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# On Correction Factor in Scaling Law for Low Pressure DC Gas Breakdown

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**Abstract.** The low pressure gas breakdown described by Paschen's law in Townsend theory, i.e. the breakdown voltage as a function of gas pressure  $p$  and the electrode distance  $d$ , provides an accurate description of breakdown in DC discharges when the ratio between inter-electrode gap distance  $d$  and electrode radii  $R$  tends to zero. On increasing of the ratio  $d/R$ , the Paschen's curves are shifted to the region of higher breakdown voltage and higher  $pd$  values. A modified Paschen's law recently proposed is well satisfied in our measurements. However, the value of constant  $b$  changes not only due to gas type but also according to electrode gap distance; furthermore, gas breakdown voltages are considerably modified by plasma-wall interactions due to glass tube proximity in the discharge.

## 1. Introduction

By classical Townsend theory, for a parallel electrodes DC discharge at low pressure, the breakdown voltage is given by [1]

$$V_{br} = \frac{Bpd}{C + \ln pd} \quad \text{with} \quad C = \ln \frac{A}{\ln(1 + 1/\gamma) + 1} \quad (1)$$

where  $A$  and  $B$  are constants depending on the gas type. This expression arises from only kinetic considerations of gas ionization. In practice, we have a loss of electrons by diffusion in the discharge chamber. When we take into account the hydrodynamic conditions of the system [2], the equation (6) of [3] leads to the same equation (1), but with

$$C = \ln \frac{A}{\ln \left\{ 1 + \frac{1}{\gamma} \left[ 1 + \frac{2.4^2}{\alpha V_{br} d} \frac{D}{\mu} \left( \frac{d}{R} \right)^2 \right] \right\} + \frac{2.4^2}{V_{br}} \frac{D}{\mu} \left( \frac{d}{R} \right)^2} \quad (2)$$

where  $\mu$  and  $D$  are the mobility and the coefficient of the transverse diffusion of electrons respectively, and  $\alpha$  is the first Townsend's coefficient which is a function of pressure, voltage and gap distance. The second term multiplying  $1/\gamma$  is usually negligible. So, when we disconsider it in eq. (2), we recover an import result

$$\frac{V_{br(\min)}}{pd_{(\min)}} = B \quad (3)$$



which is known as Stoletov's point and indicate where the ionization capability of electrons is maximum [4]. Here  $pd_{(\min)}$  denotes the value of  $pd$  when  $V_{br}$  is minimum. This ratio is verified experimentally with good agreement [3].

In order to have a simple equation to describe the breakdown voltage behavior, Lisovski *et al.* [3] propose the following empirical relationships:

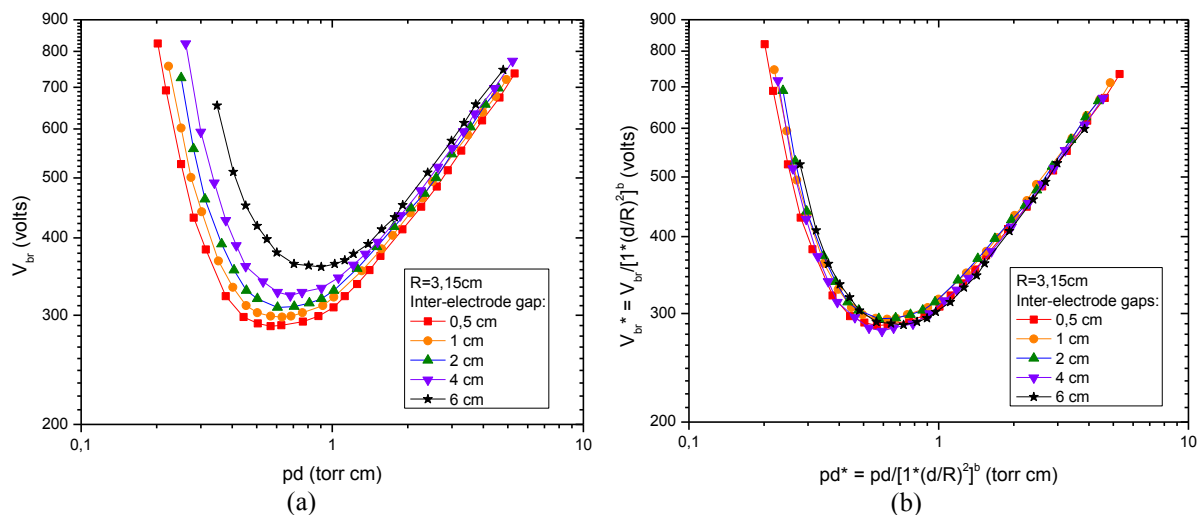
$$V_{br} = V_{br}^* \left[ 1 + \left( \frac{d}{R} \right)^2 \right]^b \quad (4)$$

and

$$pd = pd^* \left[ 1 + \left( \frac{d}{R} \right)^2 \right]^b \quad (5)$$

where  $V_{br}^* = f(pd)$  and  $pd^*$  are the ordinary values of Paschen's curves when no diffusion is taken in account, i.e., when the ratio  $d/R$  tends to zero in equation (2).

