Paschen's Breakdown Voltage in Air and Pure Gases

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Abstract: This work is devoted to a numerical and analytical calculation of breakdown voltage in electrical discharge of Air, Argon, Carbondioxide, Helium, Hydrogen, Krypton, Neon, Nitrogen and Xenon. It was performed using MATLAB which was based on the numerical solutions of the two moments of Boltzmann equation coupled with Poisson's equation to calculate the breakdown voltage according to the product of the electrode spacing and pressure (*pd*). The electrode spacing of 2.5, 5.0 and 7.0cm were used. Paschen's curves were generated in these spacing which have a strong agreement with the empirical values. The minimum breakdown voltage for Air, Argon, CO_2, He, H_2, Kr, Ne, N_2 and Xe are respectively 222.2, 101.5, 327.7, 130.0, 225.2, 181.1, 203.1, 215.6 and 111.6 Volts.

Introduction

Plasma is a quasi-neutral gas of charged and neutral particles which exhibits collective behavior. Plasma is produced when an electrically neutral gas absorbs enough energy for it to become ionized and electrically conducting. In laboratory plasma, this is achieved by placing a large voltage across electrodes, the applied electric field accelerates stray charge and breakdown process begins [1]. Plasma breakdown, also referred to as plasma ignition, is an important fundamental process in plasma science and has a long history of study. It started in the late nineteenth century; Paschen's [2] was the first scientists to study the electrical breakdown of dielectric gases between metallic electrodes, and then formulated the so-called Paschen's law which has been so effective in the prediction of electrical breakdown in gases. Recently, the breakdown physics has known more interest [3-5], because many plasma applications are influenced by this process, and its understanding is very necessary for the development of these devices and particularly for the optimization of the energyused. Such applications are diverse, including cleaning of exhaust gases [6], ignition of light sources [7, 8] material processing using pulsed plasma sources [9, 10]. Among other applications, the treatment of temperature-sensitive surfaces such as biological material is of interest, in particular the interaction of plasma with living cells, tissues and bacteria, e.g. for cultivation, deactivation or remedial treatment of diseases [11].Hexamethyldisiloxane(HMDSO) plasma-polymerized thin films can be assayed for a large number of applications in several fields such as protective anti-scratch coatings, barrier films for food and pharmaceutical packaging, corrosion protection layers, coatings for biocompatible materials and low-k dielectric layers for microelectronic applications. More recently, much effort is endowed in creating an appropriate plasma source for biomedical applications [12], in control of greenhouse gases [13]. Although the breakdown theories are appropriate for many developed situations [14], some physics and kinetics aspect are poorly understood. For the more complicated discharge systems used in many applications, it is very difficult to predict the general features such as the timing of the breakdown and the necessary voltage. For these reasons, several numerical and theoretical [15-17] works are developed to understand the breakdown mechanism. The main aim of this work is to calculate the breakdown voltage in electrical discharge, using rare gases and to understand how the discharge geometry and other parameters affect these processes. The simulation code used in this work is the MATLAB [18]. The breakdown voltage as a function of the *p.d* (pressure times the electrode spacing) product are calculated. This Paschen's curves represent a balance between the numbers of electrons lost by diffusion and drift in the inter-electrode gap and the number of secondary electrons generated at the cathode [19].

The governing equations

1. 2D Fluid model

In this paper, a two dimensions fluid model obtained by solving the two moments of the Maxwell-Boltzmann and the Poisson's equation could be solved using the finite difference scheme. The two moments of Maxwell-Boltzmann equations are the momentum and continuity equations and the Poisson's equation are represented by

$$\frac{\partial n}{\partial t}+\nabla.(nu)=G-L \qquad (1)$$

$$\frac{d^2\phi}{dx^2}=-\frac{en_0}{\varepsilon_0}(n_i-n_e) \qquad (2)$$

$$mnv_m u=qnE-\nabla p \qquad (3)$$

Where n is the particle density (i for ion positive or negative and e for electron), u is the average velocity, the right hand side of (1) represents the source term of the continuity equation, E is electric field, ε_0 is permittivity of vacuum, P is the pressure and $E=-\nabla\phi$.

