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The Maxwellian nature of free-electrons' gas spectrum of noble gases at low pressure

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A B S T R A C T

A free-electrons' gas spectrum shape in gases under the influence of the electrical field is considered in the theoretical part of the paper. Based on the nature of electrons' interaction with ions and molecules (or atoms) of gas, it was concluded that the spectrum is Maxwellian, if noble gases and subpressures are used. This conclusion was experimentally verified in the Townsend's region of electrical discharge. The gases used were Helium, Neon, Argon, Xenon and Krypton. The utilized pressures ranged from 0.3 Pam to 10 Pam. Interelectrode distances were in the range of 0.1 mm–1 mm. It has been assumed that the free-electrons' gas spectrum is of the Maxwellian type by means of the mathematical analysis of macroscopically measurable consequences, and this assumption has been verified through the experiment. New constants enabling electrical discharge parameters' calculation in the Townsend's region have been presented according to Townsend's, Takashi's and Maxwell's expressions.

1. Introduction

Gases in nature represent a gas mixture of neutral atoms (or molecules), ions and electrons. Ions and electrons, created by photoionization, positive-ion ionization and metastable ionization, form a free-ions gas and a free-electrons gas. Each of these components represents a partial "gas" to which the Gas Mixture Laws is valid. The free-electrons' gas has a decisive role in electrical breakdown in gases [1–3]. Namely, the electrical breakdown of gases occurs as a result of collision of free electrons, accelerated by an electrical field, and atoms (or molecules) of gas, which in turn creates new free electrons and ions, which possibly leads to forming the self-sustaining mechanism (positive feedback). Self-sustained discharge forming is controlled by the collision processes' relations comprising charged particles and their transport properties. It can be concluded that the process development of gas electrical breakdown depends on the relative efficiency of mechanisms for generation and annihilation of free electrons, which determine both spectral distribution and free-electrons' gas density during the electrical discharge [4–6].

In normal conditions, i.e. without the electrical field influence, free-electrons' gas spectral distribution (as well as other gas mixture components) is of the Maxwellian type [4,7]. Nevertheless, when such a gas mixture is found within a direct electrical field, one drift component is superpositioned in the direction of the field by thermal speeds of its charged constituting components [8,9]. Generally speaking, in such a case, free electrons and ions' gas spectrum is no longer of the Maxwellian type. The reason for this is the non-elastic nature of these collisions in the field direction. Namely, a part of free-electrons and free-ions gas energy, taken over from the electrical field, is lost due to the excitation of neutral molecules' rotational and vibration quantum mechanical states. In addition to this, the deviation from the Maxwellian shape of free-electrons and free-ions gas spectrum also occurs due to their Coulomb interaction with other free electrons and ions. However, these phenomena do not occur in the case of atomic (i.e. noble) gases at low pressures (100 Pa–10^4 Pa) (atomic gases do not have rotational and vibration states, the ionization degree is small at low pressures, and consequently the interaction between the charged particles is negligible). As a result of this, the condition may be considered as the free electrons' interactions are of elastic type, so that the Maxwellian spectrum is not disturbed owing to the electrical field influence. The aim of this paper is to verify the statement on the Maxwellian nature of free-electrons gas spectrum, and to check the possibility of its application in the electrical discharge modeling process for noble gases at low pressures.

2. Electrical breakdown of gases

As mentioned above, electrical breakdown of gases is a self-sustaining process based on the primary and secondary processes

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of electrical discharge in gases. The basic primary process of gas discharge is electron ionization. Electrons ionization occurs when a free electron on a single free path takes over the energy from the electrical field that is greater than (or equal to) the electrons' bond energy in neutral atoms (or molecules). More precisely, this electron becomes an initial electron. This enables electron to perform ionization in the ensuing collision. Once the ionization has been initiated, it leads to the free electrons' avalanche. When the free electrons' avalanche, created in this way, reaches the anode, the process would stop if there were not secondary gas discharge processes, which provide a positive feedback leading to a sequence of avalanches which sum results in the breakdown. Secondary gas discharge processes are divided into cathode active processes (ionic ejection, photoemission and metastable ejection) and the gas active processes (positive-ion ionization, photoionization and metastable ionization). If the dominant secondary processes are active at the electrodes, breakdown occurs according to the Townsend mechanism. If the dominant secondary processes are active in the gas, breakdown occurs according to the streamer mechanism [10–13].

Townsend's (primary) ionization coefficient α and secondary ionization coefficient γ are introduced in order to mathematically formulate conditions for the Townsend and streamer mechanisms of breakdown.

