaned, the current-voltage characteristics have a typical classical monotonically increasing form. Under clean conditions and with thorough degassing of the cathode material, the current-voltage characteristics acquire an *S*-shaped form in voltage U – current I coordinates. Contamination of the cathode surface and the presence of molecular components in the gas medium lead to a change in the role, composition, and energy of the particles bombarding the cold cathode. Under the condition that the emission properties of the cathode depend on the modification of the emitting layer due to the implantation of working particles into the surface, the functional parameters of the AGD (discharge voltage, current, the nature of its flow, and the efficiency of EB generation) will be determined by the purity of the working medium and the state of the emitting surface.

It is therefore of interest to investigate high-voltage AGD in other inert gases. The aim of the present work is a comparative study of the current-voltage characteristics and the energy efficiency of EB generation in an AGD in helium, neon, and argon in the direct current regime at elevated (more than 1000 V) voltages under conditions where controlled and uncontrolled impurities of the working medium and the cathode material are minimized.

Experimental Setup

The studies of the discharge were carried out in a discharge cell with flat polished electrodes: a cathode made of reaction-sintered silicon carbide and a titanium anode. The interelectrode distance was 3 cm. The electrodes were separated by a glass cylinder, as well as by a multilayer insulator made of Al_2O_3 ceramic plates placed near the cathode. The inner diameters of the holes in the plates were 1.6 and 2.3 cm, which limited the area of the active discharge zone to 2 cm^2 . The temperature of the cell was monitored during the experiment and maintained at a level of $T \leq 50^\circ\text{C}$ through the use of cooling elements – radiators and coolers.

The experiments were carried out in the gas-flow regime, which was supplied through a carbon

trap cooled with liquid nitrogen at a rate of $\sim 100\text{ ml/min}$. Inert gases were used with a volume fraction of at least: helium He – 99.9999%, neon Ne – 99.999%, argon Ar – 99.998%. The purity of the working gas was assessed by the ratio of the radiation intensities of the molecular bands of hydrogen, nitrogen, and oxygen and by mass-spectroscopic measurements using an SRS RGA 200 mass spectrometer. The gas pressures were measured with a Thyracont VCC200MA4 capacitive sensor with an accuracy of $\pm 0.25\%$. A direct current source with adjustable voltage $U = 0\text{--}4000\text{ V}$ and ballast resistance $R = 20\text{--}600\text{ k}\Omega$ was used.

Before each cycle of measurements of the discharge parameters, degassing of the cell was carried out. The procedure is considered in detail in [9]. Changes in the current-voltage characteristics during the degassing of the cell and conditioning of the cathode were characterized by a gradual decrease in the discharge current. The criterion for achieving the working regime was the constancy and stable reproducibility of the current-voltage characteristic parameters during all cycles and the measurement time. In the present work, after ~ 50 hours the current-voltage characteristics acquired a steady-state character.

The energy efficiency of electron beam generation, η , determined as a fraction of the discharge power transferred to the fast electron component, including the energy of electrons that reached the anode η_{col} and the energy lost by them in the gas during excitation, ionization, and elastic collisions η_{ds} . The measurement of η was carried out by the calorimetric method and was determined as the ratio of the power of the fast electron beam to the total power expended on maintaining the discharge: $\eta = \eta_{\text{ds}} + \eta_{\text{col}}$; $\eta_{\text{ds}} = P_{\text{ds}}/P$ и $\eta_{\text{col}} = P_{\text{col}}/P$, where P_{ds} is the power dissipated in the discharge gap, P_{col} is the power released at the anode, and $P = U \times I$ is the total discharge power, where U is the discharge voltage and I is the discharge current.

The methodology for determining η_{ds} and η_{col} was based on preliminary calibration [7, 10]. For this purpose, in the absence of a discharge, the dependences of the steady-state temperature increment ΔT on the outer wall of the cell and on the anode-collector on the power supplied to the built-in ohmic heaters were measured. During the experiment, the values of ΔT in the corresponding

zones were recorded, after which the values of P_{ds} and P_{col} were reconstructed from the calibration dependences. On the basis of the obtained values, the efficiencies η_{ds} , η_{col} , and the total efficiency of electron beam generation η were calculated.