The breakdown voltage occurs when the maximum total ion density reaches a given value within a given time interval.

2. Analytical model

The analytical model is based on Paschen's law which is responsible for the getting of the breakdown voltage when dielectric air or a gas is filled between electrodes gap and the number of secondary electrons generated at the cathode ionizes and attain the breakdown point [20]. The reduced electric field is proportional to the probability of the production of secondary electrons by ion bombardment on the cathode and ionization per collision of the electron-neutral gas collisions over a large range of pressures and electrodes separation [21].

Paschen's law which gives the breakdown voltage of the dielectric gas or air in a constant electric field depends on a critical number of electron multiplications throughout the ionization process induced by collisions between electrons and gas molecules in the electrode gap is [22]

$$M=\exp(\alpha d)=1+\frac{1}{\gamma} \qquad (4)$$

Where M is the multiplication factor, γ is the secondary electron emission coefficient at the cathode and α is the Townsend's first coefficient. An empirical formula in [23] which relates the Townsend's first ionization coefficient and the applied voltage V, electrode gap d and the pressure P has been given by

$$PdA_i\exp\left(-\frac{B_iPd}{V_{br}}\right)=\ln\left(1+\frac{1}{\gamma}\right) \qquad (5)$$

Where A and B are constants depending on the gas and I stands for the gas species.

Solving for V_{br}in (5) gives:

$$V_{br} = \frac{B(p.d)}{\ln\left[A(p.d) - \ln\left[\ln\left(1 + \frac{1}{\gamma}\right)\right]\right]} \qquad (6)$$

Equation (6) is sometimes written as:

$$V_{br} = \frac{B_i Pd}{\ln(PdA_i) + b} \qquad (7)$$

Where $b = -\ln\left[\ln\left(1 + \frac{1}{\gamma}\right)\right]$ (8)

Differentiating V_{br} with respect to pd and equating the derivative to zero to get $V_{br\,min}$gives

$$V_{br\,min} = 2.718\frac{B}{A}\,ln\left(\frac{1}{\gamma} + 1\right) \; (9)$$

3 Results and Discussion

The plots of the breakdown voltage V_{br} against the pressure (p) and the product of pressure and electrode spacing (Pd) were obtained by the use of (6) and (9) to determine the minimum voltages $V_{\min}$ of air and pure gases.

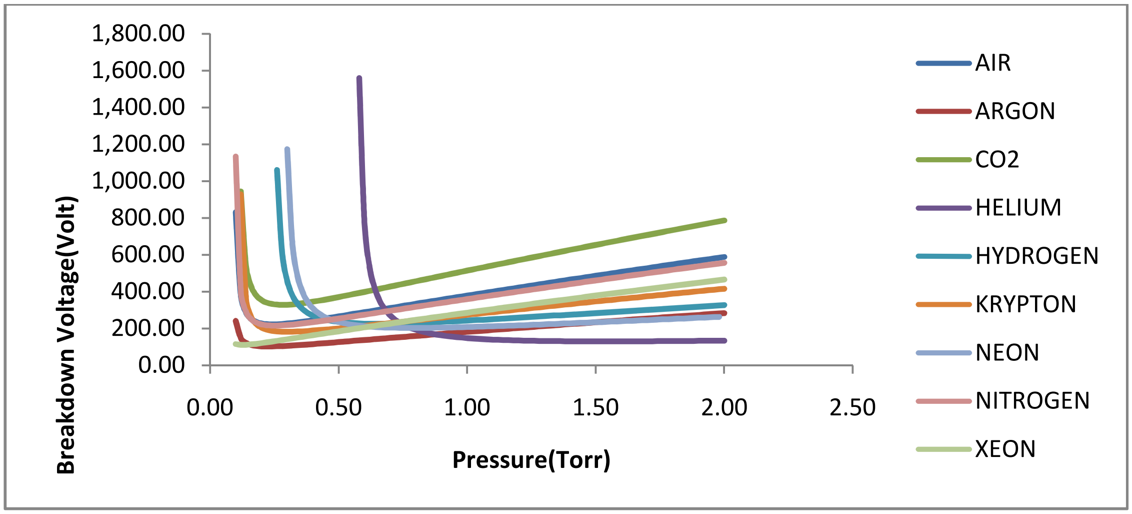

Figure 1: Breakdown Voltage as a Function of Pressure for Various Components Gases at d = 2.5cm