By this way, we get the following Paschen's curves:



**Figure 1.** Paschen's curves for nitrogen, (a) without and (b) with the scaling law ( $b = 0.12$ ) [3].

## 2. Methodology

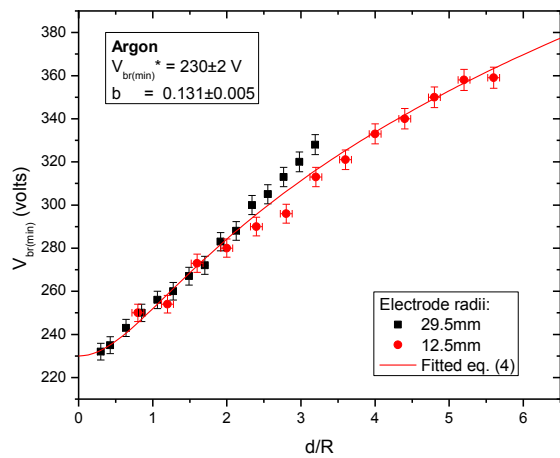
The discharges were made in chamber called "RFDC device", built for basic low temperature experimental plasma studies. The RFDC device is made of big glass cylinder of 30 cm diameter and 20 cm high, covered by two insulated brass plates. The vacuum is obtained by a mechanical pump and small turbo molecular pump of 70 l/s which can hold working pressure from  $10^{-2}$  to 1 Torr. The DC voltage can reach up to 1000 V.

Before taking measurements, we clean the cathode surface by igniting the dc glow discharge at pressure about 0,1 Torr, with current of 10-30 mA, just to remove the monolayers of gases remaining on the cathode surface in a discharge not yet sufficient to produce the cathode spots.

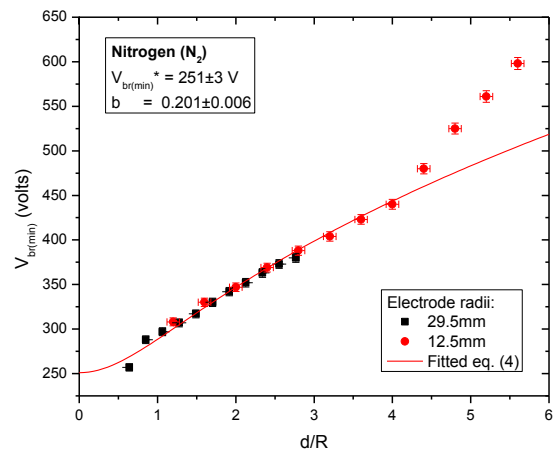
Using two distinct diameter brass electrodes, 25 mm and 47 mm, with and without a cylindrical glass tube, just enough to cover all the electrodes distance gap inside our chamber, we analyze the dependence of  $V_{br(\min)}$  with  $d/R$ . From these relationship, we get the  $V_{br(\min)}^*$  and  $b$  coefficients.

## 3. Results and discussion

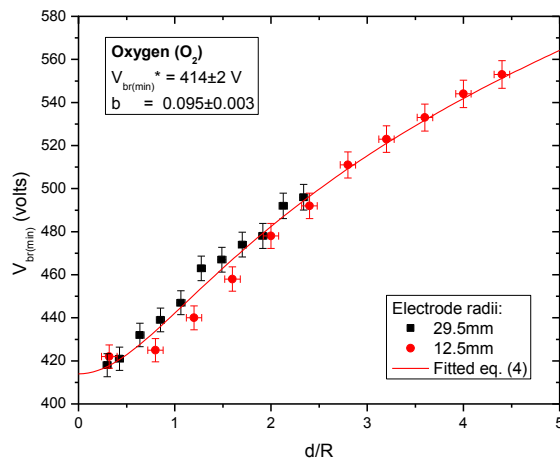
The behavior of breakdown voltage as a function of  $d/R$  ratio is presented in figures 2, 3 and 4. We obtain values of  $b$  equal to 0.131, 0.201 and 0.095 for argon, nitrogen and oxygen while Lisovski *et al.*, using stainless steel electrodes, got 0.16, 0.12, and 0.03, respectively.



