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Influence of the hot filament on the electrical breakdown characteristics in the presence of Ar/N_2

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Abstract

The influence of a hot filament on the electrical breakdown characteristics is studied for different ratios of argon and nitrogen gases for a wide range of pressure. The vacuum tube consists of two parallel plane stainless steels used as cathode and anode accompanied with a tungsten filament located behind the cathode. Paschen's curves are obtained for different ratios of argon and nitrogen as a function of pressure for various electric currents of the hot filament. The first and second Townsend coefficients as well as the ionization efficiency and secondary ionization coefficient are obtained for different filament currents. In addition, the influences of the nitrogen partial pressure on the forgoing parameters are obtained. It is shown that, increase of the filament current causes the decrease of the electrical breakdown voltage which is more pronounced in low pressures. Furthermore, introducing the nitrogen gas leads to the increase of the breakdown voltage and decrease of the ionization efficiency as well as the first and second Townsend coefficients. Moreover, it is concluded that, in the middle range of pressure, the presence of the hot filament results to the electrical breakdown which reveals the linear features.

Keywords: Electrical breakdown, Townsend coefficient, Paschen's curve, Ionization efficiency, Gas mixtures, Hot filament

Background

The gas discharges are widely used for lighting purposes and are the subjects of extensive researches on plasma-surface interaction. The nature of the mechanisms involved in breakdown has attracted much attention throughout the history of plasma physics. Some examples of electrical breakdown applications are as follows: the coronas used in pollution control, plasma display panels, (re)ignition of high intensity discharge lamps, hollow cathode devices for extreme ultraviolet production, and improvement of fluorescent lamps [1-4].

The electrical breakdown is the process in which a gas changes from electrically isolating to being electrically conducting. That highly transient process involves the creation of charge carriers as a result of various processes such as electron impact ionization and secondary emission. The breakdown between two parallel plates is rather well understood nowadays and can be described and predicted by the Townsend theory using Paschen's curves. The importance of the research of physical processes which cause to initiate electrical breakdown is to understand the behavior of the generated plasma in various gases which lay in numerous gas discharge applications [5]. However, for systems with various geometries and pressure as well as non-uniform electric field, the breakdown mechanisms are less well understood.

One of the important issues in designing and fabricating plasma devices as well as the generating plasma for a specific application is to decrease the electrical breakdown voltage to initiate the gas discharge. In the current work, a hot filament located behind the cathode is used and the breakdown characteristics and related parameters are studied in different pressures in the presence of argon and nitrogen gases. We first focus on the dependence of Paschen's curve on gas type as well as the electric current of the hot filament and in the second step; the Townsend coefficients and departure from linear characteristics are evaluated from Paschen's curves. Finally, the ionization efficiency and secondary ionization coefficient are obtained in different conditions. The paper is organized as follows: the 'Experimental setup' is introduced, and the 'Governing equations, results, and discussion' is presented, then we

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conclude the paper with a summary of discussion of the results in the 'Conclusion'.

Experimental setup

Our experimental discharge tube consists of two parallel stainless steels as the electrodes with146 mm in diameter, facing each other at the distance of 215 mm (Figure 1). The electrodes are placed in a Pyrex tube with 180 mm in diameter and 600 mm in length. The size of the system enables us to assume that there is a uniform electric field throughout the electrode region. A tungsten filament is fixed at 25-mm distance located behind the cathode. The filament is connected through a simple electrical circuit to a dc power supply ranging from 0 to 6 A. The current of the electrical breakdown is measured by the drop voltage across a resistor. The edges of the cathode and anode are inserted in PTFE insulators to maintain of the stability of the system performance. The vacuum vessel is evacuated up to 10^{-5} Torr via a rotary and also a turbo-molecular pump, and the range of the working pressure is 0.4×10^{-2} to 5.5×10^{-2} Torr.

Before the measurements of the breakdown voltage, the surfaces of the electrodes are conditioned by some pulsed discharges which results in acceptable reproducibility of breakdown voltage values (approximately 10-V difference at the minimum of Paschen's curves for each operations).

Experiments are performed for two values of filament currents as well as different ratios of argon and nitrogen gases as a function of pressure. We repeated each run five times, and the averaged values with a relative error less than 5% are reported.

