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DC GAS BREAKDOWN AND TOWNSEND DISCHARGE IN CO_2

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We report the breakdown curves and current-voltage characteristics (CVC) of the Townsend mode DC discharge we have measured in carbon dioxide. We compare the breakdown curves measured with two different techniques. With the first technique we regard as breakdown voltage the maximum voltage which we can apply across the electrodes without igniting the discharge with fixed values of the inter-electrode distance and the gas pressure. With the second technique we register the CVC of the Townsend mode in the μA-mA range and then extrapolate them to zero current. We reveal that in the nA-μA range the CVCs of the Townsend mode may have a complicated behavior due to the formation of the space charge. Therefore the second technique furnishes incorrect values of the breakdown voltage.

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INTRODUCTION

Presently the CO_2 plasma conversion [1-5] as well as the breakdown and properties of discharges in various technological chambers in carbon dioxide [6-10] attracted a large attention of researchers. It is associated with the fact that carbon dioxide is a gas whose accumulation in the Earth atmosphere gives rise to the greenhouse effect. Besides, separate parts of Mars Pathfinder Rover moving on the planet dusted surface (with the atmosphere containing around 96% of carbon dioxide) acquire a considerable charge [11]. This may lead to a breakdown of the gas gap between rover's parts with a large difference of potentials what may damage its electronic circuitry. Therefore the study of gas breakdown in carbon dioxide and of various modes of the DC discharge burning is relevant.

One usually registers the breakdown curves with three different techniques. With the first technique one usually increases the voltage slowly to the moment of breakdown keeping the inter-electrode gap and pressure values fixed, and the maximum value of the voltage which is achieved without discharge occurrence is regarded as the breakdown one (conventionally the voltage across the electrodes decreases immediately after the breakdown) [12-21]. In order to determine the breakdown voltage according to the second technique, one measures the current-voltage characteristics (CVC) of the Townsend mode of the DC discharge and extrapolates it with a straight line to zero current [22, 23]. For this one usually employs ballast resistors whose values do not exceed several megaohm, the measured discharge current amounting to several or tens μA and more. Researchers employing the third technique increase the voltage many times with different constant rates. The smallest value of the voltage at which the discharge breakdown occurred is assumed to be the breakdown one [24].

In this paper we employed the first and second techniques to register the breakdown curves of the DC discharge in carbon dioxide. Using the ballast resistor of several hundred megaohm, enabled us to perform a detailed study of CVC of the Townsend mode in the range of discharge current values below 3 μA. We have revealed that the first technique permitted us to measure just the breakdown voltage values. The second technique furnishes the incorrect results because of the complicated behavior of the CVC of the Townsend discharge before extinction.

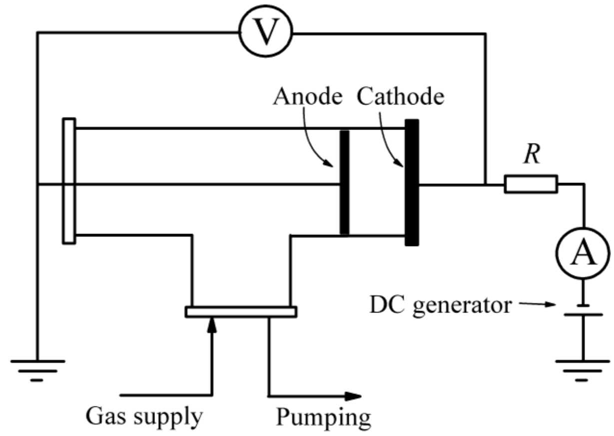

Fig. 1. The scheme of the experimental setup

1. EXPERIMENTAL

Gas breakdown was studied in the discharge chamber the scheme of which is presented in Fig. 1. The anode of 55 mm in diameter could move inside the tube of 56 mm inner diameter. The cathode was fixed as it was the flange of the tube. Both electrodes were made of stainless steel. The research was made in the range of inter-electrode gap values of 10...100 mm. We applied the ballast resistor of 620 MΩ. This enabled us to measure the discharge current values from units of nA to 2.8 μA. The readings of ammeters and voltmeter were digitized and registered with a PC.

