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Two-dimensional modeling of the electrical breakdown in rare gases

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Abstract. In this work a two-dimensional numerical study of dielectric barrier discharge has been proposed in order to understand the breakdown process in rare gases. We used a fluid model which is based on the numerical solution of the two Boltzmann equations (continuity and momentum); these equations are coupled to the Poisson's equation. This model allowed us to plot the Paschen curve, which represents the breakdown voltage as a function of pressure-distance product. The aim of the study is to optimize the applied voltage and to understand how the discharge geometry and other physical parameters such as the secondary emission coefficient affected the breakdown voltage.

1 Introduction

In the last century, more and more of the industrial applications were based on the technology of the electrical discharge as well as plasma display panels, the tubes of lighting and the arc welding [1]. The most significant question in the plasma industrial applications is the optimization of the energy consumption, which is related to the breakdown voltage [2]. However, the gas breakdown process has assumed new importance in particularly for further development these devices. Electrical breakdown in a rare gas is the process of the transition from the insulator in a conducting state, when a sufficiently intense electric field is applied between two electrode plates [3]; the value of the voltage associated with this transition names breakdown voltage or ignition voltage east corresponds to the first value of the voltage for which the discharge becomes self-sustained [4]. The gaz breakdown voltage is a state of balance between the production of electrons by secondary emission caused by the ion bombardment of the electrode and the electron loss by diffusion or absorption at the anode [5, 6]. Paschen [7] was the first scientist to study the electric breakdown of dielectric gases between metallic electrodes, and then formulate the so-called Paschen law which has been so effective in the prediction of electrical breakdown of dielectric gasses. This law establishes the dependence of the breakdown voltage as a function of the product of two parameters: pressure and inter-electrode distance [8].

The outline of this paper is as follows: the Two-dimensional fluid (2D) used in this paper is presented in Section 2. In Section 3, the salient numerical results are presented and followed by the discussion on the breakdown voltage. The conclusion of the work is summarized in Section 4.

2 Fluid Model

The physical model on which is based this work is a 2D fluid model [9]. It consists of the two first moment equations for electrons and ion transport coupled with Poisson's equation, in order to take into account the variations of the electric field [10-11]. The two Boltzmann equations (equation of continuity and momentum) and Poisson's equation are represented by [12-13]:

$$\frac{\partial n_{e,p}}{\partial t} + \vec{\nabla}.n_{e,p}v_{e,p} = S_{e,p} \tag{1}$$

$$n_{e,p}\bar{v}_{e,p} = an_{e,p}\mu_{e,p}E - \vec{\nabla}.\left(D_{e,p}n_{e,p}\right) \tag{2}$$

$$\vec{\nabla}.\varepsilon_r E = \frac{e}{\varepsilon_0}\left(n_p - n_e\right) \tag{3}$$

Where n is the density of charged particles (e for electrons, p for positive ions or negative). S is the source term of the equation of continuity, he reports the creation (ionization) and losses (attachments, recombination) of charged particles, $\bar{v}_{e,p}$ represents the average speed, E the electric field, $\mu_{e,p}$ is always positive corresponding to the mobility of electrons and ions, $D_{e,p}$ is the diffusion coefficient, ε_r and ε_0 are the dielectric and vacuum permittivity respectively.

The breakdown is said to occur when the maximum total ion density reaches a given value within a given time interval. The result will obviously depend on the initial electron and ion density (supposed to be uniform in the gap). The initial density is equal to 10^4 cm^{-3} and the maximum total ion density at breakdown is 10^{11} cm^{-3}[14]. The design of the 2D discharge cell is showed on "Figure1". The dielectric covering the electrodes has a different relative permittivity. These electrodes are separated by a distance of 0.05 *cm*. This space is filled by various gases or mixture.

