

THEORETICAL ANALYSIS OF THE RECOVERY TIMES IN LOW PRESSURE SPARKGAPS - POSITIVE ION DIFFUSION METHOD

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Abstract

Presently there are no methods ideally suitable for the calculation of recovery times of low pressure sparkgaps. However an attempt has been made to calculate and analyze the recovery times of low pressure sparkgaps based on diffusion of positive ions here. The recovery times are calculated based on the reported data of plasma diffusion rates. The spherical ambipolar and free diffusion recovery times are generally in good agreement with the experimental recovery times at higher pressures. The cylindrical ambipolar and free diffusion recovery times are an order of magnitude lower than spherical diffusion recovery times. The recovery times are not in good agreement for positive polarity experimental recovery times. The theoretical calculation of recovery times, comparison of calculated & experimental recovery times and discussions are presented in this paper.

INTRODUCTION

The electrical breakdown and pre-breakdown characteristics of gases at atmospheric pressure and above, and at low pressures are widely investigated and there is reasonable agreement on the mechanism of growth of the current in the breakdown. But the recovery processes after the sparkgap breakdown are not studied extensively at low pressures. These are due to short duration {~100ns FWHM} of the present experimental voltage pulses leading to the lower plasma densities. The cross-sectional view of experimental setup and photograph of the system used for these studies are shown in Fig.1 and Fig.2 respectively. The recovery experiments are conducted at 10mm gap for argon gas, 10 and 2.5mm gaps for hydrogen gas and 2.5mm gap for deuterium gas with gap pressure varying from 1.1Pa to 34Pa at room temperature 295K [1, 2].

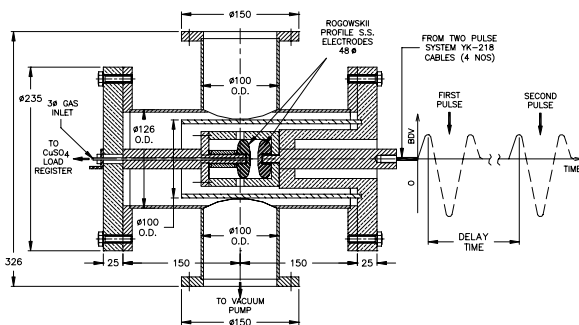


Figure 1. Cross-sectional view of experimental setup of Low Pressure Sparkgap

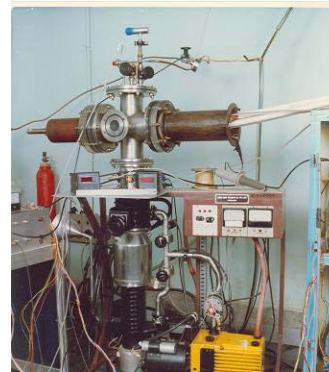


Figure 2. Photograph of the experimental setup of Low Pressure Sparkgap

The ratio of λ_e/d varies approximately from 40 for gap pressure of 1.5Pa to 1 at 23Pa and lower at higher pressures. Whenever the ratio λ_e/d is very much higher than 1, it indicates that the breakdown mechanism is initiated, developed and sustained by electrode mechanism. Here the recovery process mainly depends upon the anode temperature decay. Whenever the ratio λ_e/d is closer to 1 and lower, it indicates that the breakdown mechanism is initiated by electrode mechanism and developed and sustained by gas mechanism. Here the recovery process mainly depends upon the positive ion diffusion. Whenever the ratio λ_e/d is between these two extremes, the breakdown is initiated by electrode mechanism and sustained by gas discharge. Here the recovery process is a combination of anode temperature decay and positive ion diffusion with anode temperature decay being predominate at higher ratios and vice-versa. The recovery of the gap mainly depends upon diffusion of positive ions under the conditions of low gap current {<2.5kA}. The positive ion diffusion may be either spherical or cylindrical depending upon the discharge initiation. If the discharge is from a point then the diffusion is spherical. If it is diffuse discharge over a large surface area, then the diffusion is cylindrical. The spherical diffusion takes place when the discharge is due to pulses having risetimes in the microsecond range and above. The cylindrical diffusion is possible with applied pulses having rise times of 10 to 100ns. The positive ion diffusion may be classified as ambipolar or free diffusion, depending upon the Debye length of the plasma in the discharge. If the Debye length is less than characteristic diffusion length, then the diffusion is ambipolar and in other cases, it is free diffusion. Generally the diffusion is

ambipolar at high electron current densities and free diffusion at low electron current densities.