The breakdown curves were measured in the CO_2 pressure range of 0.01...20 Torr, and the pressure was measured with capacitive manometers (baratrons, MKS Instruments) with the maximum registered pressure of 10 and 1000 Torr, the voltage across the electrodes did not exceed 2200 V.

2. EXPERIMENTAL RESULTS

In the course of these studies the emf of the supply was increased slowly with fixed inter-electrode gap and CO_2 values. Besides the voltage across the electrodes increased, and the current remained zero in the absence of the discharge.

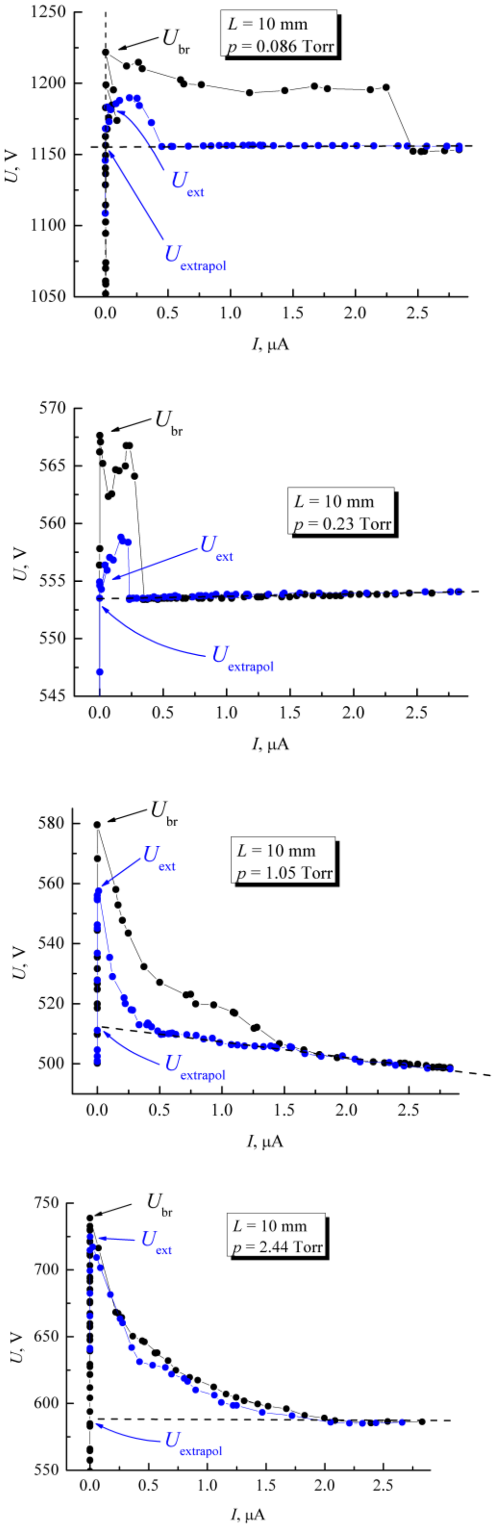

Fig. 2. CVC of the Townsend discharge with the inter-electrode gap of 10 mm and different carbon dioxide pressure values

When the voltage approached the values that were some tens volts below the breakdown one separate current jumps might occur (several nA), corresponding to separate avalanches developed between cathode and anode. However these avalanches did not lead to the discharge ignition, and after a short spike the current returned to zero valueEmf increasing caused the growth of the spike frequency but the discharge still was not ignited. When the voltage approached its breakdown value U_{br} the avalanche having passed between the electrodes started the discharge build-up, the inter-electrode voltage became lower and the subsequent emf growth led to the current increase. Fig. 2 depicts the voltage against current for different CO_2 pressure values for the 10 mm gap and Fig. 3 shows a similar dependence for the 100 mm gap. Black points indicate the CVC measured for the discharge current increasing to 2.8 μA, and blue points show the same for the current decrease down to the discharge extinction at the U_{ext} voltage.

