THEORETICAL ANALYSIS OF THE RECOVERY TIMES IN LOW PRESSURE SPARKGAPS – ANODE TEMPERATURE DECAY METHOD

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Abstract

The recovery characteristics of the low-pressure sparkgaps in the time interval of 300μs to 50ms, with stainless steel electrodes, in the pressure range of 1 to 40Pa, for gap spacings of 2.5mm & 10mm, have been determined experimentally for hydrogen, argon and deuterium gases. An attempt has been made to analyze the recovery times of low pressure sparkgaps by anode temperature rise and decay method based on liquid & solid vapour phases here. The liquid & solid phase recovery times, theoretical calculation of recovery times, comparison of calculated & experimental recovery times and discussions are presented in this paper.

INTRODUCTION

The recovery processes after the sparkgap breakdown are not studied extensively at low pressures with short duration pulses {~100ns FWHM} which do not allow sufficient time for the metal surface to melt. The cross-sectional view and photograph of the experimental setup are shown in Fig.1 and Fig.2 [1, 2]. The typical effects of electrodes after experiments, is shown in Fig.3.

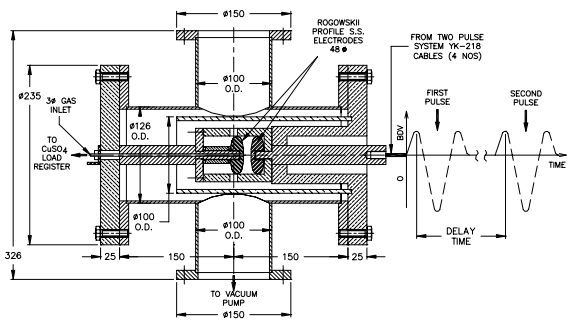

Figure 1. Cross-sectional view of experimental setup of Low Pressure Sparkgap.

Presently there are only three papers on calculation of recovery times of sparkgaps [3, 4, 5]. The experimental arc discharge times of Frind et. al. [3] are 300μs and 4500μs and currents in the range of 250A to 12kA. Since the discharges are in vacuum (1.3×10^{-4}Pa - 1.3×10^{-5} Pa) having longer pulse durations with higher currents, the anode spot has been observed in this case. The ionization potential (7.5V) is assumed to be equal to the anode drop with full recovery is assumed to be at 10^{-2} Torr with anode spot temperature decaying to 1200^{0}C for copper electrodes. However there is an order of magnitude difference between theoretical and experimental recovery times. Rich & Farrall [4] has assumed that recovery pressure is equal to twice the gap spacings as mean free path in the recovery of vacuum circuit breakers. There is good agreement in some cases and large difference in others. Tsuruta & Ebara [5] has calculated the recovery of air gaps based on gas temperature decay with the assumption as the gas temperature reduces to 300K at full recovery from peak discharge temperatures of 2000-5000K. There is good agreement at gap spacing of 3mm but the calculated recovery time is lower for 1mm and higher for 7mm than the experimental value.

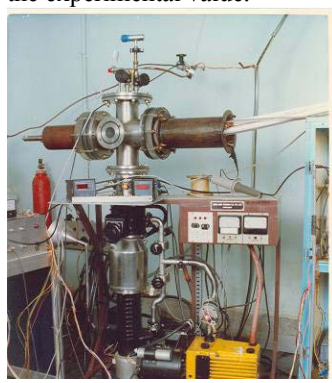

Figure 2. Photograph of the experimental setup of Low Pressure Sparkgap

Figure 3. Photograph of the typical effects of electrodes after experiments.

The recovery experiments of the present studies [1, 2] have been conducted for gases of hydrogen, deuterium and argon gases. The energy per pulse varies from 0.4 to 8J, which gives the peak power densities are of the order of 2×10^{11} W/m^2 which is lower than the critical power densities for melt zone. Presently there are no methods ideally suitable for calculation of recovery times of low pressure sparkgaps, however an attempt has been made to analyze the recovery times here by anode temperature rise and decay method based on Frind's work [3].

Recovery Time Calculation by Anode Temperature Rise and Decay Method

The rise in anode temperature for can be calculated using the following equation of Frind et. al. [3]

$$T = \frac{0.239.S.\Delta t}{\rho.C \ \{\alpha.\pi.t\}^{0.5}} e^{-\{x^2/(4.\alpha.t)\}} + 273 \quad (1)$$

Where T = Temperature in K.

