DOES ELECTRIC FIELD NONUNIFORMITY AFFECT GAS BREAKDOWN?

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This paper presents the results of studying the gas breakdown in the nonuniform constant electric field. We registered the discharge breakdown curves in nitrogen between flat electrodes of 12 mm in diameter and spaced 5 and 25 mm apart whereas the chamber diameter was 56 mm. We demonstrate that in contrast to previous studies with the narrow gap between the electrodes and the chamber wall the breakdown curves for different space values actually coincide when plotted to the $U(pL)$ scale. The Paschen law holds under conditions of our experiments though the inter-electrode spacing exceeds almost fourfold the electrode radius and the electric field axial profile for a larger spacing possesses a minimum at the inter-electrode gap center. Consequently, under condition studied the electric field nonuniformity did not affect practically the breakdown process.

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INTRODUCTION

Direct current glow discharge is widely applied in high pressure xenon and mercury lamps [1], in the processes of plasma nitridizing iron-based alloys [2], as well as for pumping gas discharge lasers (helium-neon ones, carbon oxide ones with nitrogen admixture etc) [3]. In order to optimize plasma technological processes and devices one has to know the conditions under which an electrical discharge ignites in them. An breakdown curve describes the ranges of voltage and gas pressure values whithin which a gas discharge plasma may be produced.

Breakdown curves (the dependence of the breakdown voltage U on the product of the gas pressure and the inter-electrode distance pL) in short tubes obey Paschen's law $U = f(pL)$ [4, 5]. For Paschen's law to hold the voltage at the breakdown curves minima as well as the pL product for different values of the inter-electrode distance have to remain unchanged i.e. constant. The breakdown voltage U is the function of the pL product but not of p and L separately. Therefore if the pL product remains constant in two geometrically similar discharge tubes with flat electrodes and the identical gas species then the breakdown voltage also remains the same. Consequently, for Paschen's law to hold it is necessary that the breakdown curves $U(p)$ registered for different inter-electrode distance L values match each other when plotted as a function $U(pL)$.

However the authors of a number of papers [6 - 12] found that with the pL values fixed the discharge breakdown voltage values in narrow gaps were remarkably lower than those for longer inter-electrode distance values. They demonstrated that on increasing the inter-electrode distance keeping the pL product fixed the breakdown voltage grew. Papers [7 - 11] studied in detail the discharge ignition in cylindrical tubes in the broad range of the distance values L between flat electrodes of radius R with the ratio values of $L/R \le 3$ [7 - 10] and $L/R \le 60$ [11]. They found that Paschen's law holds only for the gas breakdown in short discharge tubes when $L/R \le 1$. In the range of $L/R > 1$ increasing the inter-electrode distance L leads to the shift of breakdown curves $U(p)$ to the region of higher breakdown voltage values U and higher gas pressure ones. When the condition $L/R > 20$ holds, the breakdown curves with the distance L growing experience a shift to the range of higher voltage U values with the gas pressure at their minima remaining almost unchanged [11].

In paper [12] the influence of the electrode diameter (55, 25, 12, 5, 2.4 and 0.8 mm) on discharge ignition in nitrogen was studied in the discharge tube of 56 mm in diameter with the inter-electrode distance of 25 mm. The authors of paper [12] found that decreasing the electrode diameter led at higher gas pressure to the discharge ignition at lower voltage values than for large electrodes and at low gas pressure they observed the shift of breakdown curves to higher voltage breakdown values. They discovered that all registered breakdown curves intersected at the nitrogen pressure value of $p \approx 0.9$ Torr which was close to the inflection point of the breakdown curves for large electrodes. However the authors of paper [12] did not study the gas breakdown at different inter-electrode gap values, therefore one cannot draw a conclusion from their results on the applicability of Paschen's law for nonuniform electric fields.

The authors of paper [13] registered the breakdown curves of the discharge between the flat anode and cathodes of different design: a flat one and conical ones of different height keeping constant the minimum inter-electrode distance. They observed that the minima and the right-hand sections of breakdown curves matched, and only the left-hand sections differed. At lower pressure values they observed the divergence of left-hand branches of breakdown curves for the cathodes of different design.