One observes in Figs. 2, 3 that almost in all cases the breakdown voltage $U_{br,}$ determined according the first technique is substantially higher than the voltage of discharge extinction U_{ext} and the voltage $U_{extrapol}$ found by extrapolating the CVC of the Townsend mode to zero current with a straight line. At different values of the gas pressure and inter-electrode gap the quantity $\Delta = U_{br} - U_{extrapol}$ may amount from 10 to 150 V. It is the largest when the time between the successive discharges was not less than 1 minute but with frequent breakdowns it decreases substantially, and the "memory effect" [24] is observed.

Again, at low pressure, especially at the left-hand branch of the breakdown curve $U_{br}(p)$ (in the gas pressure range to the left of its minimum) the CVC of the Townsend mode is strongly dependent on the discharge current value. It is clear from Fig. 3 where the CVC is presented for the gap of 100 mm and the gas pressure of 0.023 Torr. After a slow voltage increase a breakdown occurred at U_{br} = 1411 V, and at once the voltage was decreased and a discharge current appeared. By increasing the emf of the supply this current was increased to about 1 μA (solid black points), and then by decreasing the emf the current was lowered to zero (black circles), The discharge extinction occurred at U_{ext} = 1338 V. After that the voltage was first lowered during several seconds by 20 V and then it was increased smoothly with the same rate (solid red points). On approaching the voltage value of 1387 V a repeated discharge breakdown occurred, after several pulsations the voltage across electrodes decreased sharply, and by increasing the emf the current was increased to 2 μA. Then the emf was lowered, the current also was lowered (red circles) down to the discharge extinction (which occurred at the higher voltage value of U_{ext} = 1345 V). Third time the voltage was first lowered, then it was increased until a repeated discharge breakdown. Again one observes the current and voltage pulsations that resulted by establishing a Townsend mode. This time the current was slowly increased to 2.8 μA (solid blue points), and then decreased to the discharge extinction (blue circles). It is clear from the figure that the larger discharge current was achieved by increasing the emf, the higher the CVC of the Townsend mode runs with the emf lowering. If we establish the current value, say, at 2.8 μA and make no emf changes, then with time you will observe simultaneously the current lowering and voltage increase across the electrodes what may lead to a discharge self-extinction.

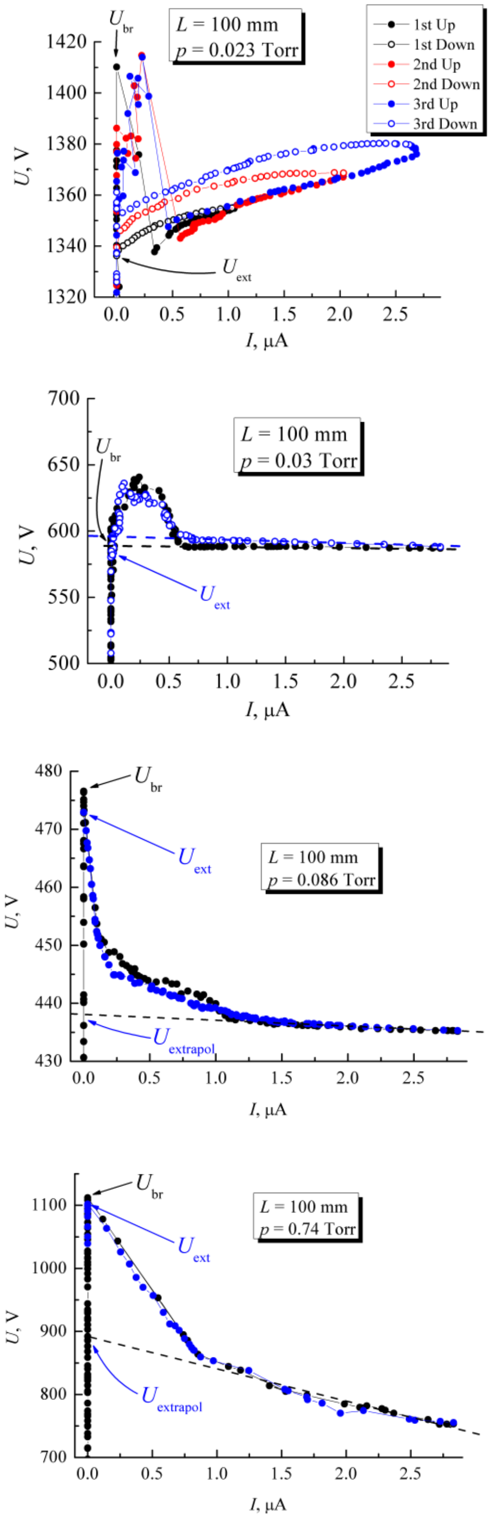

Fig. 3. CVC of the Townsend discharge for the inter-electrode gap of 100 mm and different carbon dioxide pressure values