Results and Their Discussion

In Fig. 1, as an example, a family of current-voltage characteristics of the AGD in the coordinates $I-U$ in helium at pressure $p_{He} = 0.9$ and 10 Torr, neon $p_{Ne} = 0.5$ and 2 Torr, and argon $p_{Ar} = 0.5$ and 0.8 Torr, measured after performing the procedure of degassing the cell and training the cathode, is presented.

The experimental results demonstrated:

in helium, with increasing pressure, the dependences $I(U)$ change their character, and at $p_{He} \geq 4.3$ Torr they change character – they cease to be monotonically increasing. With increasing voltage, regions of decreasing current appear, and the magnitude of this drop increases with increasing gas pressure, reaching a maximum for the highest pressure. For example, for the current-voltage characteristic at $p_{He} = 10$ Torr, three regions can be traced:

- growth of I with increasing voltage up to $U \approx 400\text{--}500$ V;
- decrease of I with increasing voltage up to $U \approx 1100\text{--}1400$ V;
- repeated growth of I with increasing voltage.

In [11], it was experimentally shown that in a high-voltage discharge in helium, in which electron beams with $\sim$ keV energies are generated, the current-voltage characteristics have the power-law form $j \sim p^x U_c^y$ with exponents $x = 2$; $y = 3$; where j is the current density; U_c is the cathode potential drop, which under conditions of high values of U_c is practically equal to the voltage U applied to the discharge gap. The dynamics of change in the parameters x and y makes it possible to trace the transformation of the current-voltage characteristic when the discharge conditions change. In the present work, in a direct current discharge in helium, the exponent 'y' changes over the entire region of the current-voltage characteristic:

- for all pressures $y > 3$ at $U < 300$ V;
- at $U \approx 750\text{--}900$ V it reaches its minimum with the value $y \approx 1$ at $p_{He} \approx 0.9$ Torr;
- becomes negative $y \approx -0.3$ at $p_{He} \approx 10$ Torr and increases, for example at $U \approx 2100$ V 'y' ≈ 1.8 and 1 at $p_{He} \approx 0.9$ and 10 Torr, respectively.

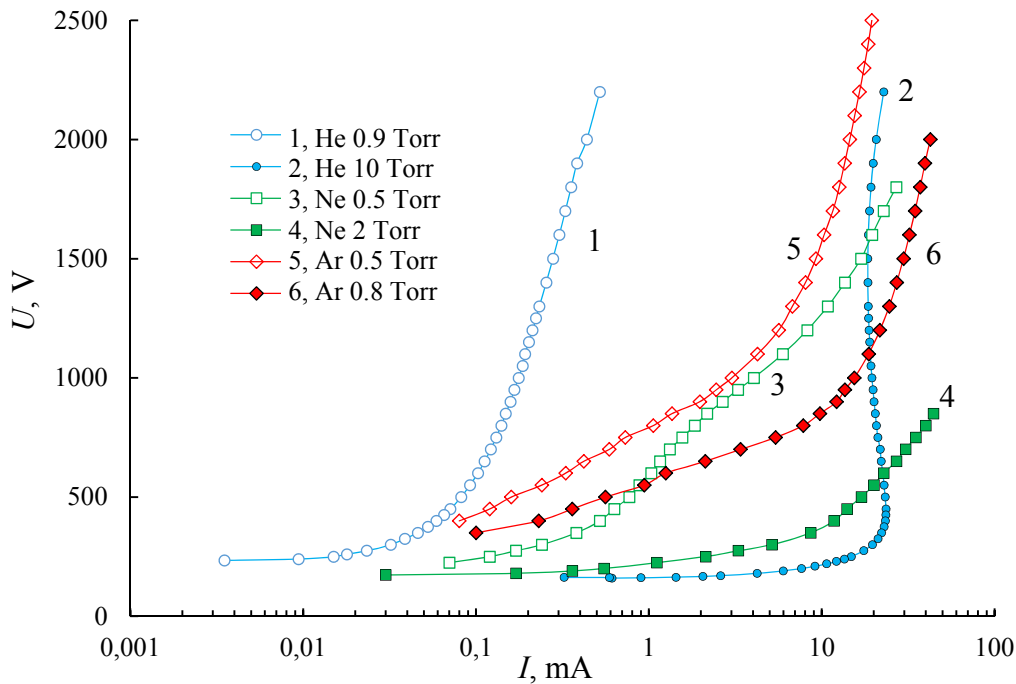


Fig. 1. Dependence of the discharge current I on voltage U at different pressures of the working gas p : He, $p_{He} = 0.9$ (1), 10 Torr (2); Ne, $p_{Ne} = 0.5$ (3), 2 Torr (4); Ar, $p_{Ar} = 0.5$ (5), 0.8 Torr (6)