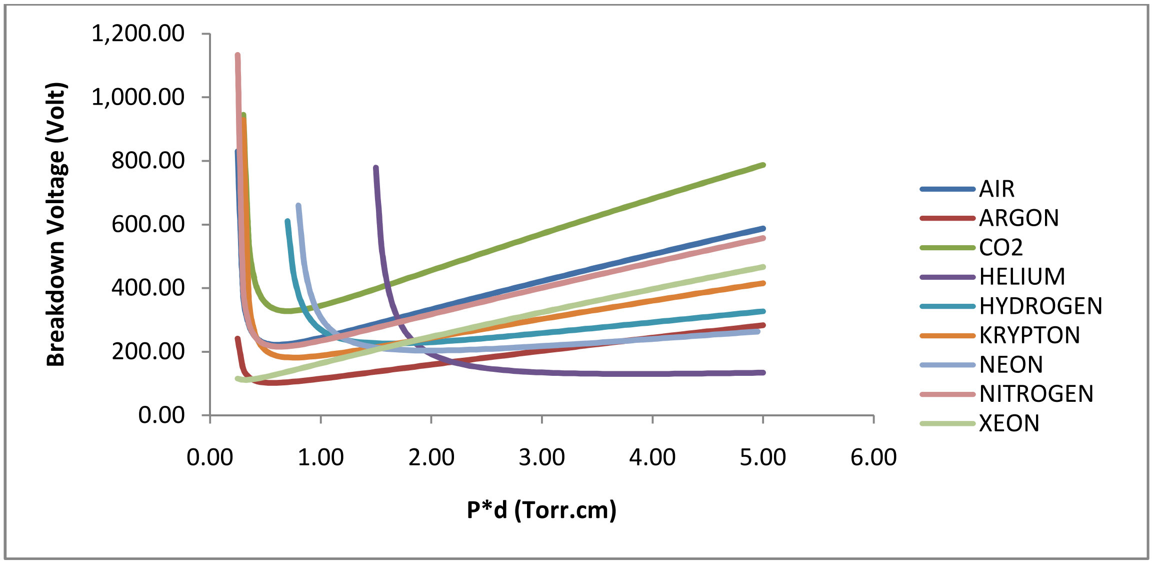

Figure 2: Breakdown Voltage as a Function of the Product of Pressure and Electrode Spacing (P*d) at d = 2.5 cm.