Therefore the CVC of the Townsend mode is not a fixed dependence of voltage and current under conditions of the left-hand branch of the breakdown curve and, it may experience strong changes during the period of the discharge burning.

Probably even with the lowest currents the charged particles are generated in the Townsend discharge (disturbing the vacuum distribution of the electric field), the excited molecules are formed together with the products of gas molecule dissociation (including long-lived metastable ones [25]), and charges accumulate on the tube walls. At low pressure, especially at the left-hand branch of the breakdown curve $U_{br}(p)$ there also may occur the sputtering of the cathode surface due to ion bombardment that may add its contribution into the gas content and state of the tube walls. Conventionally the gas before breakdown does not contain charged particles (apart from not very numerous primary electrons generated in the inter-electrode gap due to cosmic radiation and a natural radioactive background of the Earth), the molecules are not excited, the gas does not contain dissociation products, and the tube walls are free of surface charges. Therefore one can hardly regard as correct the assumption that the voltage obtained as a result of extrapolation of the CVC (registered in the μA-mA current range) to zero current $U_{extrapol}$ describes just the gas breakdown. It is clear from Figs. 2, 3 that the genuine breakdown is observed only at the U_{br} voltage and not at $U_{extrapol}$ or U_{ext}.

Let us compare the breakdown curves we have measured with the results of other authors. Fig. 4 depicts the breakdown voltage U_{br}, the discharge extinction voltage U_{ext} and the voltage $U_{extrapol}$ one may obtain through extrapolation of the Townsend branch to zero current against the product of CO_2 pressure and inter-electrode gap pL at L = 10 mm. The same figure demonstrates the breakdown curves registered by the authors of papers [26-29]. Note that our breakdown curve $U_{br}(pL)$ agrees well with the results of other authors. The minimum of the breakdown curves in CO_2 obtained according to the first technique is observed at pL = 0.4...0.5 Torr·cm and U_{br} = 400...500 V, and the breakdown curves themselves possess the U-like form. The minimum of the $U_{extrapol}(pL)$ is broader. But the most remarkable feature of the $U_{extrapol}(pL)$ curves is the presence of a kink in the right-hand branch at the pressure almost 3 times exceeding the pressure at the minimum. To the right of this kink the $U_{extrapol}(pL)$ curve possesses the voltage values remarkably lower than those of the breakdown curves $U_{br}(pL)$ measured according to the conventional first technique. One may observe such kinks in the curves presented in papers where the second technique was employed (see [22, 23] and other similar papers) and for the "breakdown voltage" there was assumed the extrapolation voltage of the Townsend branch to zero current (of course, when these curves were measured in a sufficiently wide range of gas pressure values).

The authors of papers [22, 23] (and those of fresher papers) up to now have a difficulty to explain what processes create the presence of the kink in the breakdown curves they measured. Actually this kink was predicted theoretically in paper [14] and it is related to the so-called inflection point of the breakdown curve located at

$p = p_{min} \cdot e$ and $U = U_{min} \cdot e/2$ (where e is the base of natural logarithms). At this point the reduced electric field is equal to $E/p = B/2$ (B is the Stoletov's constant and it enters the generally accepted expression for the first Townsend coefficient $\alpha/p = A \cdot \exp[-B/(E/p)]$). To the left of the inflection point (at $E/p > B/2$) the accumulating space charge and the redistribution of the electric field within the gap impede the ionization process in the Townsend mode [20, 30, 31]. But to the right of the inflection point (at $E/p < B/2$) the field redistribution make the burning of the Townsend discharge easier, therefore in this pressure range one observes lower voltage values than in conventional breakdown curves.