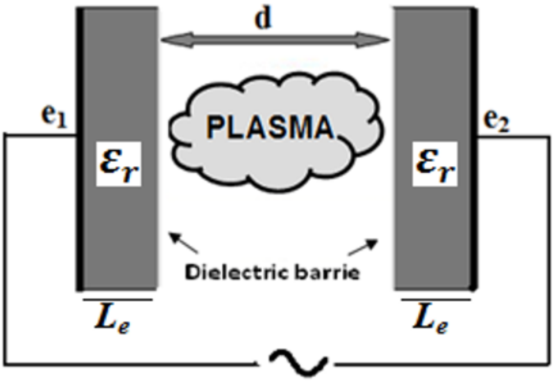

Fig.1. The geometry of the discharge cell

3 Results and discussion

3.1. Secondary emission effect

In this section we present the results of different Paschen curves obtained for argon and helium by using the fluid model described in the previous section. We took into account, the influence of second Townsend coefficient γ on the breakdown voltage. The electronic secondary emission which depends on the energy of the incident ion but also of quality external of cathode increases while the work function of the material of the electrode decreases [15]. The secondary mechanism of emission, which can in this case take place with cathode, has a "kinetic and potential" origin. The output of the majority of materials being about 4 eV, the kinetic energy gained by the ions in the discharge plasma can be sufficient to extract the secondary electrons from cathode [16-17]. Several empirical expressions of the emission coefficient by cathode ionic bombardment γ (the number of electrons emitted by incidental ions) are given in the literature [18-19]

$$\gamma = 0.032(0.78\,\varepsilon_i - 2\phi) \tag{4}$$

With ε_i the potential energy of the incidental particle (ion), ϕ the work function of the solid, table 1 shows the values of secondary emission coefficient (γ) in argon and helium discharges according to the used cathodes materials.

Table 1. Secondary emission coefficient

Cathode material	**γ He**	**γ Ar**
Ag(Silver)	0.31	0.09
Mg(Magnesium)	0.38	0.16
Al(Aluminium)	0.34	0.11

We calculated the Paschen voltage for two pure gases, argon and helium which are evoked by the two following figures.

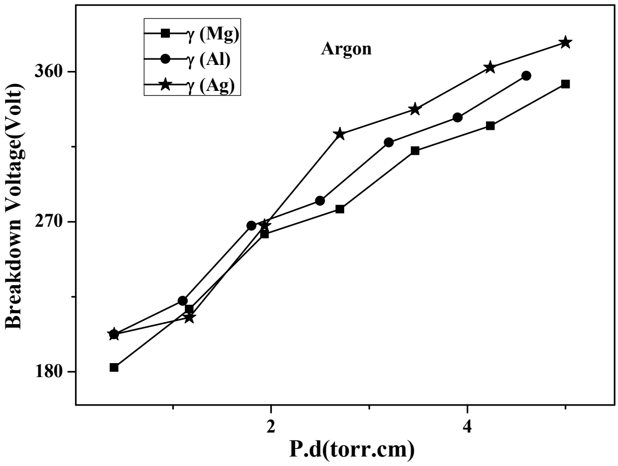

Fig.2. Calculation of the breakdown voltage for argon as a function of the product p.d, by using three cathode materials Mg, Ag and Al.

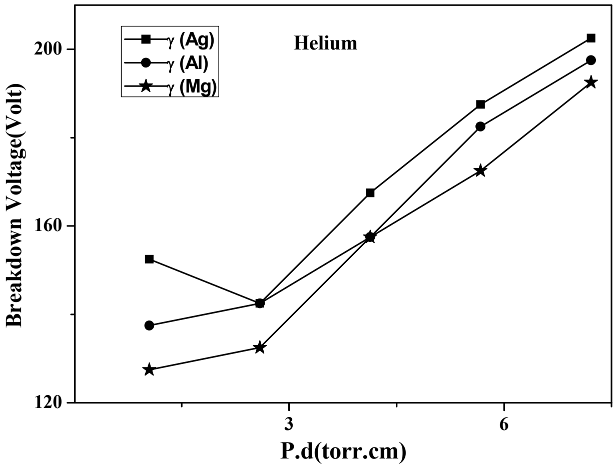

Fig.3. Dependence of the breakdown voltage on the pressure-gap spacing product in helium. Square, circle symbol correspond to the silver, magnesium material, and the results of aluminium cathode are obtained by star symbols

Figure 2 shows the Paschen curves for Ar gas obtained by simulation 2D fluid, using the three cathodes. The breakdown voltage (V_b) for the three cathodes occurs at the value of (p.d) varies from 0.5 to 5 torr.cm. The minimum breakdown voltage (V_{bmin}) was found to depend upon the type of the cathode material. This can be related to the difference in the work function of the different cathodes. However, the breakdown voltage increases gradually when increasing p.d, which can be attributed to the decrease in the ionization cross-section. Therefore, electrons need more energy to breakdown the discharge gap; resulting in an increase of V_b. we measured the breakdown voltage in Ar discharge using the secondary emission coefficient of Ag and Al cathode. The minimum breakdown voltage (V_{bmin}) was found to be 202 Volt at (p.d_{min}) = 0.3 torr.cm, while in the minimum breakdown (V_{bmin}) was found to be 182 Volt at (p.d_{min}) = 0.4 torr.cm for the type of cathode Mg. Figure 3 shows the typical Paschen curves for helium discharge using the three cathodes. The minimum breakdown voltage, (V_{bmin}), for the three cathodes, occurs at a value of (p.d_{min}) = 1 torr.cm. (V_{bmin}) has been found for He discharge at 127, 137 Volt and 152 Volt for magnesium and aluminium and silver cathodes, respectively. One can notice that the breakdown voltage increases for the larger work functions of the cathode materials. That wants to say a secondary emission coefficient smaller.