**Figure 2.** Behaviour of minimum breakdown voltage as a function of  $d/R$  for argon.



**Figure 3.** Behaviour of minimum breakdown voltage as a function of  $d/R$  for nitrogen.



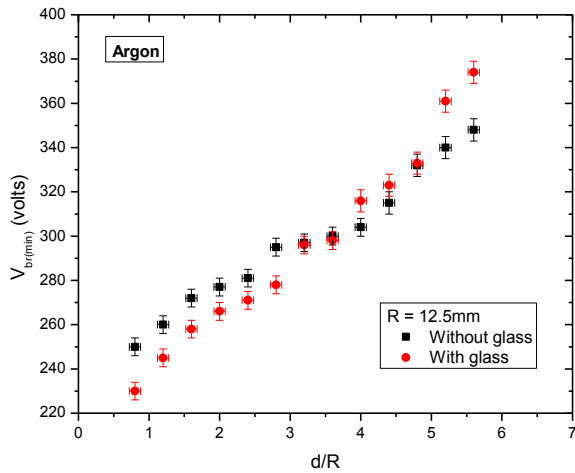
**Figure 4.** Behaviour of minimum breakdown voltage as a function of  $d/R$  for oxygen.

These results are in good agreement with the empirical relationship (4), except for nitrogen when  $d/R$  is greater than 4. For example, for nitrogen at  $d/R = 5.6$ ,  $b$  should be 0.25 in equation (2) to give the real minimum breakdown voltage  $V_{br(min)}$  with the same ordinary breakdown voltage  $V_{br(min)^*}$ .

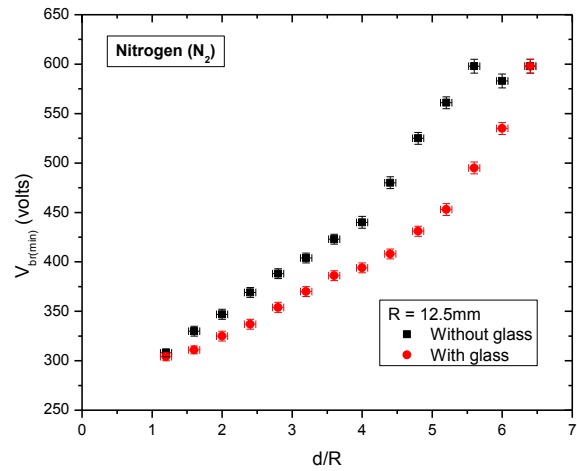
When a glass tube of about same diameter as electrode is added (figures 5, 6 and 7), the proposed scaling law do not provide a good description of minimum breakdown voltage for all range of  $d/R$ . Analyzing the breakdown voltage with  $d/R$  in the range 0 to 3, the same interval considered by Lisovskiy, we got  $b$  equal to 0.097 for argon and 0.13 for nitrogen. The oxygen data don't change appreciably on this range.

For the electrode with  $R = 29.5$  mm, the minimum breakdown voltage with glass tube is lower than the normal breakdown voltage, similarly as shown above, but both datas (with glass) do not overlap each other.

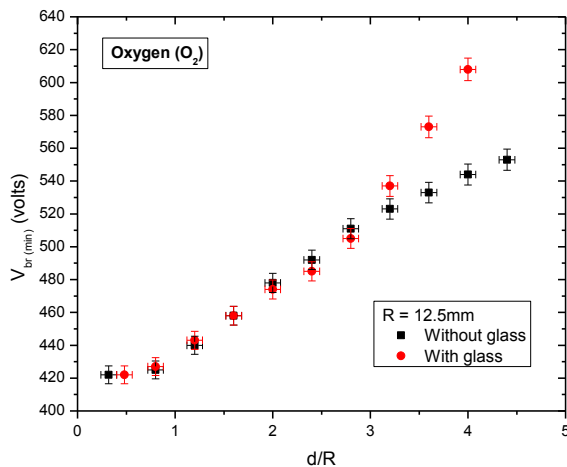
Thus we emphasize the large variation in the value of coefficients  $b$ , particularly for nitrogen, which is similar to value obtained by [3] when the discharge chamber (or glass tube) is large enough just to cover the electrodes; and the non compatibility of the model for high values of  $d/R$ .



**Figure 5.** Behaviour of minimum breakdown voltage as a function of  $d/R$  for argon (with glass tube).



**Figure 6.** Behaviour of minimum breakdown voltage as a function of  $d/R$  for nitrogen (with glass tube).



**Figure 7.** Behaviour of minimum breakdown voltage as a function of  $d/R$  for oxygen (with glass tube).

#### 4. Conclusion

The simple scaling law proposed by Lisovskiy *et al.* can describe very well the breakdown voltage in a limited range of  $d/R$  which can differ for each gas. However, the correction factor in the scaling law could depend not only on the gas type but also on others parameters such as  $D$  and  $\mu$ . The diffusion and mobility of electrons and ions have an import role in the discharge ignition, so the presence or absence of wall close to electrodes affects the discharge. They may strongly alter the  $b$  coefficient and restrict even more the range of validity of the scaling law for Paschen's curves.

#### Acknowledgements

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#### References

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