Governing equations, results, and discussion

The first Townsend coefficient α is the inverse of the number of ionizing collisions per centimeter which is a fundamental parameter in understanding the electrical breakdown features and determines the gas gain. The determination of α is restricted to those values of pressure and distance which the discharge takes place. The first Townsend coefficient α depends on many parameters, and the main ones being the nature of the gas, electric field, and pressure which can be expressed as follows [6,7]:

$$\frac{\alpha}{p} = A \exp\left(-\frac{Bp}{E}\right) \tag{1}$$

where p is the pressure; E, the electric field; and A and B, the constants which depend on the gas type. Values of the coefficients for argon and nitrogen are $A_{\mathrm{Ar}} = 12\ \mathrm{cm}^{-1}\ \mathrm{Torr}^{-1}$, $B_{\mathrm{Ar}} = 180\ \mathrm{V\ cm}^{-1}\ \mathrm{Torr}^{-1}$, and $A_{N_2} = 12\,\mathrm{cm}^{-1}\,\mathrm{Torr}^{-1}$ and $B_{N_2} = 342\ V\ \mathrm{cm}^{-1}\ \mathrm{Torr}^{-1}$, respectively, which can be found in [8,9]. The ionization coefficient η can be defined as the number of ionization events caused by an electron in passing through a potential difference of 1 V which can be expressed as $\eta = \frac{\alpha}{E}$. In the Townsend discharge, the charge particle density is quite low. Consequently, the population of excited states by electron-ion recombination processes will be small, and hence, the ionization function is defined as the number of electrons produced in the gaseous medium by a single electron passing through a potential of 1 V. The Townsend secondary coefficient, γ, represents the number of electrons liberated from the cathode per positive ion arriving there and incorporates the emission of

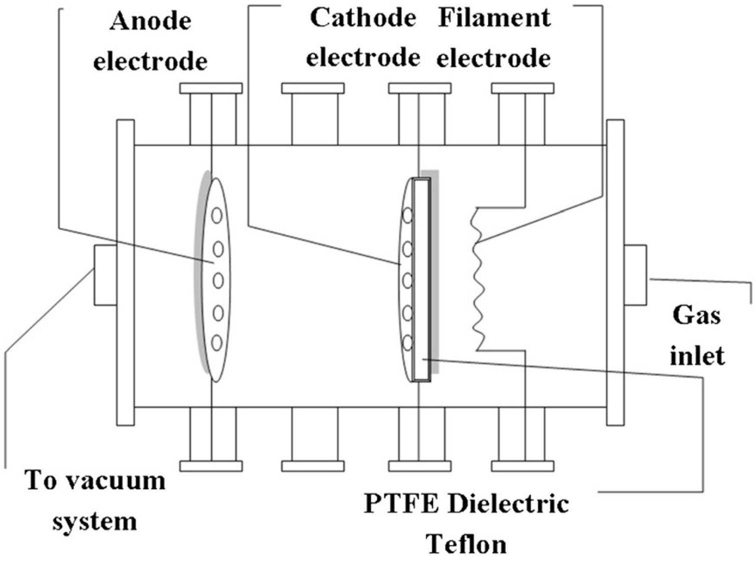

Figure 1 Schematic of the discharge tube for the measurement of the breakdown voltage.

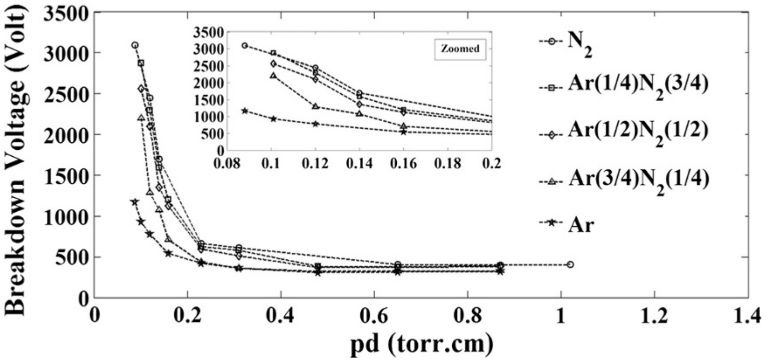

Figure 2 Breakdown voltage in the absence of the hot filament. Breakdown voltage (V_B) for various ratios of argon-nitrogen as a function of *pd* in the absence of filament.

electrons from the cathode under the action of radiation, metastable atoms, and positive ions and can be obtained via the following relation [7]:

$$\gamma = \frac{1}{e^{\eta V_B} - 1} \tag{2}$$

The value of γ depends on the nature of the cathode surface and the gas composition [6,10,11].

As we are going to investigate the electrical breakdown characteristics in the presence of two gas types, the value of B can be determined via the following relations [8]:

$$\frac{\alpha}{p} = A \exp\left(-\frac{B^{*}Ep}{V_B}\right) \tag{3}$$

$$B^{*} = p_{\mathrm{Ar}}B_{\mathrm{Ar}} + p_{N_2}B_{N_2} \tag{4}$$

where p_{Ar} and p_{N_2} are the relative partial pressures of argon and nitrogen respectively. It is to be noted that the argon and nitrogen gases have the same values of A.

