# The dc gas breakdown in tubes of arbitrary length

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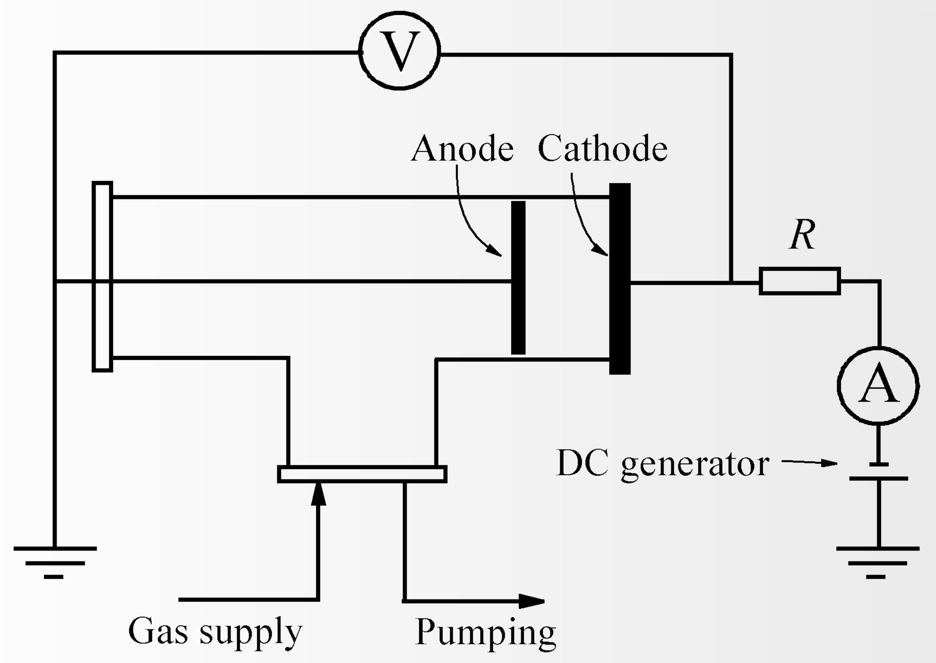
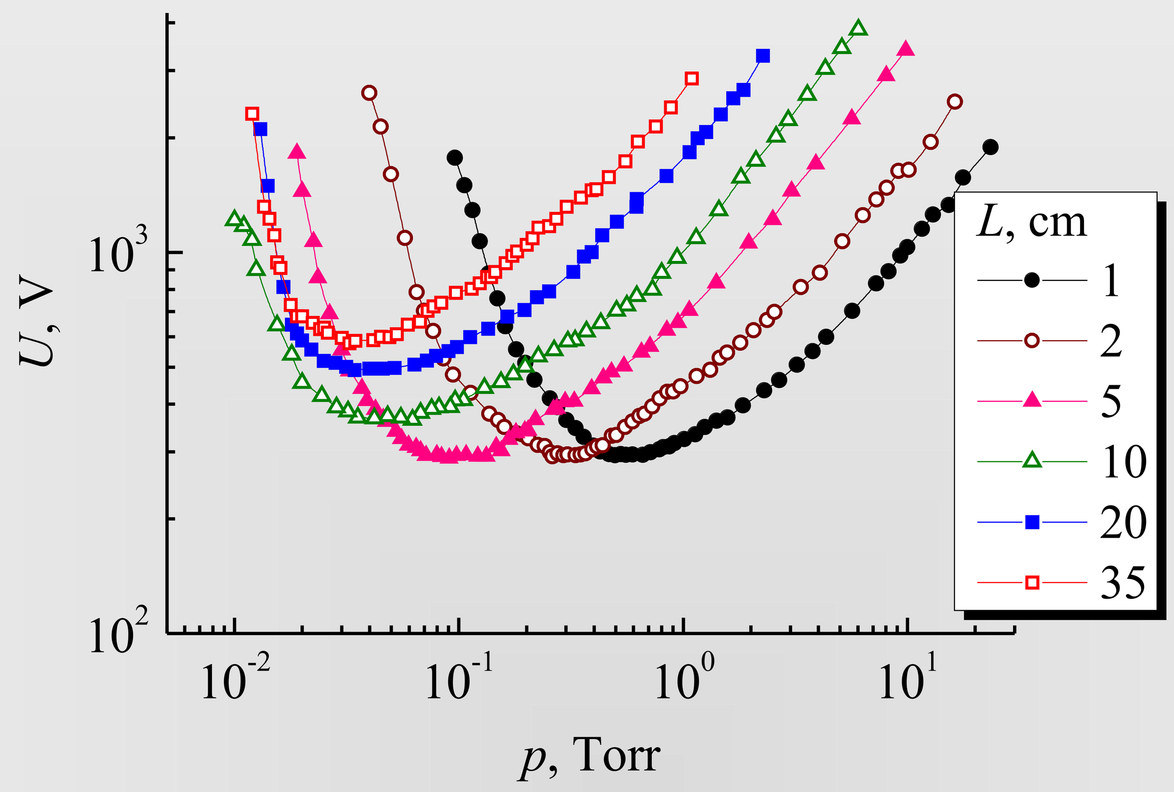
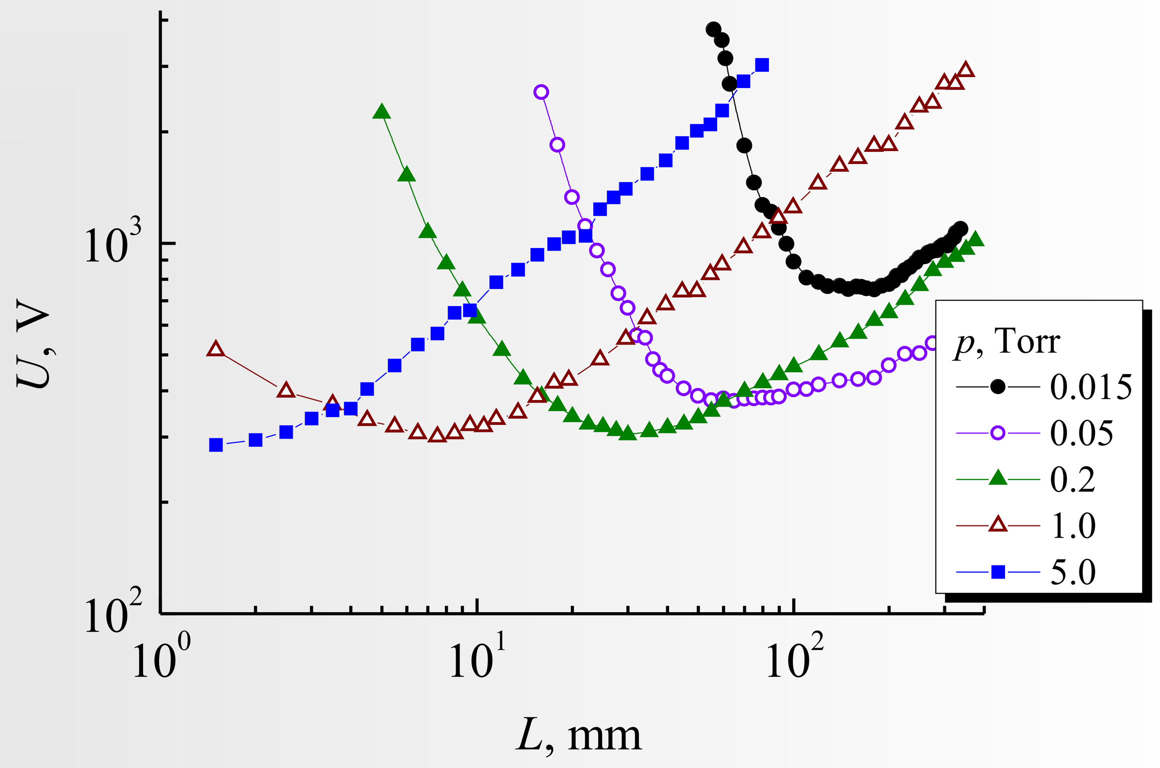
This paper has investigated the dc discharge breakdown between flat electrodes in a long tube. Two experimental techniques have been employed: 1) the breakdown voltage *U* has been measured in the broad range of gas pressure *p*, the inter-electrode distance *L* being kept fixed; 2) with the gas pressure fixed the breakdown voltage has been measured for different values of the inter-electrode distance. Therefore this study has been aimed at registering the breakdown curves employing both techniques in the same chamber. The data obtained with different techniques are compared between themselves and the causes of their differences are analyzed.