The present paper aimed to register the breakdown curves between flat electrodes with their diameter being less than the inner diameter of the discharge tube for the cases of uniform and nonuniform distributions of the electric field within the inter-electrode gap and to clarify the applicability of Paschen's law for the breakdown description in nonuniform fields.

For gas breakdown studies the discharge tube was employed of 56 mm inner diameter with flat electrodes of 12 mm in diameter spaced 5 and 25 mm apart. Studies were performed in nitrogen in the pressure range $p = 0.05…100$ Torr and dc voltage range $U_{dc} \le 3000$ B. The gas pressure was controlled with baratrons of 1000 and 10 Torr.

EXPERIMENTAL RESULTS

Conventionally the researchers register the breakdown curves between flat electrodes with about uniform distribution of the electric field strength between them. However in many gas-discharge devices one often applies small electrodes of complicated design. They produce a nonunform electric field and are located inside the chambers of large dimensions. Therefore it is of interest to register the breakdown curves between flat electrodes which diameter is less than that of the tube, and here the breakdown may develop along a longer way in the nonuniform field.

Consider the breakdown curves in nitrogen we registered for different gap values between the flat cathode and anode. Fig. 1 depicts the breakdown curves (breakdown voltage against gas pressure) for two values of the distance between flat electrodes of 5 and 25 mm which diameter was 12 mm with the inner diameter of the discharge tube of 56 mm. The same breakdown curves are shown in Fig. 2 as a function of the product of gas pressure and inter-electrode gap size *pL*. It is clear from these figures that both breakdown curves possess a conventional U-type pattern. Increasing the inter-electrode gap value from 5 to 25 mm led to the shift of the breakdown curve to the low pressure range whereas the minimum breakdown voltage was equal to about 286 V for both curves.

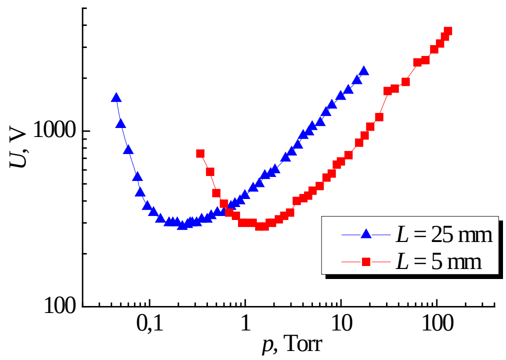

Fig. 1. Breakdown curves in nitrogen for the inter-electrode gap values of 5 and 25 mm

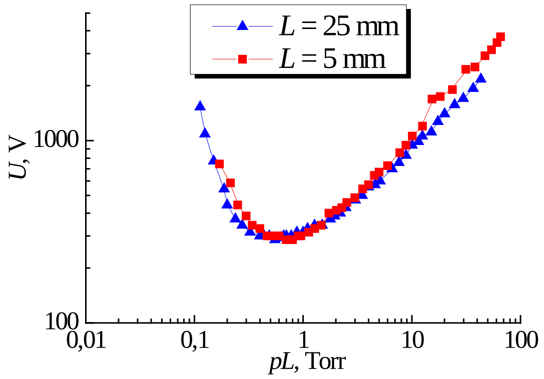

Fig. 2. Breakdown voltage against pL product for the gap values betwee flat electrodes of 5 and 25 mm

Again, it follows from Fig. 2 that at the pressure near to and to the left of the minima the breakdown curves for different gap values match practically when plotted to the *U*(*pL*) scale. One may draw the conclusion from these results that Paschen's law holds in the gas pressure range indicated. However at higher pressure values (which thrice or more exceed the pressure value at the minimum) the right-hand branch of the breakdown curve for the gap value of 25 mm runs below the curve for 5 mm.