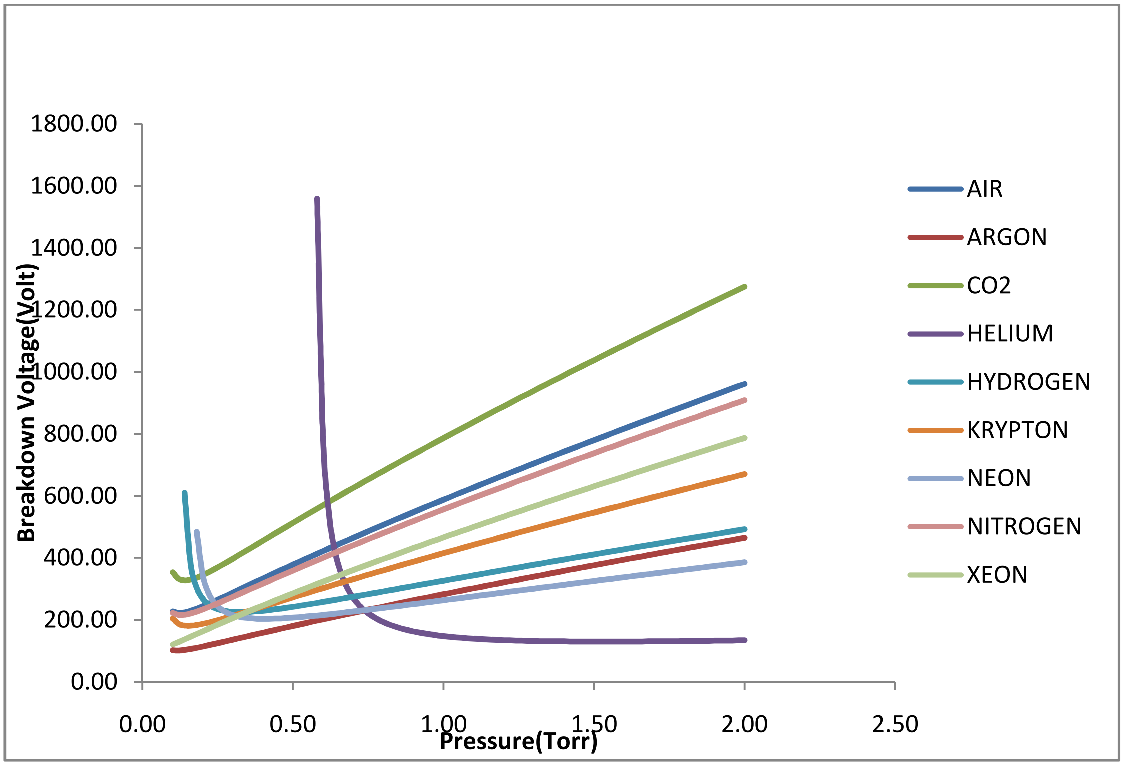

Figure 3: Breakdown Voltage as a Function of Pressure for Various Component Gases at d = 5.0cm

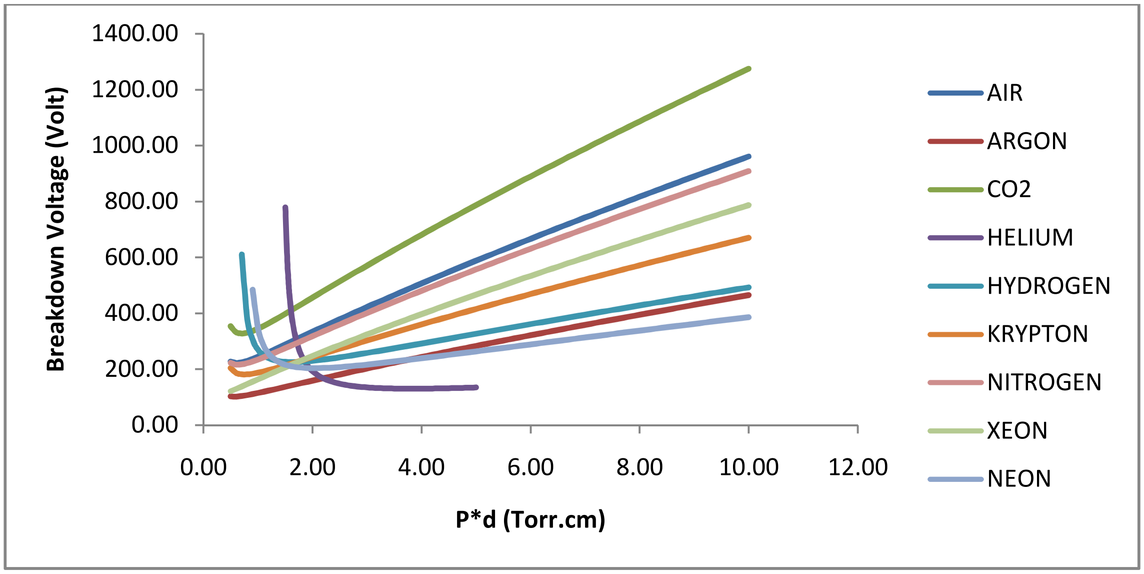

Figure 4: Breakdown Voltage as a Function of the Product of Pressure and Electrode Spacing (P*d) at d = 5.0 cm.