3.2. Dielectric barrier effect

In this subsection, we determine the Paschen curves according to pressure-distance product for a mixture of 10% of xenon in neon (see Figure 4), for a distance between electrodes d = 100 µm and for different value from the dielectric permittivity. We notes according to the figure 4, that the relative permittivity play a very significant role in the breakdown voltage, we notice an increase in the permittivity ε_r, conduit to breakdown voltage very small, and that (V_{bmin})= 282,5 Volt at $\varepsilon_r = 3$, and for $\varepsilon_r = 12$ (V_{bmin}) equal to 242.5 Volt, for the same product (p.d_{min}) = 2,33 torr.cm. In figure 5, the breakdown voltage si also determined for different values of the dielectric width. We observe an increase of the breakdown voltage when the width L_e of the dielectric increases and for a product (p.d_{min}) = 1.3 torr.cm, the Paschen minimum (V_{bmin}) is equal to 196 Volts and 228 Volts for a width of 7.5 µm, 15 µm, respectively.

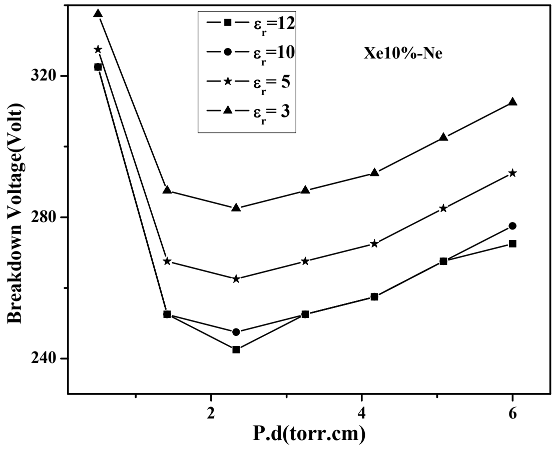

Fig.4. Plots of measured breakdown voltages versus product of the pressure and the width gap between electrodes in mixture Xe10%-Ne, for different values from the permittivity

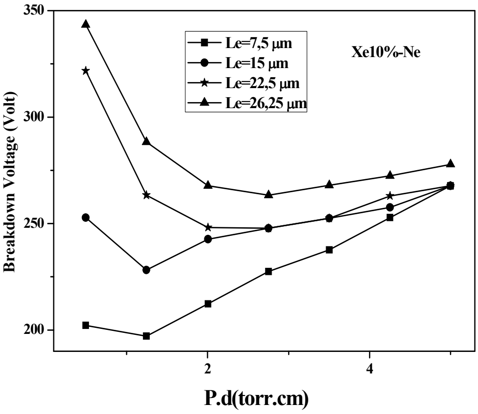

Fig.5. Breakdown voltage measurements as a function of pressure and gap spacing in Xe10%-Ne. This result represent the fluid calculation, the secondary electron emission coefficient for xenon ions is set to 0.05, for neon equal to 0.5, for several values of L_e (width of the dielectric barrier)

4 Conclusion

The breakdown voltage has been measured for Ar and He discharges using three different cathode materials as well as Aluminium, Silver and Magnesium. The minimum breakdown voltage for the three different cathodes occurs at the value of $p.d_{\min}$ equal to 0.5 torr.cm for Ar discharge and at $p.d_{\min}$ varing from 1 to 2.4 torr.cm for He discharge. It is concluded that the minimum breakdown voltage increases with the increase of the work function of the cathode materials, and high secondary emission coefficient. From the Paschen curves for Ar and He gases, it is clear that the minimum breakdown voltage of He gas is lower than that of Ar gas. This can be attributed to the higher efficiency of secondary ionization processes in He discharge than in Ar discharge. In the second part, we illustrated the influence from the two-dimensional geometry on the Paschen voltage. These results show that the breakdown voltage is very affected by the dielectric barriers (width and permittivity).

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