GAS BREAKDOWN IN DC ELECTRIC FIELD IN A DISCHARGE TUBE WITH FLAT AND CONICAL CATHODES

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This paper reports dc breakdown curves we registered between a flat anode and cathodes of various design: a flat one and cones of different height; the least inter-electrode distance was kept constant. We observed that the minima and the right-hand branches of breakdown curves coincided practically whereas the left-hand ones did not. At lower pressure values a divergence of left-hand branches of breakdown curves was registered for cathodes of different design. For conical cathodes the breakdown occurs either near its sharp tip or at the lateral surface of the cone at some distance from its tip.

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INTRODUCTION

Direct current glow discharge is broadly employed in xenon and mercury high pressure lamps, plasma processes of nitriding iron-based alloys as well as for pumping gas discharge lasers (helium-neon, carbon dioxide ones with a nitrogen admixture etc). For optimizing plasma technologies and devices one has to know the conditions for igniting a discharge in them. An breakdown curve depicts the ranges of voltage and gas pressure within which gas discharge plasma can be produced. Electrodes of complicated design are often used in discharge devices. For example, in high pressure xenon lamps the cathode may have a cone shape and a more massive anode may be either flat or a slanted cone. The parts and materials hardened via nitriding form the part of a cathode and they may be of rather different shapes. Therefore it is of large interest to study the ignition of the dc discharge between the electrodes of various designs.

In spite of a large number of papers devoted to studying the dc discharge ignition, one conventionally devotes main attention to the gas breakdown between flat parallel electrodes [1–10], between a plane and a point [11] or between parabolic-shaped electrodes [12]. The available reference data [13, 14] on igniting the discharge between electrodes of complicated design are contradictory and they need refinement. Therefore this paper aimed at measuring breakdown curves between a flat anode and cathodes of conical shape.

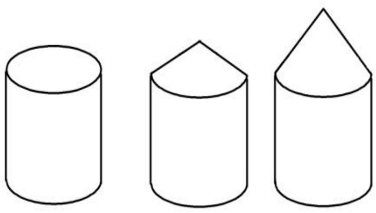

Fig. 1. Shapes of cathodes employed in this study

This paper reports the breakdown curves we registered for the dc discharge between a flat anode and the cathodes of different design (a flat one as well as two types of cones of different height), whereas the shortest distance between the electrodes was kept constant. We found that the minima and right-hand branches in all cases practically matched though the left-hand branches differed. At lower pressure values we observed the different behavior of left-hand branches of breakdown curves for cathodes of different design.

1. EXPERIMENTAL

Experiments were performed at the nitrogen pressure of $p = 0.06\ldots10$ Torr within the dc voltage range of $U_{dc} \le 3000$ V. The flat anode and the cathodes were made of stainless steel 12 mm in diameter; they were located inside a glass tube of 13 mm inner diameter. The flat anode was of the conventional cylindrical shape with a flat butt. The conical cathodes were 5 and 10 mm in height, respectively. In the experiments with conical cathodes the shortest distance between them and the flat anode was 5 mm. In the case of the flat cathode the inter-electrode distance values were 5 mm, 10 mm and 15 mm.

A dc supply was connected to the cathode whereas the anode was grounded. The discharge current data were registered with a digital ammeter, and the voltage data were registered with a digital voltmeter. An external resistor of 50 kOhms was switched into the discharge circuit for limiting the current and impeding the cathode spots appearance.

The technique for breakdown curve registering was as follows. With nitrogen pressure fixed the voltage across the electrodes was increased smoothly up to the moment of breakdown, which was detected through the appearance of glow in the inter-electrode gap together with the discharge current. We regarded the maximum voltage before the discharge ignition as the breakdown one.

2. EXPERIMENTAL RESULTS

First consider the breakdown curves of the discharge in nitrogen we have registered for different gap values between the flat cathode and anode.

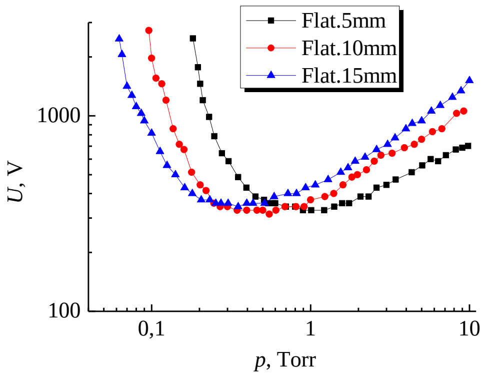

Fig. 2. Breakdown curves in nitrogen for the following gap values between flat electrodes: 5, 10, 15 mm