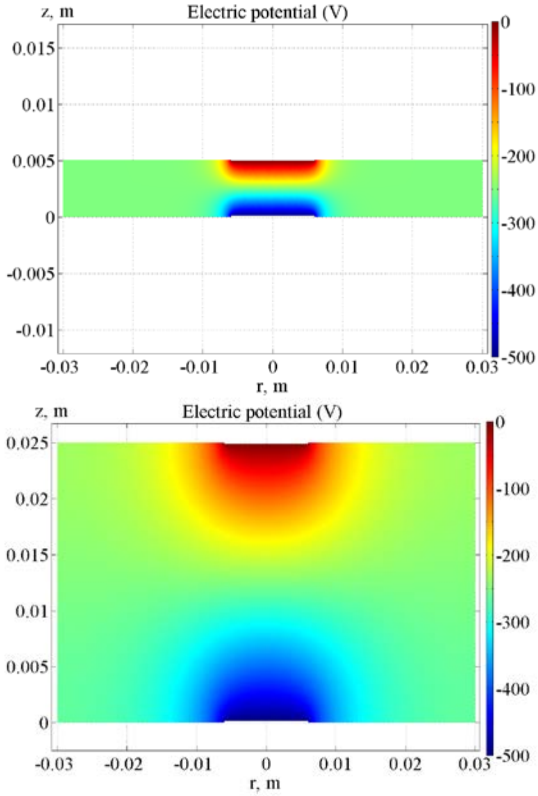

Fig. 3. Electric potential distribution in gaps between flat electrodes of 5 and 25 mm

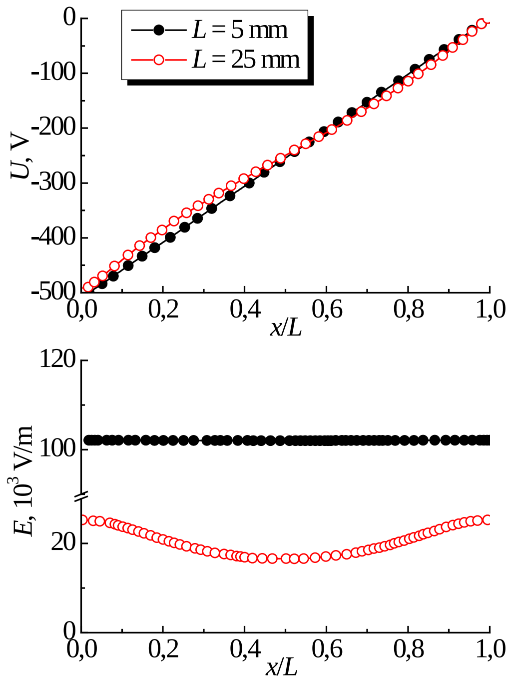

Fig. 4. Axial distributions of electric field strength and potential for the gaps between flat electrodes of 5 and 25 mm

Fig. 3 shows the potential profiles calculated with the FemLab code (COMSOL, Inc., www.comsol.com) [14] for the electrodes of 12 mm in diameter spaced 5 and 25 mm apart and located in the chamber of 56 mm in diameter. In both cases it was assumed that the inter-electrode voltage drop was 500 V. Correspondingly, Fig. 4 presents the axial distributions of the potential and the electric field strength between the same electrodes. The figures demonstrate the linear pattern of the potential variation within the gap of 5 mm whereas the field remains constant. However for larger gap of 25 mm between the electrodes the potential ceases to be linear whereas the electric field strength is maximum near the electrodes but it decreases fast when one departs from their surface and possesses a minimum at the central region.