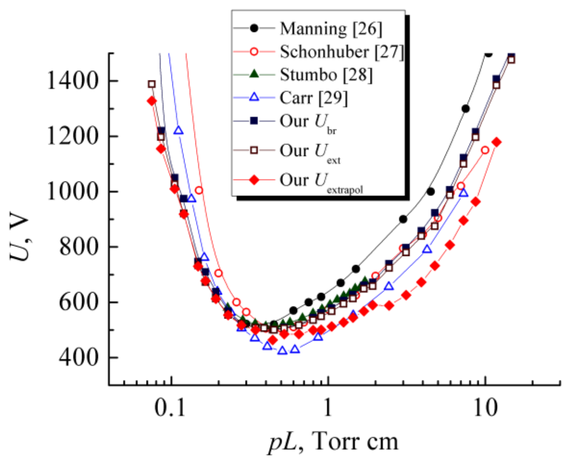

Fig. 4. Breakdown voltage U_{br}, the discharge extinction voltage U_{ext} and the voltage $U_{extrapol}$ obtained by extrapolation of the Townsend branch to zero current against the product of CO_2 pressure and the inter-electrode gap pL (in this case L = 10 mm), and breakdown curves measured by the authors of papers [26-28]

CONCLUSIONS

One may make the following conclusion: gas breakdown and Townsend discharge burning (in the μA–mA current range) are completely different phenomena. Under breakdown electron avalanches develop in the discharge chamber in which surface and volume charges are absent from the start, gas molecules are in the ground state, the products of molecule dissociation are absent. In the Townsend discharge of the μA–mA range there are already available sufficiently high concentrations of charged particles in the gap between the electrodes and on the tube walls perturbing the vacuum distribution of the electric field, and the excited molecules and dissociation products (and at low pressure the products of cathode sputtering by ion bombardment) may play a considerable role in discharge sustaining. Therefore it is not correct to describe the gas breakdown by extrapolating the CVC of the μA–mA Townsend discharge to zero current. This CVC describes a discharge that is already burning (self-sustained or with an additional source of charged particles thanks to irradiation of the gas volume or the cathode surface with UV radiation) and not the discharge breakdown.

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ПРОБОЙ ГАЗА В ПОСТОЯННОМ ЭЛЕКТРИЧЕСКОМ ПОЛЕ И ТАУНСЕНДОВСКИЙ РАЗРЯД В CO_2

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Измерены кривые зажигания и вольт-амперные характеристики (ВАХ) таунсендовского режима DC разряда в углекислом газе. Сравниваются кривые зажигания, полученные двумя различными методами. В первом методе за пробойное принимается максимальное напряжение, которое при фиксированных значениях расстояния между электродами и давления газа можно без зажигания разряда приложить к электродам. Во втором методе измеряются ВАХ таунсендовского режима в мкмА-мА диапазоне и затем экстраполируются на нулевой ток. Показано, что в диапазоне нА-мкА из-за формирования пространственного заряда ВАХ таунсендовского режима могут иметь сложное поведение. Поэтому второй метод дает некорректные значения пробойного напряжения.

ПРОБІЙ ГАЗУ В ПОСТІЙНОМУ ЕЛЕКТРИЧНОМУ ПОЛІ І ТАУНСЕНДІВСЬКИЙ РОЗРЯД У CO_2

В.О. Лісовський, С.В. Дудін, П.П. Платонов, В.Д. Єгоренков

Виміряні криві запалювання і вольт-амперні характеристики (ВАХ) таунсендівського режиму DC розряду у вуглекислому газі. Порівнюються криві запалювання, отримані двома різними методами. У першому методі за пробійну вважається максимальна напруга, яку при фіксованих значеннях відстані між електродами і тиску газу можливо без запалювання розряду прикласти до електродів. У другому методі вимірюються ВАХ таунсендівського режиму в мкА-мА діапазоні і потім екстраполюються на нульовий струм. Показано, що в діапазоні нА-мкА через формування просторового заряду ВАХ таунсендівського режиму можуть мати складну поведінку. Тому другий метод дає некоректні значення пробійної напруги.