Δt = Pulse Time Interval = 100ns & $\{\Delta t/(t)^{0.5}\}$ ..(2)
$= \Delta t^{0.5}$ for incremental calculation
S = Specific heat flux from arc to the surface
ρ = density gm/cm^3 = 7.54, C = Specific Heat = 0.115
α = Thermal diffusivity= 0.12
t = time since heat pulse is applied, s
x = depth below electrode surface, cm = 0.1mm
The factor 0.239 allows specific heat flux to be in watts/cm^2.

The temperature of the anode reduces due to cooling of the electrode as well of vaporization of the electrode during the initial period. This can be calculated using the equation of Frind et. al. [3]

$$T_F = \frac{0.239.WE(T).\Delta t}{\rho.C\ \{\alpha.\pi.t\}^{0.5}}\ e^{-\{x^2/(4.\alpha.t)\}} + 273 \quad ... (3)$$

For incremental calculations, this equation reduces to

$$T_F = \frac{0.239.WE(T).(\Delta t)^{0.5}}{\rho.C\ \{\alpha.\pi\}^{0.5}}\ e^{-\{x^2/(4.\alpha.\Delta t)\}} + 273 \ldots (4)$$

where $WE(T) = 16200.[T / 2000]^{9.91}$ .for copper electrodes .....(5)
$= 19970.[T / 2216]^{10.5}$ .for stainless steel electrodes .....(6)
with Δt = Pulse Time Interval = 100ns & $\{\Delta t/(t)^{0.5}\}$
$= \Delta t^{0.5}$ for incremental calculation
WE(T) = Anode temperature decay flux of the vaporization of anode surface in time Δt.
anode drop V_a = 25volts for H_2 at 26.7Pa
= 16-18 volts for D_2 at 133.3Pa-667Pa
= 15.3 volts for Argon at 66.7Pa

In the present work, the metal surface has been assumed to vaporize within the pulse duration time of 100ns due to high peak power density. Hence the discharge is assumed to be predominately gas discharge and for calculation of anode temperature rise and anode drop is assumed to be gas discharge anode drop. The recovery times are calculated based on the reported data of anode drops. The typical H_2 gas anode temperature decay as a function of Time Characteristics and peak anode temperature as a function of gap pressure characteristics are shown in Fig.4, and Fig. 5 respectively. The peak temperatures are lower than anode spot formation temperatures and higher than for anode foot-points. Hence it can be concluded that only the anode foot-points can be formed as per Gundersen [6] and Klapas et. al. [7]. Once the temperature decays to respective vapour pressure temperatures {1806K & 1612K at 1.2Pa for hydrogen, 1813K & 1617K at 1.3Pa for deuterium & 1819K & 1622K at 1.5Pa for argon gases for liquid & solid phases}, the sparkgap has recovered completely (full recovery).

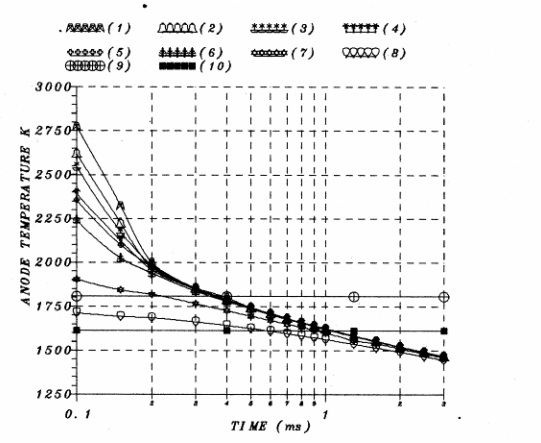

Figure 4. H_2 gas anode temperature decay vs Time Characteristics, 48mm Dia. S.S. Electrodes, 10mm Gap.
(1)- 2.1Pa, -Ve, (2)- 2.1Pa, +Ve, (3)- 5.5Pa, -Ve, (4)- 5.5Pa, +Ve, (5)- 8.5Pa, -Ve, (6)- 8.5Pa, +Ve, (7) 12.1Pa, -Ve, (8)-12.1Pa, +Ve, (9)- Liquid Vapour Phase Temperature-1806K, 1.2Pa, (10) Solid Vapour Phase Temperature-1612K, 1.2Pa.