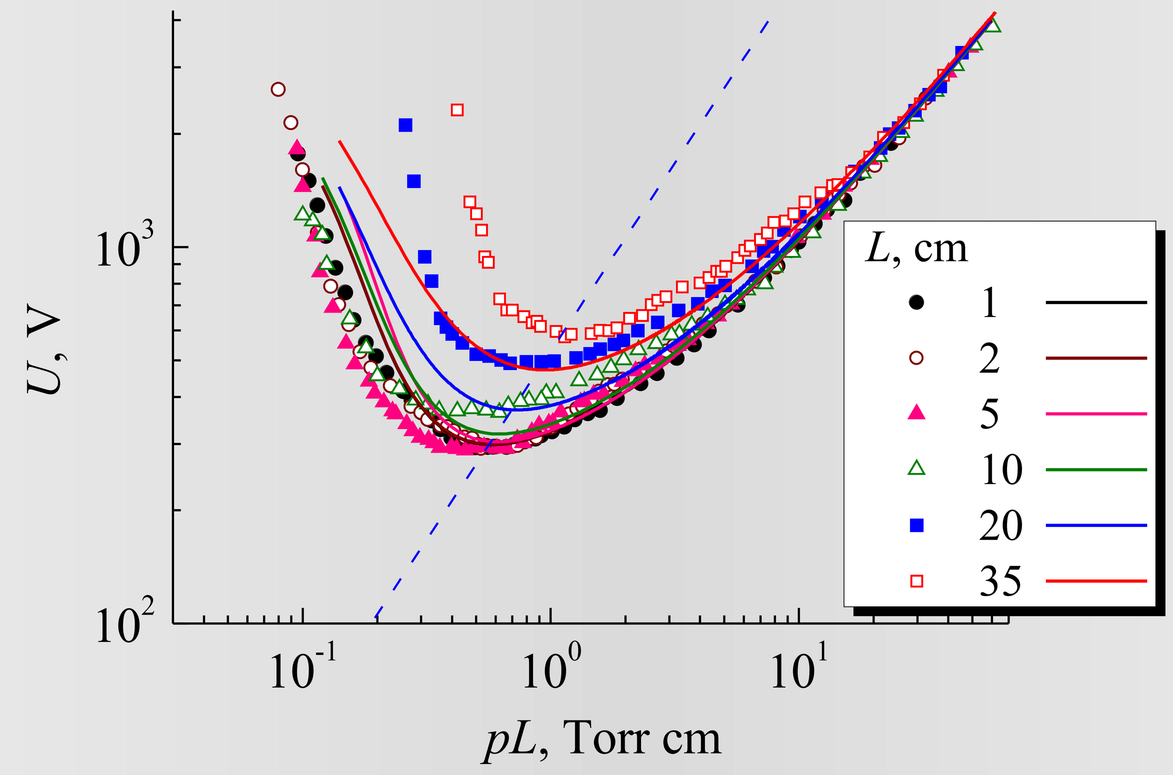



**The scheme of the experimental setup**

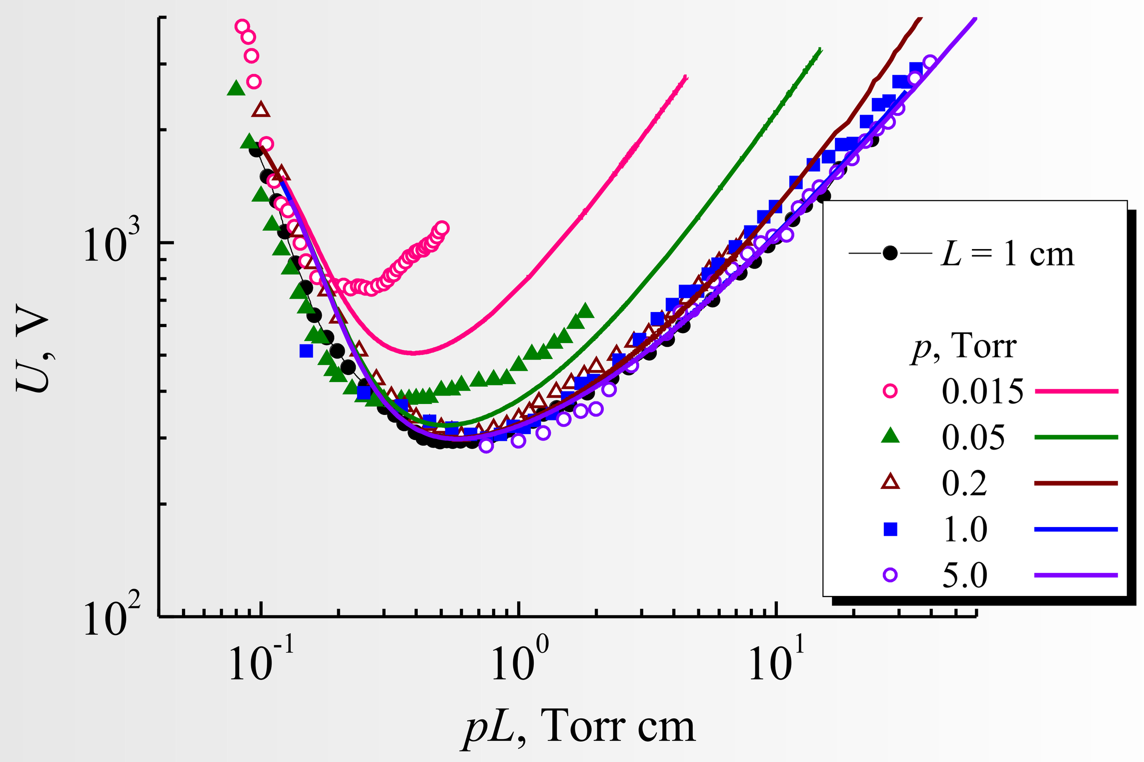
The discharge tube was made of glass in the form of a letter T with the inner diameter of 56 mm. The gas was pumped out and fed through the flange located at the base of the vertical section of the T-chamber. The cathode was simultaneously a flange, it was located at one end of the horizontal portion of "T", and a potential from the DC generator was fed to it. A flange was located at the opposite end of the horizontal section of "T" through which a grounded anode was introduced. It may move along the discharge chamber axis. The cathode and anode were of stainless steel and they had the diameter of 55 mm. The distance between the electrodes can vary from 1 to 350 mm. Experiments have been performed in high purity nitrogen.




