Analysis of Anode Temperature decay of spark gap electrodes on its Recovery times

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Abstract **- The theoretical analysis of anode temperature rise and decay methods has been made. The mechanism of evaporation from highly heated anode was explained and recovery times were estimated. The effect of anode temperature decay on the recovery times of spark gap for a pulse having 10μs pulse width and current of 30kA for Cu and Stainless Steel has been estimated. A transient heat transfer model was made in FEM based software to analyze the temperature decay. An attempt has been made to compare the calculations with the simulated results. Theoretical calculations of recovery times, heat transfer simulation model results and discussions are presented in this paper.**

keywords **- Anode temperature decay, Anode materials, Spark gap recovery, Specific heat flux, Vaporization**

1. INTRODUCTION

The pulse repetition frequency (PRF) of a pulse generator depends on the recovery rate of the sparkgap switches. The recovery process of sparkgap is a complicated phenomenon and depends on many factors. Because of its Inability to operate under tens of kA and MV range, the solid state switches like insulated-gate bipolar transistors, thyristors and thyratrons are not suitable for high power applications. The potential applications of pulsed power technology are industrial, medical, ion implantation and welding. For such applications, spark gap exhibits many of the desired characteristics. However, the lifetime and pulse repetition frequency (PRF) are the main limitations of the spark gap. The PRF of a pulse generator depends on the recovery rate of the spark gap switches. The recovery process of spark gap is a complicated phenomenon and depends on many factors. The recovery mainly depends upon (i) The first pulse (or main pulse) breakdown voltage (FBDV), wave shapes, current magnitude and reversal, (ii) Temperature recovery of anode, (iii) gas type and its temperature recovery (iv) pressure. An experimental study of recovery characteristics of spark gaps by [1-3] using H_2, N_2 and SF_6 gasses for a current of 30KA and a pulse width of 60ns hasbeen conducted. Hydrogen has the best recovery characteristics compared to SF_6 and N_2. The recovery of air gaps based on gas temperature decay has been calculated by [4]. The recovery time is lower and higher for 1mm and 7mm gaps respectively than the experimental values, but there is a good agreement for the 3mm gap.

The temperature is an important factor in the recovery process of the spark gap switch. The breakdown in the gap is initiated by the breakdown of micro-projections on the cathode[5]. The plasma produced acts as a source of electrons and results in breakdown of the gap due to gaseous discharge. In low current discharge, the anode is basically passive and acts as a collector of positive ions. In high current discharges, a fully developed anode spot is formed. This anode spot has a temperature near atmospheric boiling temperature of anode material and is a source of metal vapors and ions. The formation of anode spot is preceded by anode foot-point, which is luminous but cooler than anode spot [6], [7]. In present calculations it is assumed that anode foot-points can be formed as per [8], [9]. These have low temperatures compared to anode spots. Electrode surface evaporates due to discharge current in the gap depending upon the energy transferred to anode. The recovery process depends upon the metal vapor ejected from the electrode due to temperature rise of anode. The metal vapor decreases the pressure in the gap that reduces the breakdown voltage of the gap.

The anode temperature rise and decay of sparkgap plays vital role in the pulse repetition frequency (PRF) of the pulse generator. The theoretical analysis of temperature recovery of both copper and Stainless Steel electrodes for a pulse having 10us pulse width and current of 30kA has been made in the following sections. An equivalent heat flux for a 30kA pulse has been calculated and is applied on to anode by using a transient heat flow equation to see the temperature decay. This anode temperature decay process is also observed with a simulation model developed using FEM based software.

2. THEORETICAL ANALYSIS

The anode surface temperature is calculated based on the input heat-flux density to the anode surface and heat-decay mechanisms for different anode materials. To see the anode temperature rise and decay, a transient heat flow equation has been sought out for a semi-infinite solid. The differential equation for the temperature distribution t(x, τ), for the surface temperature of a semi-infinite solid lowered from $t_i$to t_0, is

$$\frac{\partial^2 t(x,\tau)}{\partial x^2} = \frac{1}{\alpha}\frac{\partial t(x,\tau)}{\partial t} \quad \ldots\ldots (1)$$

Where, t = temperature (K)
τ = time (s)
α = thermal diffusivity (cm_2 /s).