We attempt to, experimentally, investigate the influence of the hot filament and gas type on the electrical breakdown characteristics. The Figure 2 represents the electrical breakdown voltage as a function of *pd* for different of argon-nitrogen ratios in the absence of hot filament. As can be seen, by increasing the values of *pd*, the breakdown voltage decreases which is a feature of the left hand side of Paschen's curve. However, by comparing the breakdown characteristics of argon with respect to nitrogen, it can be observed that the breakdown voltage of argon is lower than nitrogen gas, and by raising the nitrogen concentration with respect to argon, the breakdown voltage increases which is more pronounced in lower working pressures. Furthermore, in high values of *pd*, the difference between the breakdown voltage for argon and nitrogen disappears.

Figure 3 demonstrates the breakdown voltage in the presence of the hot filament located behind the cathode for various ratios of *Ar* and N_2. In the current case, the behavior of the left hand side of Paschen's is the same with Figure 2. However, the presence of hot filament in low pressures leads to the decrease of the breakdown voltage. In fact, the hot filament produces more initial electrons which gain energy from the drop voltage throughout the discharge region, and by impact to the neutral background gas, more electrons release which finally lead to the

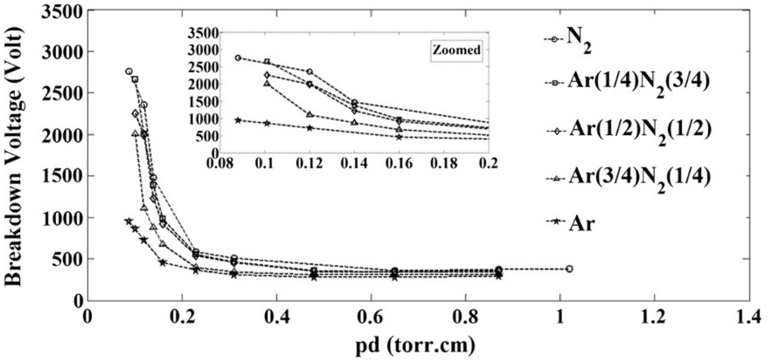

Figure 3 Breakdown voltage in the presence of the hot filament. Breakdown voltage (V_B) for argon, nitrogen, and their mixtures as a function of *pd* (Paschen's curves) for value i_f = 5 A of filament current.

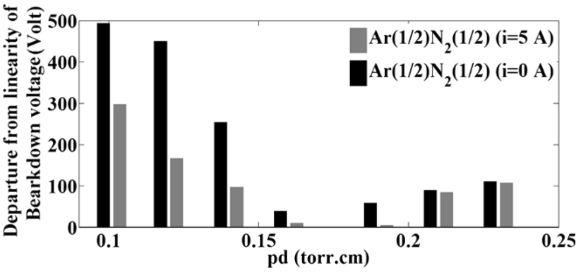

Figure 4 **The departure from linearity of the breakdown voltage.**

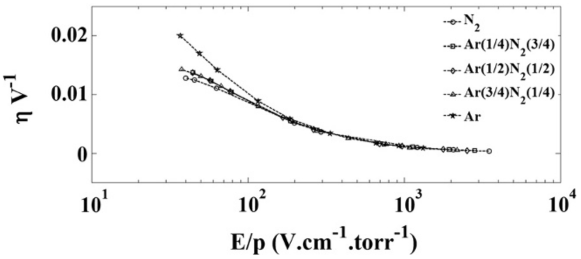

Figure 6 **Ionization efficiency (η) as a function of $^{E}/_{p}$ for different argon-nitrogen gas ratios.**

decrease of the breakdown voltage. However, in high pressures, due to the decrease of collision mean free path, the influence of filament disappears.

Now, we concentrate on the linear behavior of the electrical breakdown in the presence of two types of gas. The breakdown characteristic is linear if the breakdown voltage of two mixed gases with the same concentrations is equal to the average of breakdown voltage of each, i.e., $\bar{V}_{\left\{\mathrm{Ar}(^1/_2)N_2(^1/_2)\right\}=\frac{V_{\mathrm{Ar}}+V_{N_2}}{2}}$. However, in the real cases, there are some nonlinear features which are responsible for the departure from the linear behavior of electrical breakdown. Figure 4 shows the degree of nonlinearity of mixed gases as a function of *pd* for two values of electric current of the hot filament. From that Figure 4, one can conclude that in low as well as high pressures, the nonlinearity is high, while in the middle range of pressure, the system behaves approximately linear, in which the interesting point is that the presence of hot filament results in the decrease of nonlinearity. It is to be noted that, in high pressure, the presence of hot filament has no influence on nonlinearity which can be a consequence of the decrease of ionization collision frequency.