**Breakdown curves $U(p)$ and $U(pL)$ measured for different inter-electrode distance values (the first technique).**




**Breakdown curves $U(L)$ and $U(pL)$ measured for different gas pressure values (the second technique).**

**With the first technique we have found that at small inter-electrode distance values ($L$ < 5 cm) the gas breakdown is well described with Paschen's law, i.e. on the $U(pL)$ graph breakdown curves practically match each other. At larger $L$ values one observes a shift of breakdown curves to the lower pressure range as well as to the range of higher breakdown voltages. The breakdown curves measured with the first technique possess an important feature that their minima are located on the straight line corresponding to the maximum ionization ability of electrons (Stoletow's constant) and the right-hand branches of all curves approach one another.**

**The dc gas breakdown criterion in tubes of arbitrary length [1].**

$$A(pL)\exp\left(-\frac{B(pL)}{U}\right)=\frac{D_{e0}}{\mu_{e0}}\frac{(2.4)^2}{U}\left(\frac{L}{R}\right)^2+\gamma A(pL)\exp\left(-\frac{B(pL)}{U}\right)\times$$

$$\times\left\{\exp\left[A(pL)\exp\left(-\frac{B(pL)}{U}\right)-\frac{D_{e0}}{\mu_{e0}}\frac{(2.4)^2}{U}\left(\frac{L}{R}\right)^2\right]-1\right\}$$

$$\alpha/p = A\cdot\exp(-B/(E/p))$$

The modified Paschen's law is $U = f(pL, L/R)$.

**The multiplication coefficient**

$M = \exp(\alpha L)$ for the uniform constant electric field

$$M=\exp\left[\int_0^L \alpha(z)dz\right]=\exp\left[\int_0^L A\cdot p\cdot\exp\left(-\frac{B\cdot p}{E(z)}\right)dz\right]$$ for the non-uniform field

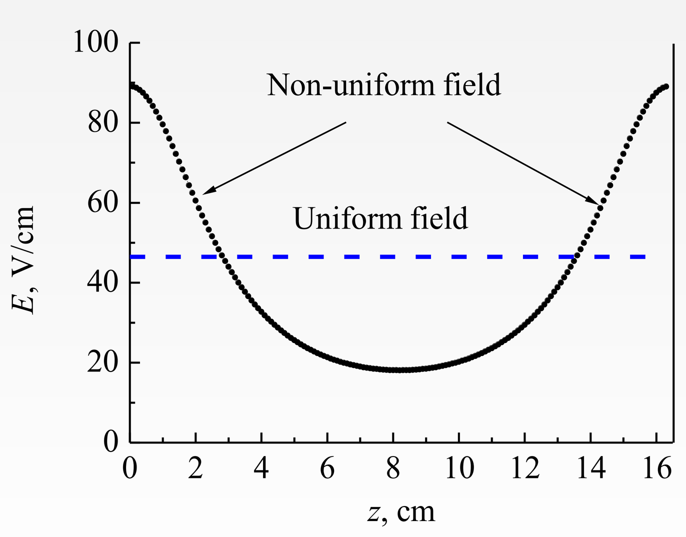
$$E(z)=\frac{U\cdot R}{\pi}\cdot\left(\frac{1}{z^2+R^2}+\frac{1}{(L-z)^2+R^2}\right) \quad [2]$$