The free and ambipolar diffusion recovery times for spherical and cylindrical diffusions are calculated for hydrogen, argon and deuterium gases using the equations [3, 4] for the temperature range of 10K to 1000K. The general equation for diffusion of positive ions with no sources of electrons is given by

$$D \nabla^2 n = -\{n/\tau\} = -(1/D\tau) Dn \dots\dots\dots (1)$$

The solution to the above equations with a lowest mode (k=1) is given by

Cylinder. $n = n_0 \text{ COS } (a x) J_0(br), \dots(2)$

$$a^2 + b^2 = (1/D\tau) \dots\dots\dots(3)$$

With the boundary condition of $n=0$ at the walls of radius r and height h .

$J_0 =$ Bessels function, $a = \pi/h, b = (2.405/r)$

$$(1/\lambda)^2 = (\pi/r)^2 + (2.405/r)^2 \dots\dots\dots(4)$$

Sphere $(1/\lambda)^2 = (\pi/r)^2$ or $\lambda = r/\pi \dots\dots(5)$

where $r =$ Sphere radius.

$\lambda_k^2 = D \tau_k, \lambda =$ Characteristics diffusion length,

$\tau =$ decay constant.

The free and ambipolar diffusion time constants are given by

(i) **Free diffusion time constant** $= \tau_f = \lambda^2 / D_+ \dots(6)$

(ii) **Ambipolar diffusion time constant,** $\tau_a = \lambda^2 / D_a \dots\dots\dots(7)$

where $D_+, D_- =$ diffusion co-efficients for positive and negative ions,
 $D_a =$ ambipolar diffusion co-efficient = 0.1511 at NTP for hydrogen gas. For other temperatures and pressures,

$$D_a = \frac{[D_+ K_- + D_- K_+]}{[K_+ + K_-]} \dots\dots\dots (8)$$

$K_-, K_+ =$ mobilities for negative & positive ions. Where D, T, P & $D_0 T_0 P_0 =$ diffusion coefficient, temperature and pressure at temperature T and T_0 respectively. The diffusion coefficient at N.T.P. used in the calculation of recovery times are given in Table 1. The typical spherical diffusion recovery times (ambipolar) as a function of temperature for various gap pressures are plotted in Fig.3 for hydrogen gas. The spherical and cylindrical (ambipolar and free) diffusion recovery times as a function of gap pressure are plotted in Fig.4 to Fig.6 for a temperature of 295K {room temperature}, for hydrogen, deuterium & argon gases respectively. The corresponding experimental full recovery time characteristics are reproduced here for comparison [1, 2]. This calculated recovery time characteristic is a straight line in log-log

scales. The recovery time increases with increase in gas pressure and decreases with increase in temperature. The spherical and cylindrical diffusion recovery times increase with molecular weight of the gas and pressure in the gap.

Table 1

Parameters	H ₂ gas	D ₂ gas	Argon gas
D ₊ (m ² /s)	123 x10 ⁻⁵	108.1 x10 ⁻⁵	32.2 x10 ⁻⁵
D ₋ (m ² /s)	190 x10 ⁻⁵	166.9 x10 ⁻⁵	40.95x10 ⁻⁵
K ₊ (m ² /s/V)	5.19 x10 ⁻⁴	4.60 x10 ⁻⁴	1.37 x10 ⁻⁴
K ₋ (m ² /s/V)	8.15 x10 ⁻⁴	7.10 x10 ⁻⁴	1.70 x10 ⁻⁴

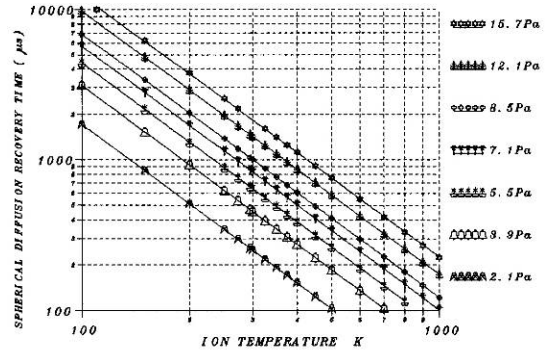


Figure 3. Spherical Ambipolar Diffusion Recovery Times vs +Ve Ion Temperature Characteristics. H₂ gas, 48mm Dia. S.S.Electrodes, 10mm Gap.

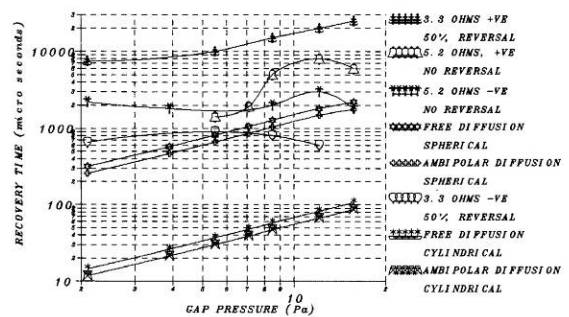


Figure 4. Hydrogen gas Diffusion Recovery Times vs Gap Pressure Characteristics, 48mm Dia., 2.5/10mm Gap.