In neon, the changes in the current-voltage characteristics during the operation of the discharge under clean conditions are less pronounced. With decreasing gas pressure, a transformation of the current-voltage characteristic is observed, but in the studied pressure range, regions with negative differential conductivity were not obtained. Up to voltages $U \approx 300$ V, the exponent $y > 3$; at $U \approx 500$ – 600 V the minimum value ' y ' ≈ 1.5 – 1.8 ; with a further increase in U , it increases. This, similarly to the case in helium, may indicate a change in the mechanism of electron emission [9]. At $p_{\text{Ne}} = 0.5$ Torr, the dependence $y(U)$ has a more complex form: at $U \approx 1000$ V the maximum value ' y ' ≈ 4 is reached, and with a further increase in U the parameter ' y ' decreases. Previously, such behavior of the dependence $y(U)$ was observed in an "open" discharge in helium [9].

In argon, no significant transformation of the current-voltage characteristic was observed, and the minimum value of ' y ' was not reached. At $U > 300$ V, the values of ' y ' are close for all the studied pressures and decrease from ' y ' ≈ 5 at $U \approx 300$ – 600 V to ' y ' ≈ 1.3 at $U \approx 1500$ – 2800 V.

In Fig. 2a–c, the measurement results the fractions of energy dissipated in the discharge gap η_{ds} , at the anode–collector η_{col} , and their total efficiency η in helium ($p_{\text{He}} = 4.7$ and 10.2 Torr), neon ($p_{\text{Ne}} = 0.5$ and 1.5 Torr), and argon ($p_{\text{Ar}} = 0.35$ and 1 Torr) are presented. The general tendency is an increase in the efficiency of fast electron generation with increasing U for all the studied gases and pressures. At the same time, the nature of the influence of pressure is different (Fig. 2c): in helium, with increasing p_{He} the efficiency grows as $\eta \sim p_{\text{He}}$, in neon this dependence is weakly pronounced, and in argon an inverse dependence is observed – $\eta \sim 1/p_{\text{Ar}}$. At $U \approx 3000$ V, the maximum efficiency is realized in neon $\eta \approx 90\%$, in helium it is $\eta \approx 80\%$, in argon, it does not exceed $\eta \approx 40\%$ at helium, neon, and argon pressures of 10.2 , 0.5 , and 0.35 Torr, respectively. The dependences of the fraction of beam energy released at the anode–collector $\eta_{col}(U)$ have a similar character. With increasing voltage, η_{col} increases monotonically. The maximum values are realized in the series $\text{Ar} \rightarrow \text{Ne} \rightarrow \text{He}$, while with increasing pressure for each of the gases η_{col} decreases. The

dependences of the fraction of energy released in the discharge gap $\eta_{ds}(U)$ have a more complex character. In the voltage range $U = 1000$ – 3500 V, for argon a monotonic weak growth is observed, for neon a sharp increase at $U = 1000$ – 1500 V with subsequent saturation at $U \geq 1500$ – 2000 V, and in helium this dependence has an extreme character with a maximum in the region $U \approx 1000$ – 1500 V.

It is clearly seen that the contributions of the quantities η_{ds} и η_{col} to the total efficiency of electron beam generation differ substantially depending on the kind of gas. For example, in helium at $p_{\text{He}} = 4.7$ Torr and $U = 2100$ V, the total generation efficiency $\eta \approx 66\%$ is formed as $\eta_{col} \approx 50\%$ and $\eta_{ds} \approx 16\%$. In turn, for neon at the same voltage $U = 2000$ V and $p_{\text{Ne}} = 1.5$ Torr, $\eta \approx 71\%$, $\eta_{ds} \approx 43\%$, and $\eta_{col} \approx 28\%$ are observed, and for argon at $p_{\text{Ar}} = 0.75$ Torr and the same voltage, $\eta \approx 31\%$, $\eta_{ds} \approx 23\%$, and $\eta_{col} \approx 8\%$.