Starting from the assumption that a single electron creates α new electrons on the path length in the field direction, we can conclude that the free electrons number increase by n free electrons on the path $\mathrm{d}x$ is:

$$\mathrm{d}n = \alpha(x)n\mathrm{d}x \tag{1}$$

Based on the expression (1) and the analysis of experiment results [14], two expressions of the α coefficient dependence on the electrical field E and pressure p are provided:

$$\alpha = C_1 p \exp\left[-C_2\left(\frac{p}{E}\right)\right] \tag{2}$$

$$\alpha = k_1 p\left[1 - \exp\left(\frac{\frac{E}{p} - k_2}{k_3}\right)\right] \tag{3}$$

where $C_i(i = 1,2)$ and $k_i(i = 1,2,3)$ constants depend on the gas type and the range of the pd product (pressure multiplied by interelectrode distance), to which the expressions (2) and (3) are applied.

The expression (2) is often called the Townsend expression, while the expression (3) is often called the Takashi expression [15,16].

However, the α coefficient dependence on the pressure and electrical field is most precisely obtained by starting from the definition according to statistical physics [2]:

$$\alpha(p,E) = n_0\int_{\varepsilon_1}^{\infty}\sigma_i(\varepsilon)\nu f(\varepsilon)\mathrm{d}\varepsilon \tag{4}$$

where ν and ε are the speed and kinetic energy of free electrons; σ_i is the cross-section for ionization; ε_i is the ionization potential (bond energy) of the observed gas, and $f(\varepsilon)$ is the free-electrons gas spectrum. Under the assumption that the free-electrons' gas spectrum is of the Maxwellian type, and originating in the expression (4) the following expressions are obtained:

$$\alpha = C\cdot p\left(\frac{p\varepsilon_i}{ZE} + 2\right)\exp\left(-\frac{p\varepsilon_i}{ZE}\right) \tag{5}$$

where

$$C = C_1\exp(C_2 pd) \tag{6}$$

and

$$Z = Z_1(pd)^{Z_2} \tag{7}$$

while p is the gas pressure, d is the interelectrode distance, and E is the electrical field, and C_1,C_2,Z_1 andZ_2 are constants which depend on the type of gas.

Secondary ionization coefficient γ does not depend on the electrical field and pressure, but it depends on the electrode material and the electrode surfaces' processing type. Due to that, γ may be, under constant experiment conditions, considered constant [17,18].

With ionization coefficients defined in such a way, it can be demonstrated that the condition for gas breakdown according to the Townsend mechanism is:

$$\gamma\int_0^d \alpha(x)e^{\int_0^x \alpha\mathrm{d}x}\mathrm{d}x = 1, \tag{8}$$

while the condition for gas breakdown according to the streamer mechanism is:

$$\int_0^d \alpha(x)\mathrm{d}x = 10,5. \tag{9}$$

Expressions (8) and (9) are significantly simplified in case of the homogenous electrical field [19,20].

3. The experiment and the experiment results' processing

The measurements have been performed in the well-controlled laboratory conditions. During the measurement, a disassembling gas chamber and the corresponding vacuum-gas circle have been used. Experiment parameters comprised gas types and the interelectrode distance. Applied gases were noble gases (Helium, Argon, Neon, Xenon and Krypton). The electrodes that provided a pseudohomogenous electrical field were of the Rogowski shape and were made of copper. Before each measurement series electrodes were sandblasted. By sandblasting electrodes, it was enabled the statistic sample of the dc breakdown voltage random variable to be independent from the irreversible changes interelectrode topography during a single measurement series. The *U*-Test has demonstrated that 1.000 random variables of the dc breakdown voltage statistic sample belong to a unique statistic distribution with the statistic uncertainty of 0.5% (in case of polished electrodes, for the same conclusion, statistic uncertainty equals 5%).

After multiple chambers' vacuuming up to the pressure of 10^{-4} mbar and 1 bar pressure working gas filling, the chamber pressure was calibrated by a special doses valve. This pressure enabled a spectroscopic purity of working gas during a single measurement series. Namely, with the aim of testing gas purity in the chamber, and utilizing the same procedure, a glass chamber was filled. After developing a stable electrical discharge the presence of any other gas was not detected by means of spectral analysis. Chamber sealing was good. Measuring pressure of Helium at 10 mbar (reduced to 0 °C) during a 24-h period indicated no variations in pressure, which means that it was constant during a single measurement series for each of the noble gases (He has the smallest