Fig. 2 depicts the breakdown curves in nitrogen for three gap values between flat electrodes, namely, 5 mm, 10 and 15 mm. It is clear from the figure that all breakdown curves possess a conventional U-shape pattern. Increasing the gap value from 5 to 10 mm led to a shift of the breakdown curve to the region of lower gas pressure values, whereas the minimum ignition voltage is approximately 329 V for both curves. As the inter-electrode distance $L = 5$ mm is less than the tube radius $R = 6.5$ mm, and the distance $L = 10$ mm exceeds it a little, the Paschen law is valid here. For gap values of 5 and 10 mm the gas pressure values at the breakdown curve minima amount to 1 Torr and 0.5 Torr, respectively. Therefore on the $U(pL)$ graph both these breakdown curve must coincide. However the inter-electrode gap of 15 mm exceeds the discharge tube radius by 2.3 times, therefore the deviation from the Paschen law is observed. This breakdown curve is shifted not only to the region of higher pressure values but also to the region of higher breakdown voltage values achieving now 357 V in the minimum. Such a violation of the Paschen law is described in detail in papers [5-9] and it is due to higher loss of electrons due to diffusion to discharge tube walls under the inter-electrode distance increase.

The breakdown curves for flat electrodes described above will be compared below with those for conical cathodes.

As was already outlined above, the design of a conical cathode is widely applied today, e.g. in xenon and mercury high pressure lamps. In such lamps the anode is manufactured as a massive slanted cone or flat part. Therefore the data given below may be of large practical interest. We performed our study with two conical cathodes of 5 and 10 mm in height, respectively. The registered breakdown curves for these cathodes are shown in Fig. 3.

It is clear from the figure that these breakdown curves coincide with the breakdown curve for flat electrodes with the inter-electrode gap of 5 mm near and to the right of the minimum. At lower gas pressure values breakdown curves for conical cathodes run in the range of lower gas pressure values than those for flat ones. Note that first the breakdown curve for the cone 10 mm in height ran more to the left of the curve for the cone 5 mm in height but at breakdown voltage values above 1400 V and low gas pressure values these two breakdown curve coalesced practically. Consequently, at higher gas pressure values and near the breakdown curves minima the breakdown with conical cathodes occurs near their tips regardless of their height and at the same voltage values registered for the flat electrodes with the 5 mm gap. At lower pressure values those lines of force are optimum for the discharge ignition which begin at the anode and end on the lateral surface of the cone at a certain distance from its tip. One can draw a conclusion from see Fig. 3 that for the cone of 10 mm in height the optimum lines of force for the breakdown are shifted from its point farther than ones for the cone of 5 mm in height. However with further lowering the gas pressure the length of these optimum lines of force becomes approximately equal for both conical electrodes what follows from the coincidence of breakdown curves for these cathodes.

The gas breakdown condition inside the flat gap with the nonuniform field has the form

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

where α is the first Townsend coefficient for gas molecule ionization through electron impact, γ is the ion-electron emission of the cathode surface, L is the inter-electrode distance (for flat electrodes) or the length of the electric line of force (for electrodes of complicated design). In the electron avalanche propagating from the cathode to the anode a certain number of ion-electron pairs have to be generated. 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 uniform or strongly nonuniform field. The integral in formula (1) exactly equals the $\alpha \cdot L$ product corresponding to the respective breakdown voltage of the gap in the uniform field between flat electrodes. Under an “optimum line” we mean the electric field line of force for which the breakdown criterion (1) holds. For low gas pressure (to the left of the breakdown curve minimum) the gas breakdown along the short path (short line of force) is impeded because electrons run along this path and escape to the anode having no time during this passage for the production of a number of ion-electron pairs required for gas breakdown. Electric field strength along a longer line of force than the optimum one would be lower; the electrons would acquire less energy which would not be sufficient for the ionization of gas molecules. Comparing the breakdown curve for a conical cathode with the breakdown curves for flat electrodes one may evaluate the length of the line of force optimum for discharge ignition at the gas pressure under consideration.