The condition for gas breakdown within the flat gap for the nonuniform field has the form [15]

$$\int_0^L \alpha\left[E(z)\right]dz = \ln\left(1+1/\gamma\right). \qquad (1)$$

In the electron avalanche propagating from the cathode to the anode a certain number of ion-electron pairs have to be produced. This number is determined only by the secondary ion-electron emission coefficient and it does not depend on the circumstance whether the breakdown occurs in the uniform or strongly nonuniform field. The integral in formula (1) is exactly equal to the value of the $\alpha\cdot L$ product corresponding to the breakdown voltage for this gap in the uniform field between large flat electrodes. In weak electric fields the first Townsend coefficient α

$$\alpha = p\cdot A\cdot \exp\left(-\frac{B}{E/p}\right). \qquad (2)$$

rises with the growth rate increasing with E increasing (A and B constants depend on ion species) and in very strong fields its growth rate decreases. Fig. 5 shows how the first Townsend coefficient divided by gas pressure α/p and ionization ability of electrons η depend on the reduced electric field E/p. The maximum ionization ability of electrons is observed at the reduced electric field value $E/p = B$. In Fig. 5 this value is shown with a vertical line. The inflection point of the $\alpha(E)$ function is located at the value of the reduced electric field strength $E/p=B/2$ and it is also shown in the figure.

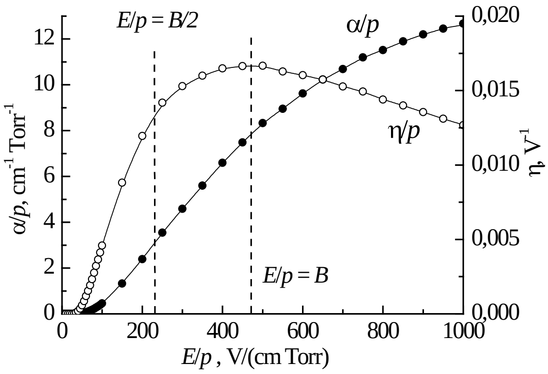

Fig. 5. First Townsend coefficient and ionization ability of electrons against reduced electric field

To the right of the inflection point the non-distorted breaking reduced field is $E/p<B/2$, and the redistribution of the potential between the electrodes, if the voltage between them $U = \left|\int_0^L E dx\right|$ is identical for the cases of uniform and nonuniform distributions of the electric field, makes the conditions for the gas breakdown easier because the enhanced field introduces a larger contribution into integral (1) than the weakened field subtracts. To the left of the inflection point ($E/p> B/2$) the process of ionization multiplication is impeded because of the redistribution of the electric field in the discharge gap [16] and the breakdown voltage increases, what we observe in Fig. 1.

From the considerations outlined above one may draw the following conclusion: the ionization process is made easier in the nonuniform field at sufficiently high pressure (to the right of the inflection point). Therefore the right-hand branch of the breakdown curve for the inter-electrode distance of 25 mm runs below that for the distance of 5 mm.

Note also that the minima of the breakdown curves for the gaps of 5 and 25 mm in Fig. 2 coincide despite the fact that the axial profile of the electric field for the larger gap is not uniform but it possesses a minimum at the center of the inter-electrode gap. Consequently, the electric field nonuniformity did not affect practically the breakdown process under conditions of our experiments. In discharge tubes with the electrodes spanning over almost all its cross section the diffusion escape of electrons to the tube walls plays a large role. Fig. 6 presents the breakdown curves for the inter-electrode gaps of 5 and 25 mm for three different sets of electrode and tube diameter values. In the first set the electrode and tube diameter values were equal to 12 and 56 mm, respectively (these curves are depicted above in Figs. 1 and 2). In the second set we employed the electrodes of 55 mm in diameter placed inside the tube of 56 mm in diameter. The third set employed the electrodes of 12 mm in diameter placed inside the tube of 13 mm in diameter. Note that in the second and third sets the electrodes almost closed the cross section of the tube.

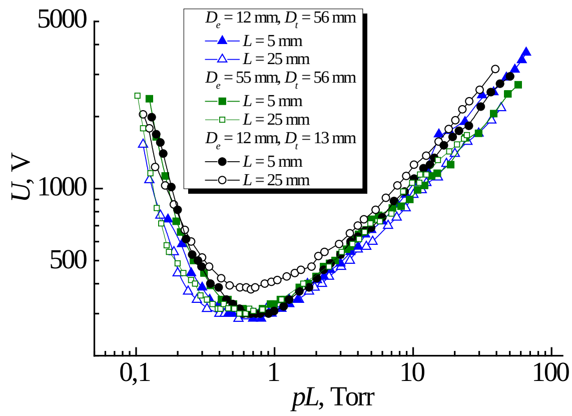

Fig. 6. Breakdown voltage against pL product for the gaps of 5 and 25 mm between flat electrodes for different diameters of electrodes and tubes