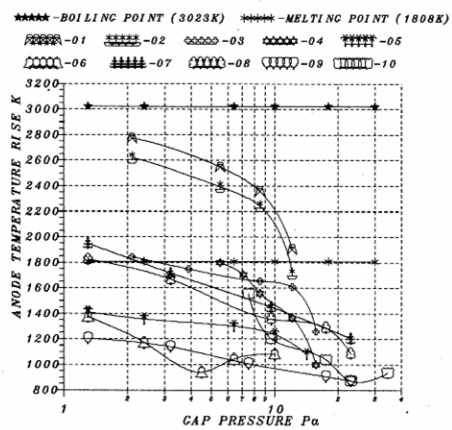

Figure 5. Anode temperature Rise vs Gap Pressure Characteristics, 48mm Dia. S.S. Electrodes, 10mm Gap.
H_2 gas, 50% Rev., 3.3Ohms, 10mm Gap-[01- -Ve, 02-+Ve] H_2 gas, 0% Rev., 5.2Ohms, 2.5mm Gap-[03- -Ve, 04-+Ve] D_2 gas, 0% Rev., 5.2Ohms, 2.5mm Gap-[05- -Ve, 06-+Ve] Ar gas, 50% Rev., 3.3Ohms, 10mm Gap-[07- -Ve, 08-+Ve] Ar gas, 0% Rev., 5.2Ohms, 10mm Gap-[09- -Ve, 10-+Ve].

RESULTS AND DISCUSSIONS

The typical estimated anode temperature decay full recovery times with gap pressure characteristics for hydrogen and argon gases are shown in Fig.6 and Fig.7. There is a small difference in recovery times of positive and negative polarities due to some difference in peak temperatures. This difference is not significant. The negative polarity recovery times are in good agreement with solid phase recovery times in case of hydrogen gas with 50% current reversals (gap currents of 5kA, Fig.6). The experimental recovery times are nearly two times

in case of 2.1Pa for hydrogen gas and 1.5Pa for argon gas. There is a large difference between experimental and solid phase recovery times for both argon and hydrogen gases under positive polarity with 50% current reversal. (seven times solid phase recovery time at 1.5Pa, argon gas and at 2.1Pa hydrogen gas). This process cannot explain this large difference between positive and negative polarities with large current reversals.

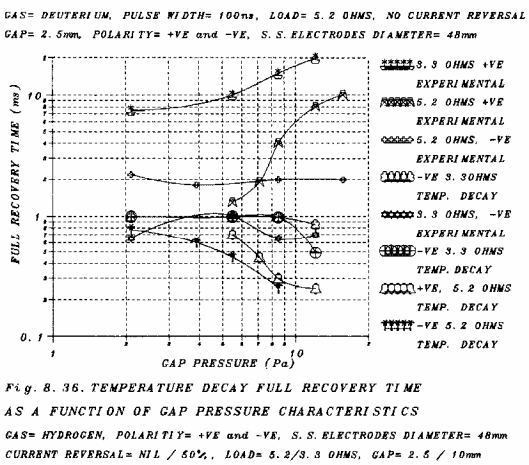

Figure 6. Temperature Decay full recovery times vs Gap Pressure Characteristics, H_2 gas, 48mm Dia. S.S. electrodes, 2.5mm /10mm Gaps, Load=5.2 & 3.3 Ohms.

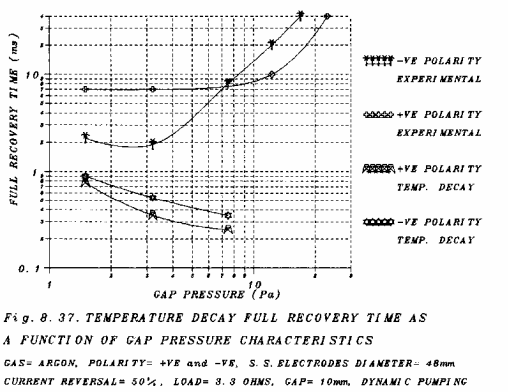

Figure 7. Temperature Decay full recovery times vs Gap Pressure Characteristics, Ar gas, 48mm Dia. S.S. electrodes, 10mm Gap, Load= 3.3 Ohms, 50% Rev.

CONCLUSIONS

The anode spots cannot be formed but anode foot-points can be formed on anode for the present experimental currents. The anode temperature decay recovery time reduces drastically close to melting point temperature and increase in pressure. This does not fit well with the experimental recovery times. For short duration pulses and for anode temperatures greater than melting point, a combination of liquid and solid phase may be responsible for recovery of the gap. Generally the recovery of the gap depends upon the combination of these processes for temperatures between melting point and solid vapour pressure temperature.

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