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Influence of the breakdown mechanism to the left of the Paschen minimum on the breakdown temperature of the free electron gas Maxwell spectrum

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ABSTRACT

Dc breakdown of helium in the range to the left of the Paschen minimum is examined. An expression relating breakdown voltage to the *pd* product (pressure × inter-electrode distance) and the breakdown temperature of the free electron gas Maxwell spectrum is derived. The type of breakdown mechanism is deduced by submitting the measured values of breakdown voltage in the range to the left of the minimum to a statistical analysis that treats the dc breakdown voltage as a random variable. Fitting the derived expression to experimental results allows breakdown temperatures to be determined, along with ways of applying them under different breakdown mechanisms.

1. Introduction

In the range to the left of the Paschen minimum, inter-electrode gap breakdown turns from the gas mechanism to the vacuum mechanism [1,2]. Gas mechanism, which is present in the proximity of the Paschen minimum (and so also to the left of it) is of Townsend type [3–5]. Once the electron mean free path becomes greater than the inter-electrode distance, conditions for multiplicative mechanisms cease to exist, and breakdowns start to take place through vacuum mechanisms [6,7]. Onset of vacuum breakdown mechanisms makes the Similarity Law ineffective, which also means that the Paschen Law is no more valid. The change from gas to vacuum breakdown mechanism does not appear at a strictly defined point, but occurs over a transitional region in which the two mechanism can coexist [3,8].

Every gas can be viewed as a mixture of gases which comprise neutral atoms (or molecules), positive ions (and/or negative ions, if the gas is electronegative), and free electrons. Effective temperature of the energy spectrum of the free electron gas, which to a first approximation can be considered a Maxwell spectrum [9], determines if a self-sustaining multiplication mechanism that results in breakdown occurs or not. Effective temperature of the free electron gas Maxwell spectrum for which breakdown ensues is called the breakdown temperature. The goal of this study is to identify breakdown mechanisms in noble gases in points to the left of the Paschen minimum, as well as the corresponding behavior of the breakdown temperature.

2. DC breakdown of SF_6 gas in points to the left of the Paschen minimum

Insulating properties of a gas or gas mixture depend crucially on the energy of free electrons in it, as well as on the processes of their generation and disappearance [10]. These processes are characterized by the Townsend coefficients. The first Townsend coefficient is related to the process of free electron generation in a gas, and represents the number of free electrons generated by ionization events per unit length in the direction of the field (ionization coefficient α). The second Townsend coefficient represents the number of electrons that disappear per unit length in the direction of the field, by being attached to electronegative atoms or molecules (attachment coefficient η). Processes of ionization and attachment are probabilistic, and the probability for their

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occurrence is expressed through the so called effective cross-section [11]. Gas helium, observed in the paper, being a noble gas, belongs to electropositive gases, so its attachment coefficient (η) value is zero. Secondary Townsend coefficient γ describes the processes that make the discharge self-sustained (through a positive feedback). Secondary Townsend coefficient is the number of free (secondary) electrons created per single primary avalanche. Processes that result in creation of secondary electrons can be active either at the cathode (which corresponds to the Townsend breakdown mechanism, typical for small values of the *pd* product), or within the gas (which corresponds to the streamer breakdown mechanism, typical for large values of the *pd* product).

For a non-homogeneous electric field, the condition for breakdown around the Paschen minimum, which occurs via the Townsend mechanism, is given by the expression [12]:

$$\int_0^d \gamma \cdot e^{\int_0^d [\alpha(x)-\eta(x)]\mathrm{d}x} \cdot \alpha \mathrm{d}x = 1 \tag{1}$$

where integration is performed along the line of highest electric field, except in case of the anomalous Paschen effect [13].