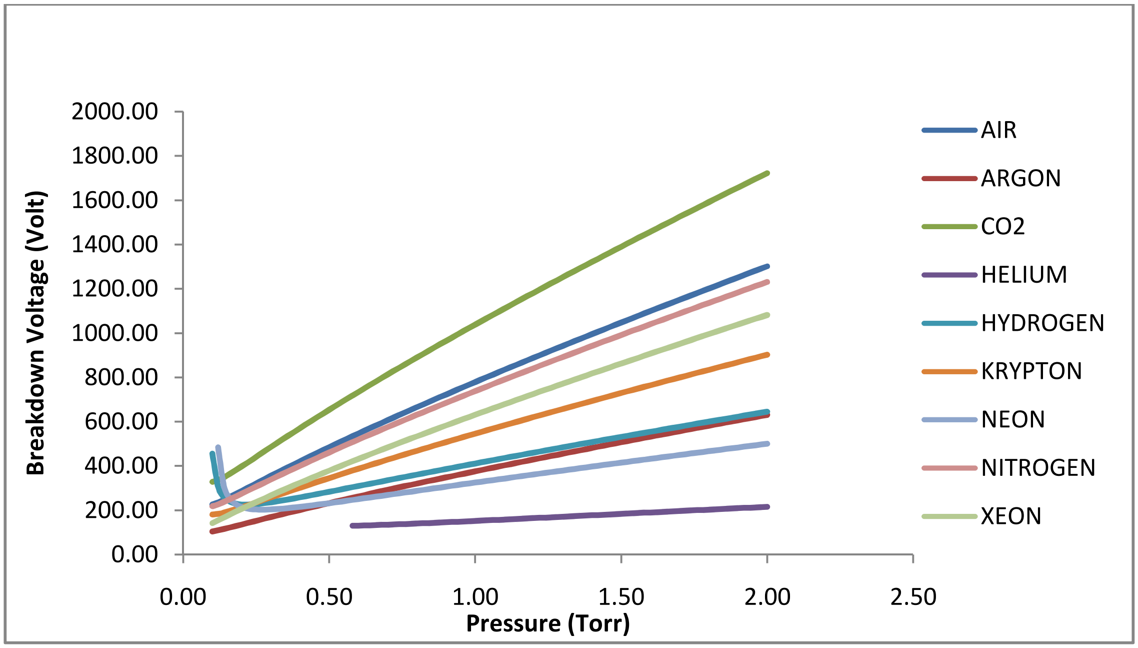

Figure 5: Breakdown voltage as a Function of Pressure for Various Component Gases at d=7.0