The efficiency is related to the total emission coefficient $\langle \gamma \rangle$ as $\eta = \langle \gamma \rangle / (\langle \gamma \rangle + 1)$ [12]. At present, there are practically no reliable data on $\langle \gamma \rangle$ under clean conditions. For comparison, one can use the results of [13], in which the value $\langle \gamma \rangle \approx 0.98$ was obtained in helium at $U = 4000$ V, caused mainly by emission under the action of fast atoms. Under present investigation conditions, $\langle \gamma \rangle \approx 2$ at $U = 2000$ V, which indicates a significant contribution of photoemission to the electron current from the cathode. One can estimate the magnitude of the efficiency of electron beam generation proceeding from the fraction of energy losses in the discharge zone. In a high-voltage AGD, the main part of the applied voltage is concentrated in the cathode layer. In the quasi-neutral region beyond the cathode drop, the electric field is significantly smaller; therefore, the contribution of the low-energy electron component to the direct energy release is negligibly small. At a voltage at the cathode U , the maximum energy of runaway electrons can reach $E \approx eU$. The fraction of energy lost by such electrons in the region beyond the cathode sheath is $\sim (\eta_{ds} \cdot E)$. The fraction of energy η_{ex} of the electron beam expended on the excitation of resonant states of the working gas atom, without taking into account recombination population, has the values $\eta_{ex} \approx 0.3$ – 0.4 [14–16]. Given the geometrical

factor $R_s \approx 0.112$, characterizing the interception of radiation, the number of photons reaching the cathode is: $N_{ph} \approx eU \cdot \eta_{ex} \cdot \eta_{ds} \cdot R_s / h\nu$, where $h\nu = 19.8$; 16.7 and 11.6 eV is the energy of resonant photons in helium, neon, and argon, respectively.

Consequently, the number of generated photoelectrons, Ne, born thanks to radiation from the discharge gap:

$$N_e \approx eU \cdot \eta_{ex} \cdot \eta_{ds} \cdot \gamma_{ph} \cdot R_s / h\nu. \quad (1)$$