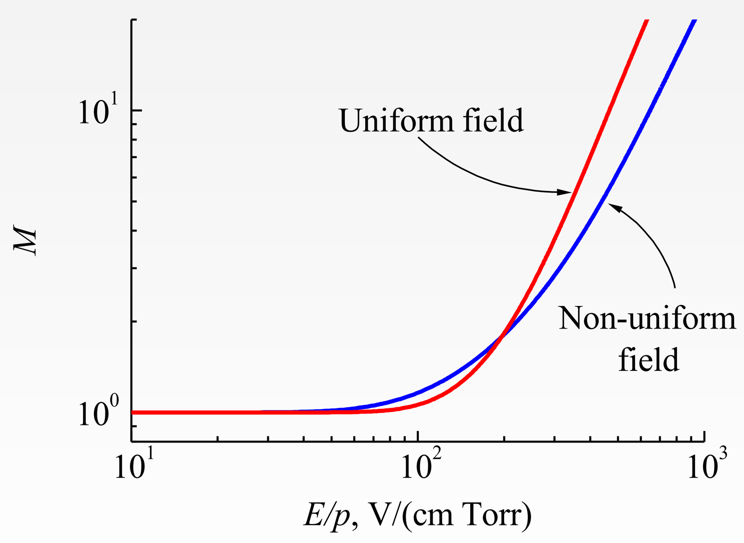
**When one fixes the gas pressure and registers the breakdown voltage $U(L)$ for different $L$ (with the second technique), then the $U(L)$ curves possess an U-shaped pattern and with the gas pressure increasing they are displaced down and to the left, with the minimum breakdown voltage of the curves $U(L)$ decreases. The left-hand branches of the $U(pL)$ curves match for all pressure values because they refer to narrow gap values when Paschen's law holds. But increasing the inter-electrode distance $L$ leads to the increase of diffusion loss of electrons on the tube walls which area also increases. Therefore the right-hand branches of such breakdown curves at low pressure run in the region of higher breakdown voltage values in contrast to respective branches of the curves obtained according to the first technique. That is, on decreasing the gas pressure the breakdown curves $U(pL)$ are shifted to the range of higher breakdown voltage values and lesser $pL$ product values. At the minima of such breakdown curves the ionization ability of electrons is not maximum as a result of a considerable diffusion loss of electrons and non-uniform axial distribution of electric field strength.**

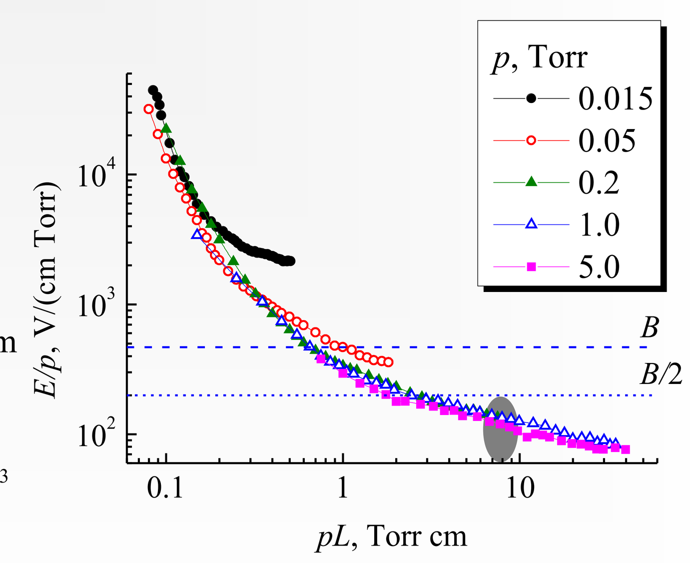
**We have clarified how breakdown criterion [1] describes the breakdown curves measured according to the first and second techniques.**

**What concerns the first technique, the calculated breakdown curves are in good agreement with the experimental data for narrow inter-electrode distance values (5 cm and less). But at larger distance values $L$ the agreement between the experimental data and calculations deteriorates, that is, the calculated breakdown curves run below the measured ones.**

**With the second technique the breakdown curves $U(pL)$ calculated for the pressure values of 1 Torr and higher practically match each other and experimental curves. On decreasing the pressure the calculated right-hand branch runs remarkably higher than other curves (for 0.2 Torr) and then the breakdown curves are shifted as a whole to the range of higher breakdown voltage values and small values of the $pL$ product (for 0.05 Torr and especially 0.015 Torr). With the first technique as well as in this case the experimental breakdown curves run substantially above the calculated ones.**




[1] V.A. Lisovskiy, S.D. Yakovin, and V.D. Yegorenkov, J. Phys. D: Appl. Phys. 33 2722 (2000).

[2] V.A. Lisovskiy, R.O. Osmayev, A.V. Gapon, S.V. Dudin, I.S. Lesnik, and V.D. Yegorenkov, Vacuum. 145 19 (2017).