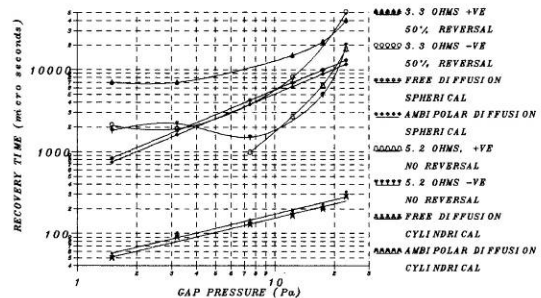


Figure 5. Argon gas Diffusion Recovery Times vs Gap Pressure Characteristics, 48mm Dia., 10mm Gap.

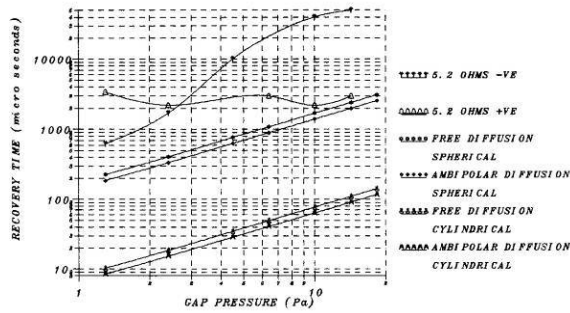


Figure 6. Deuterium gas Diffusion Recovery Times vs Gap Pressure Characteristics, 48mm Dia., 2.5mm Gap.

The cylindrical diffusion recovery times are only tens of microseconds at 295K. These are an order of magnitude lower than the spherical diffusion recovery times. The ambipolar diffusion recovery times are lower than free diffusion recovery times and the difference between them is small.

DISCUSSION

The recovery times are inversely proportional to the diffusion coefficients, which depends on the experimental temperatures. The diffusion coefficients increase with increase in temperature and decrease with increase in pressure. The recovery times decrease with increase in temperature and increase with increase in pressure and molecular weight of the gas. The volume discharge characteristics of cylindrical diffusion are an order of magnitude lower than the spherical diffusion times and not in good agreement with the experimental results. The spherical diffusion recovery times are in good agreement with the experimental recovery times. The difference between ambipolar and free diffusion recovery times is very small. The ratio of ambipolar and free diffusion recovery time is of the order of 0.8125 to 0.8136 in the pressure range of 1.2Pa to 34.7Pa. This small difference is due to lower current in the discharge. The diffusion process is a combination of free and ambipolar diffusion processes. At lower pressures and lower impedances ($<5\text{Pa}$ & $\geq 5\text{kA}$), the recovery due to anode temperature decay plays a major role. At slightly higher pressures (5-10Pa & 2-5kA), the recovery due to spherical ambipolar and free diffusion plays a major role. At pressures greater than 10Pa ($\leq 2\text{kA}$) free diffusion plays a major role. The large difference in recovery times by spherical ambipolar and free diffusions compared to experimental recovery times at low pressures is partly due to metal vapour diffusion.

CONCLUSIONS

The cylindrical diffusion recovery times cannot explain the process of recovery in a low-pressure sparkgap for the present E/p range. It may be a suitable process for higher E/p range. The spherical ambipolar and free diffusion recovery process is suitable to analyze the experimental recovery times for negative polarity with current reversals but is not suitable for positive polarity in a low pressure sparkgap. Whenever the experimental recovery times are faster than ambipolar diffusion recovery times, the recovery of low pressure sparkgap may be a combination of spherical and cylindrical diffusion processes. The recovery time of a low-pressure sparkgap depends upon the anode temperature rise and decay (metal vapour diffusion) as well as free and ambipolar diffusion processes. At higher pressures, the recovery due to ambipolar and free diffusion plays a major role.

ACKNOWLEDGEMENTS

The author is thankful to staff members of Accelerator and Pulse Power Division for useful discussions and support. Grateful thanks are due to my guides, Dr.P.H.Ron, former Head, Accelerator and Pulse Power Division, BARC, Mumbai, and former Professor G.R.Nagabhushana and former Professor R.S.Nema, Department of High Voltage Engineering, Indian Institute of Science, Bangalore, for stimulating discussions and valuable guidance. Grateful thanks are also due to Dr. A.K.Ray, Director, Beam Technology Development Group, BARC and Shri D.P.Chakravarthy, Head, APPD, BARC, for their keen interest and encouragement.

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