In papers [13, 14] the authors studied the effect of breakdown along a long path on the shape of breakdown curves of the dc micro discharges (with inter-electrode gap values of 20 to 500 microns), as well as for those of 1…2 cm (the authors call these gap values the “standard” ones). They registered the CVC of the Townsend regime and extrapolated it to the voltage axis at small discharge current values and regarded the obtained value as a breakdown voltage. In paper [14] the authors employed the flat cathodes as well as those of complicated design (a cathode with a step as well as a flat cathode with a cylindrical indentation near its axis). It was demonstrated that for the cathodes of complicated design with small gaps the left-hand side of the breakdown curve is relatively flat with the minimum shifted to lower values of the *pL* product. At high *pL* values the breakdown curves for the micro discharges are similar to the curves at the “standard” pressure/gap and the discharge is ignited between the upper cathode surface and the anode. At low *pL* values the discharge is ignited along the longest path, and on gas pressure decreasing the breakdown voltage increases fast. The same pattern of the breakdown curves is also observed for the cathode with a cylindrical indentation. However, some questions arise concerning the technique of breakdown voltage measurement as well as to the results obtained. Note that in paper [13] the authors remark that for micro discharges it is difficult to obtain a stably burning Townsend regime, and that a correct extrapolation to zero current cannot be made. Registered breakdown curves for micro discharges happened to be shifted to the region of higher breakdown voltage values by about 80…100 V compared with ordinary gap values. At high gas pressure values corresponding to the right-hand side of the breakdown curve the breakdown conventionally happens to occur along the shortest path with the largest electric field. From the data in Fig. 3 of paper [14] one observes that at *pL* = 3 Torr·cm the Townsend discharge occupies only a portion of the upper surface of the step-like cathode, therefore the breakdown has to occur at the same voltage that is characteristic for flat electrodes with the gap value equaling to the gap between the anode and the upper section of the cathode. However at the same *pL* values for flat electrodes the breakdown voltage is equal to about 280 V, and the for the step-like electrode it is about 420 V, i.e. 1.5 times higher. The discharge would hardly ignite at higher voltage values if there are all required conditions for gas breakdown at lower voltage values. Therefore the technique of registering the breakdown voltage values for the cathodes of complicated design from the CVC of the Townsend discharge employed in papers [13, 14] needs refinement.

CONCLUSIONS

In this paper we registered the breakdown curves in nitrogen for the fixed inter-electrode gap of 5 mm. The studies were performed for a flat anode and conical cathodes of 5 and 10 mm in height. We also made additional measurements for flat electrodes spaced 10 and 15 mm apart.

We found that for narrow inter-electrode gaps of 5 and 10 mm less than or compared with the tube radius, the Paschen law is valid, i.e. breakdown curves for different gap values coincide when plotted to the *U* (*pL*) scale. However for a longer gap of 15 mm the breakdown curve deviates to the range of higher voltage values, i.e. the Paschen law is not valid.

For conical cathodes the breakdown at high gas pressure occurs near their tips regardless of their height, besides the breakdown curves near to and to the left of their minimum are close to the breakdown curve for flat electrodes with the gap of 5 mm. At low pressure those lines of force are optimum for the discharge ignition which start at the anode and finish at the lateral surface of the cone at some distance from its tip.

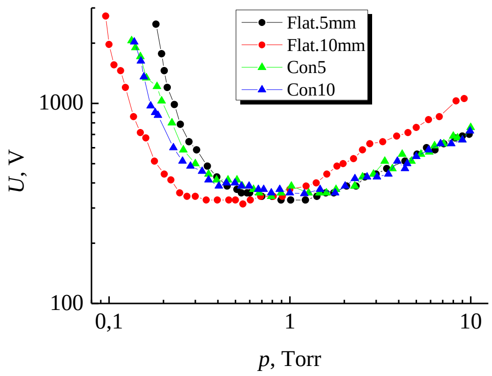

Fig. 3. Breakdown curves in nitrogen for the gap values between flat electrodes of 5 and 10 mm, as well as for conical cathodes

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ПРОБОЙ ГАЗА В ПОСТОЯННОМ ЭЛЕКТРИЧЕСКОМ ПОЛЕ В РАЗРЯДНОЙ ТРУБКЕ С ПЛОСКИМ И КОНИЧЕСКИМИ КАТОДАМИ

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

Измерены кривые зажигания разряда между плоским анодом и катодами разной геометрии – плоским и коническими различной высоты, при этом наименьшее расстояние между электродами сохранялось постоянным. Получено, что минимумы и правые ветви кривых зажигания во всех случаях практически наложились, различны были только левые ветви. При более низких давлениях наблюдается расхождение между левыми ветвями кривых зажигания для катодов различных геометрий. Для конических катодов пробой происходит вблизи их острия либо на боковой поверхности конуса на некотором расстоянии от его острия.

ПРОБІЙ ГАЗУ В ПОСТІЙНОМУ ЕЛЕКТРИЧНОМУ ПОЛІ В РОЗРЯДНІЙ ТРУБЦІ З ПЛОСКИМ ТА КОНІЧНИМИ КАТОДАМИ

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

Виміряні криві запалювання розряду між плоским анодом і катодами різної геометрії – плоским та конічними різної висоти, при цьому найменша відстань між електродами зберігалася постійною. Отримано, що мінімуми і праві гілки кривих запалювання у всіх випадках практично накладалися, різні були тільки ліві гілки. При більш низькому тиску спостерігається розбіжність між лівими гілками кривих запалювання для катодів різних геометрій. Для конічних катодів пробій відбувається поблизу їх вістря або на бічній поверхні конуса на деякій відстані від його вістря.