From the data of paper [11] it follows that Paschen's law is valid when the inter-electrode distance L does not exceed the diameter (double radius R) of the tube (electrodes), i.e. for $L/R \le 2$. This case is observed with the second set when the maximum inter-electrode distance did not exceed the radii of the tube and electrodes. In longer tubes when inter-electrode distance exceeds the tube and electrode radii noticeably, breakdown curves minima are shifted to the range of larger breakdown voltage values (what we observe in Fig. 6), and Paschen's law ceases to be valid. In our case when the inter-electrode distance around 4 times exceeds its radius and the tube radius is 4.7 times larger than the electrode one, electron loss due to diffusion escape to the walls practically does not play any role.

CONCLUSIONS

This paper reports the breakdown curves in nitrogen its authors registered for two inter-electrode distance values of 5 and 25 mm, the electrode diameter was 12 mm, and the inner diameter of the discharge chamber was 56 mm. We found that for flat electrodes the breakdown curves for different inter-electrode gap values actually coincide when plotted to the $U(pL)$ scale. A conclusion may be drawn from them that under conditions of these experiments (the inter-electrode distance about four times exceeds its radius) Paschen's law holds despite the fact that the axial profile of the electric field for a larger gap possesses a minimum at the center of the inter-electrode gap. Consequently, the nonunform pattern of the electric field distribution does not affect practically the breakdown process. The discharge tube radius exceeds 4.7 times the electrode one; therefore the electron loss to the walls due to diffusion escape of them plays no role for short gaps of 5 and 25 mm.

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ВЛИЯЕТ ЛИ НЕОДНОРОДНОСТЬ ПОСТОЯННОГО ЭЛЕКТРИЧЕСКОГО ПОЛЯ НА ПРОБОЙ ГАЗА?

В.А. Лисовский, Р.О. Осмаев, В.Д. Егоренков

Представлены результаты исследований пробоя газа в неоднородном постоянном электрическом поле. Измерены кривые зажигания в азоте для расстояний между плоскими электродами 5 и 25 мм соответственно, при диаметрах электродов 12 мм и камеры 56 мм. Показано, что в отличие от результатов предыдущих исследований с узким зазором между электродами и стенкой камеры кривые зажигания для различных расстояний практически совпадают, если их построить в масштабе $U(pL)$. При условиях данных экспериментов (расстояние между электродами примерно в 4 раза превышает их радиус) выполняется закон Пашена, несмотря на то, что осевой профиль электрического поля для большего зазора имеет минимум в центре промежутка между электродами. Следовательно, неоднородность распределения электрического поля в данных условиях практически не оказала влияния на процесс пробоя.

ЧИ ВПЛИВАЄ НЕОДНОРІДНІСТЬ ПОСТІЙНОГО ЕЛЕКТРИЧНОГО ПОЛЯ НА ПРОБІЙ ГАЗУ?

В.О. Лісовський, Р.О. Осмаєв, В.Д. Єгоренков

Представлені результати досліджень пробою газу в неоднорідному постійному електричному полі. Виміряні криві запалювання у нітрогені для відстаней між плоскими електродами 5 і 25 мм відповідно, при діаметрах електродів 12 мм і камери 56 мм. Показано, що на відміну від результатів попередніх досліджень із вузьким зазором між електродами і стінкою камери криві запалювання для різних відстаней практично збігаються, якщо їх побудувати в масштабі $U(pL)$. За умовами цих експериментів (відстань між електродами приблизно в 4 рази перевищує їх радіус) виконується закон Пашена, незважаючи на те, що осьовий профіль електричного поля для більшого зазору має мінімум у центрі проміжку між електродами. Отже, неоднорідність розподілу електричного поля за даних умов практично не мала впливу на процес пробою.