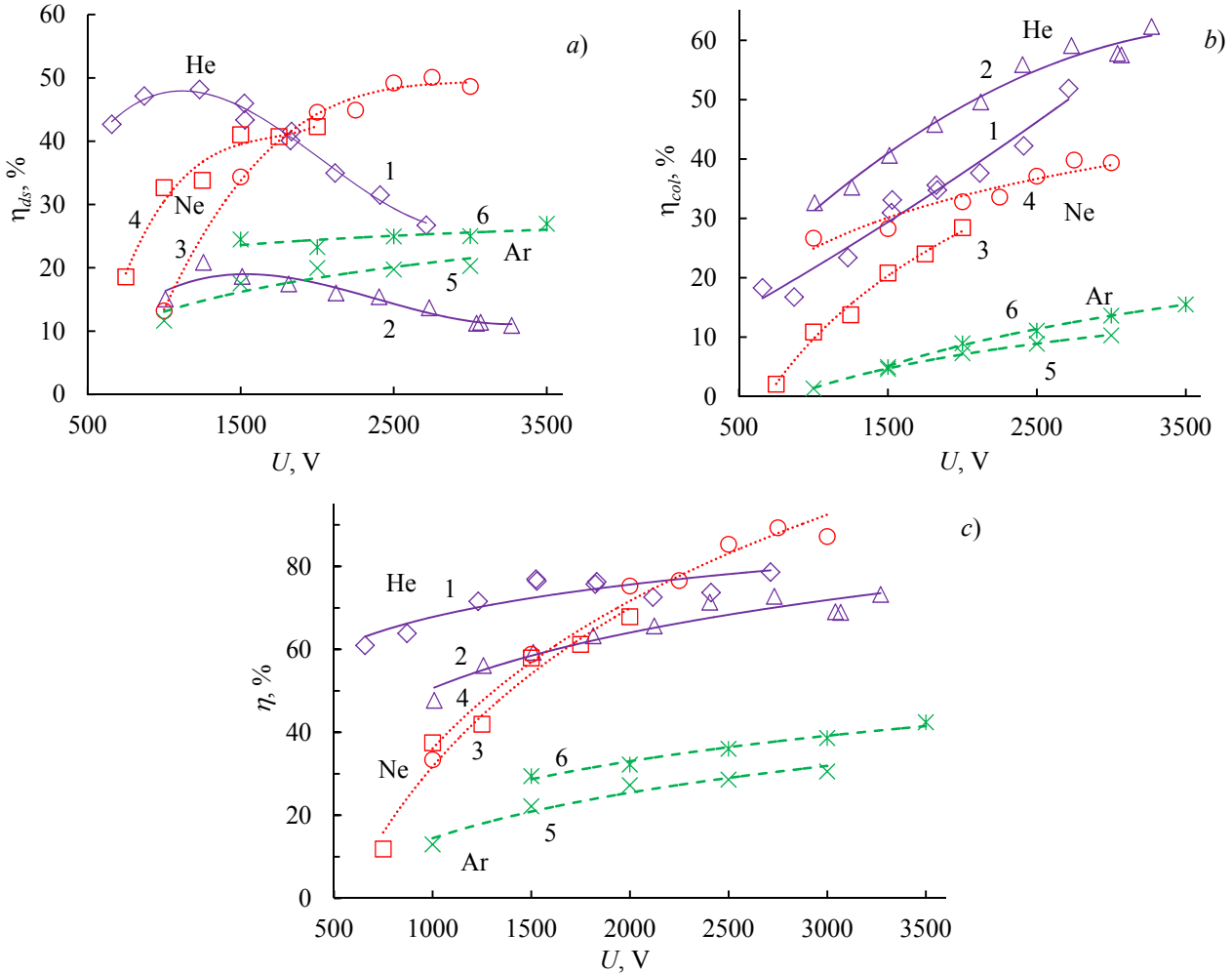


Fig. 2. Comparison of the dependences of the fractions of energy lost in the discharge gap $\eta_{ds}(U)$ – (a), at the collector $\eta_{col}(U)$ – (b), and their sum $\eta(U)$ – (c) on the voltage U at different pressures of the working gas p in He ($p_{He} = 10.2$ (1), 4.7 (2) Torr), Ne ($p_{Ne} = 1.5$ (3), 0.5 (4) Torr), and Ar ($p_{Ar} = 1$ (5), 0.35 (6) Torr)

Calculation by formula (1) shows that in He, Ne, Ar at $U = 2000$ V at $p_{He} = 10$ Torr, $p_{Ne} = 1$ Torr, and $p_{Ar} = 0.75$ Torr and values of the photoemission coefficient $\gamma_{ph} \approx 0.3$; 0.28, and 0.15 [17, 18], the number of photoelectrons born per one primary fast electron is $N_e \sim 0.505$; 0.50, and 0.196, respectively. Under the assumption that at $U \geq 2000$ V the beam is formed predominantly at the expense of photoemission, the calculated efficiency of electron beam

generation would be $\eta \approx 50.5$; 50, and 19.6%, respectively. From the obtained estimates it is evident that the calculated values are smaller than those obtained experimentally ($\eta \approx 72.6$; 75.5, and 30.6%). This indicates that under real conditions of the AGD, the contribution of photoemission is substantial, but not the only source of electron generation. An additional contribution may be made by other channels of secondary electron emission (primarily potential

emission under the action of ions and metastable atoms). Let us note that the geometrical factor R_s does not take into account the non-uniform excitation along the discharge gap, and η_{ex} in the proposed estimate does not depend on the electron energy and is taken as constant.

Conclusion

Thus, this work carried out a comparative study of the anomalous glow discharge in inert gases (He, Ne, Ar) at voltages above 1000 V under conditions of high purity of the gas medium and the cathode material. It is shown that the maximum efficiency of EB generation under the studied conditions is achieved in helium $\eta \approx 80\%$, neon $\eta \approx 90\%$, and argon $\eta \approx 40\%$ with a nonmonotonic form of the current-voltage

characteristic. Estimates of η under the assumption of operation under conditions of modification of the cathode by the working gas demonstrate that the main mechanism for sustaining the discharge is photoemission, and the discharge under such conditions is characterized by a high energy efficiency of the electron beam. Further development of this research direction presupposes the study of the AGD in the voltage range > 4 kV for obtaining beams with energies on the order of $\sim$ keV and a theoretical study of the mechanisms of electron emission.

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