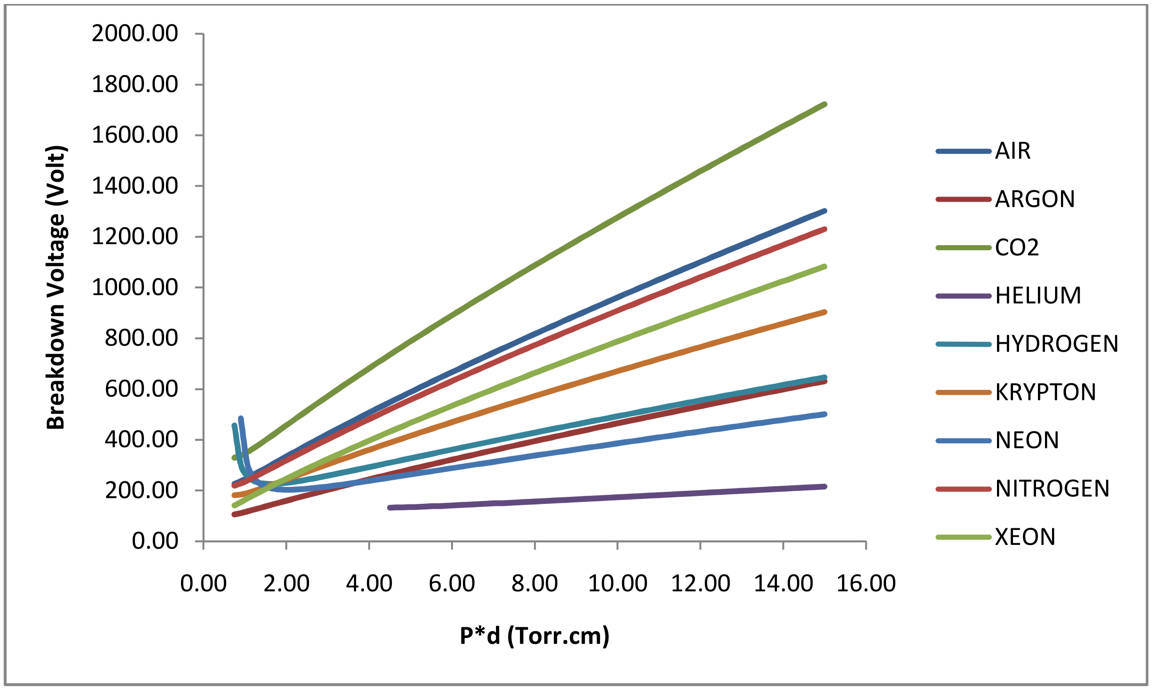

Figure 6: Breakdown Voltage as a Function of the Product of Pressure and Electrode Spacing (P*d) at d = 7.0 cm.

The Paschen'scurves are shown in Figures 1, 2, 3, 4, 5 and 6 at electrode separations of 2.5, 5.0 and 7.0 cm. These composite curves are generated using the Paschen's law for pure gases of Argon, Carbon dioxide, Helium, Hydrogen, Krypton, Neon, Nitrogen, Xenon and Air as well. The curves are plots of breakdown voltage (V_{br}) as a function of pressure P (Torr) and the product of pressure and electrode spacing (*pd*). The curves of breakdown voltage (V_{br}) as a function of pressure P (Torr) and the product of pressure and electrode spacing (*pd*) have similar shapes. The minimum breakdown voltage for Air, Argon, and Carbon dioxide, Helium, Hydrogen, Krypton, Neon, Nitrogen and Xenon at electrodes separation of 2.5, 5.0 and 7.0 cm are respectively 222.2, 101.5, 327.7, 130.0, 225.2, 181.1, 203.1, 215.6, and 111.6 volts. The product of pressure and electrodes separations (*pd*) are respectively 0.6, 0.56, 0.7, 3.8, 1.6, 0.75, 2.05, 0.65 and 0.325 Torr.cm. It can be seen from the Paschen's curves of Figures 1 - 6 that the pressure decreases as the electrodes separation increases. To the left of the minimum breakdown voltages of the gases and air, the breakdown voltage decreases with increasing *pd*. In these regimes, the gas is not very dense or the electrodes are very close; thus, even if a large number of secondary electrons are emitted, there is a low probability that any will collide with neutral atoms during the journey from the cathode to the anode. As *pd* increases, collisions are more likely to occur, and therefore the breakdown voltage is lower; thus, the Paschen's curves for air and pure gases have negative slopes in this region. When *pd* increases, beyond the curves' minimums, collisions may be too frequent rather than too rare. In this regime, an electron on its way to the anode may collide so frequently that a larger input voltage is required for it to build up enough energy to ionize a neutral atom. The electron-neutral collision frequency and thus the voltage required increases with *pd*, explaining the positive slopes of the Paschen's curves at large *pd*.

4.Conclusions

The breakdown voltages of Air, Argon, Carbondioxide, Helium, Hydrogen, Krypton, Neon, Nitrogen and Xenon respectively 222.2, 101.5, 327.7, 130.0, 225.2, 181.1, 203.1, 215.6, and 111.6 volts irrespective of the electrode spacing and the product of the electrodes spacing and pressure. The values of the breakdown voltages air and pure gases are in strong agreement with the experimental values.

5.References

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