Figure 5 shows the first Townsend coefficient as a function of reduced electric field for different argon and nitrogen ratios. Since the presence of the filament does not lead to the variations of the first Townsend coefficients significantly and that quantity depends just on the gas type and reduced electric field, therefore we report the results of the first Townsend coefficient just in the absence of filament. As can be seen, increase of reduced electric field results to amplifying the first Townsend coefficient. However, by comparison of the results for argon with nitrogen gas, it can be seen that the value of α for argon is higher than the nitrogen gas. This result is in agreement with the results of Figures 2 and 3. In fact, by amplifying the first Townsend coefficient, the discharge can be produced with a lower electric potential. In addition, in high reduced electric field, the difference of α for argon and nitrogen diminishes.

Figure 6 shows the ionization efficiency as a function of reduced electric field for pure argon and pure nitrogen gases and their mixtures in the absence of the filament current. The maximum value of η occurs at values of $^{E}\!/_{p}$ corresponding to the electron energy for optimum production of metastable gas atoms [12]. In addition, the maximum value of the ionization efficiency depends on the inverse of ionization potential of the gas, and therefore, the presence of the filament does not lead to the variation of ionization efficiency significantly. In addition, it can be seen that the ionization efficiency for argon gas is higher than nitrogen gas, while for high values of reduced electric field, that difference disappears.

In Figure 7, we show the results of the variation of secondary ionization coefficient with respect to the reduced

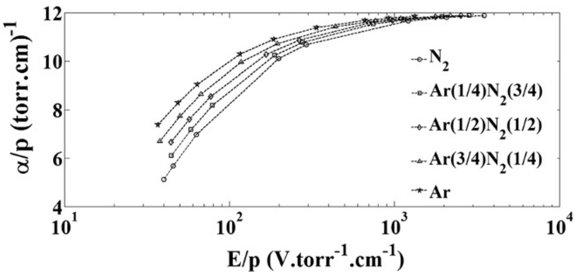

Figure 5 **The first Townsend coefficient *α* as a function of reduced electric field $^{E}/_{p}$.** The five curves are obtained for argon, nitrogen, and their mixtures.

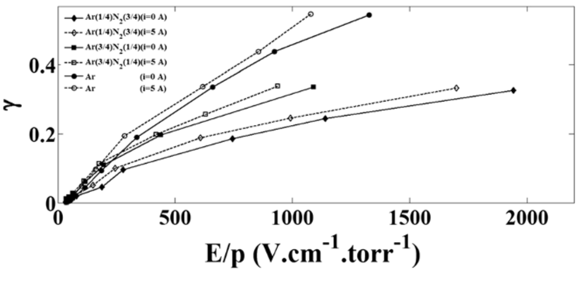

Figure 7 **The variation of the secondary ionization coefficient (γ) with $^{E}/_{p}$ for argon-nitrogen gases ratios.**

electric field for different ratios of Ar/N_2 for two values of electric current. Increase of the reduced electric field leads to the rising value of secondary ionization coefficient, and the presence of hot filament results to the amplifying of γ. In addition, it can be concluded that the influence of hot filament disappears in low reduced electric field. Moreover, by adding the nitrogen gas in the vessel, the secondary ionization coefficient decreases which is a consequence of the molecular features of nitrogen.

Conclusion

The electrical breakdown characteristics in the presence of a hot filament are investigated experimentally for different ratios of argon and nitrogen. The results show that the presence of the hot filament leads to the decrease of the breakdown voltage which is more pronounce in low pressures. The breakdown voltage of mixed argon/nitrogen in different ranges of pressures are measured and observed that adding nitrogen leads to the increase of the breakdown voltage. It is also shown that the filament has no drastic influence on the first Townsend coefficient and ionization efficiency while has great influence on the secondary ionization coefficient. In addition, the presence of the filament is more pronounced in the case of low pressures. Finally, it can be concluded that the presence of the hot filament leads to the linear behavior of the electrical breakdown which is more pronounce in the middle range of the pressure. In addition, departure from the linear feature increases in low and high pressures, while in the middle range of the pressure and in the presence of the hot filament, the breakdown reveals the linear behavior.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Both the authors, AFB and KY, carried out the experiments and characterizations, analyzed the data, and conceptualized the research. Both authors read and approved the final manuscript.

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