In case of a homogeneous electric field and an electropositive gas, expression (1) transforms into:

$$\gamma[\exp(\alpha d) - 1] = 1 \tag{2}$$

Townsend ionization coefficient can be expressed as a function of free electron spectrum parameters as [14,15]:

$$\alpha(x) = n_0 \int_0^\infty \sigma_i(\varepsilon) \upsilon f(\varepsilon) \mathrm{d}\varepsilon \tag{3}$$

where υ is the speed of free electrons in the spectrum, σ_i is the effective cross-section for ionization, which depends on free electron energy ε, n_0 is the density of neutral molecules, $f(\varepsilon)$ is the distribution function of free electrons according to energies. $f(\varepsilon)$ can be intricate, but to a first approximation can be considered a Maxwell distribution [16]:

$$f(\varepsilon)\mathrm{d}\varepsilon = 2\sqrt{\frac{\varepsilon}{\pi}} \cdot \left(\frac{1}{kT}\right)^{3/2} \cdot \exp\left(-\frac{\varepsilon}{kT}\right)\mathrm{d}\varepsilon \tag{4}$$

Inserting the Maxwell distribution of equation (4) into (3), integrating from ionization energy ε_i to ∞, and expressing the concentration of neutral molecules from the equation of gas state, the following equation is obtained:

$$\alpha(T_e) = 4\frac{M\sigma_{i0}}{R\sqrt{\pi}} \cdot p \cdot \frac{\varepsilon_i + 2T_e}{T_e} \exp\left(-\frac{\varepsilon_i}{T_e}\right) \tag{5}$$

where M is the gas molecular mass, σ_{i0} is the effective cross-section for ionization of a neutral gas molecule by an electron with energy ε_i, R is the Rydberg constant, and T_e is the electron temperature given by:

$$T_e = \xi\lambda eE = C_2\frac{U_d}{pd} \tag{6}$$

where C_2 is a constant dependent on the shape of the free electron spectrum and gas type [16].

Since in the range around the Paschen minimum electrical breakdown occurs exclusively by the Townsend mechanism, and if electric field is homogeneous, the condition for a dc breakdown of an electropositive gas is obtained by inserting expression (5) into (2):

$$\gamma\left\{C_1 \cdot pd \cdot \frac{\varepsilon_i + 2T_d}{T_d} \cdot \exp\left(\frac{\varepsilon_i}{T_d}\right) \cdot \exp\left(C_1 \cdot pd \cdot \frac{\varepsilon_i + 2T_d}{T_d} \cdot \exp\left(\frac{\varepsilon_i}{T_d}\right)\right) - 1\right\} = 1 \tag{7}$$

Apart from the equation (7), which is obtained under the assumption that the electrical field is homogeneous, all other equations (1–6) are valid for non-homogeneous field.

3. Experiment and processing of measurement results

Experimental procedure was conducted under well controlled laboratory conditions. The chamber and gas circuit used for experiments enabled gas pressure and inter-electrode gap to be set with type B measurement uncertainty lower than 3% (Fig. 1) [17,18]. The combined measurement uncertainty was, also, lower than 3%. Large number of measurements had influence on the said uncertainty values as well as the fact that the observed quantity is, conditionally, deterministic (dc breakdown voltage) [18]. These parameters were kept constant for long periods of time (one day or longer). Radial-shape electrodes provided a homogeneous electric field in the inter-electrode gap [6]. The electrodes were made out of copper (in the majority of cases), but for certain measurements elektron and tungsten electrodes were also used (elektron is light alloy consisting mainly of magnesium with variable amounts of zirconium, silver, zinc, aluminum or rare earth metals). The electrodes were subjected to standard polish prior to each series of measurements (in the majority of cases), but were also polished to a high gleam in certain cases. The number of changes of electrode topography per unit area, caused by breakdowns, was determined after each series of measurements, using optical (microscopic) and mechanical (talysurfic) techniques. These measurements were performed in central and edge regions of electrode surfaces.

The measurement procedure started with a desired inter-electrode distance being set and the chamber connected into the gas circuit. A vacuum pump would then evacuate the air from the chamber, until pressure dropped to 10^{-3} mbar. The chamber was then “rinsed” from remaining air, by alternately introducing and evacuating the working gas (helium). The cleaned chamber would then be filled with the working gas at a desired pressure reduced to the temperature of 0 °C in order to get comparable results obtained by the long-term measurements.

Points of the static Paschen curve were obtained from the results of 10,000 breakdown voltage measurements, conducted with a generator that provided a voltage with 8 V/s rate of rise and 1 min intervals between each two consecutive breakdowns, in order to minimize the memory effects of previous breakdown related both to the gas (increased concentration of ion–electron pairs) and electrodes (thermal instability) [8]. The electrode system was conditioned with 10,000 consecutive breakdowns prior to each series of measurements, with concurrent measurements of the V_{-4} voltage, i.e. the voltage at which prebreakdown current is 10^{-4} A.