By applying Laplace transformation, the above differential equation becomes,

$$sT(x,s) - f(x) = \alpha \frac{d^2T(x,s)}{dx^2} \quad \text{..... (2)}$$

$$\text{Where, L } [t(x,\tau)] = \int_0^\infty t(x,\tau)e^{-s\tau}d\tau = T(x,s)$$

Thus, differential partial equation (1) for the inverted transform of the function t(x,τ) turns into an ordinary differential equation for the transform T(x,s), since T(x,s) does not depend on τ.

Now introducing the special condition that the temperature of the body before cooling is the same everywhere and equal to t_i., (i.e., f(x) = t_i = constant).

$$\frac{d^2T(x,s)}{dx^2} - \frac{s}{\alpha}[T(x,s) + (\frac{t_i}{\alpha})] = 0 \quad \text{.... (3)}$$

A general solution of this differential equation may be written as,

$$T(x,s) - \frac{t_i}{s} = A_1 \exp[\sqrt{\frac{s}{\alpha}}x] + B_1 \exp[-\sqrt{\frac{s}{\alpha}}x] \quad \text{.... (4)}$$

Where, A1 and B1 are constants to be determined by the boundary conditions. Using the Laplace transformation for the boundary conditions,

$$\text{L } [t(0,\tau)] = 0, \qquad T(0,s) = 0 \quad \text{... (5)}$$

$$L[\frac{\partial t(\infty,\tau)}{\partial x}] = 0, \ \frac{dT}{dx}(\infty,s) = 0 \quad \text{.... (6)}$$

From final condition, it follows that $A_1 = 0$ and $B_1 = -\frac{t_i}{s}$, and solution written as

$$\frac{t_i}{s} - T(x,s) = \frac{t_i}{s}\exp[-\sqrt{\frac{s}{\alpha}}x] \quad \text{.... (7)}$$

By using the inverse transforms,

$$L^{-1}[(\frac{1}{s})\exp[-k\sqrt{s}]] = 1 - erf(\frac{k}{2\sqrt{\tau}}) \quad \text{... (8)}$$

In our problem $k = \frac{x}{\sqrt{\alpha}}$, and if the initial temperature is uniformly distributed over the anode length, then the equation becomes,

$$\frac{t(x,\tau) - t_0}{t_i - t_0} = erf(\frac{x}{2\sqrt{\alpha\tau}}) \quad \text{..... (9)}$$

Where *erf*(x/(2√τα)) is a Gauss error function and is defined as,

$$erf(\frac{x}{2\sqrt{\alpha\tau}}) = \frac{2}{\sqrt{\pi}} \cdot \int_0^{\frac{x}{2\sqrt{\alpha\tau}}} e^{-\eta^2}d\eta \quad \text{..... (10)}$$

Performing the partial differentiation, gives,

$$\frac{\partial t}{\partial x} = \frac{t_i - t_0}{\sqrt{\alpha\tau\pi}} \cdot e^{-(\frac{x^2}{4\alpha\tau})} \quad \text{..... (11)}$$

For a short, instantaneous pulse having specific heat flux S applied to a body, which is having zero initial temperature, then the resulting temperature rise is,

$$T_r = \frac{0.239S\Delta\tau}{\rho c\sqrt{\pi\alpha\tau}} \cdot e^{-(\frac{x^2}{4\alpha\tau})} \quad \text{..... (12)}$$

Where, T_r = Rise in temperature.

S = specific heat flux from the arc to the surface.
Δ_τ = pulse time interval in sec.
ρ = density.
c = specific heat.
α = thermal diffusivity.
τ = time since heat pulse is applied.
x = depth in the solid body.
(The factor 0.239 allows specific heat flux to be in watts)

Fig.1 shows the anode temperature rise for copper and stainless steel materials for a heat flux of $5.82*10_{11}$w/m_2.

Anode temperature will reach equilibrium value which is determined by the temperature at which, energy losses due to vaporization from the anode surface become equal to the energy input to the anode. This value of equilibrium temperature is less for Cu anodes compare to Stainless steel anodes for applied heat flux. The parameters for Copper and Stainless steel at atmospheric condition are shown in Table1.

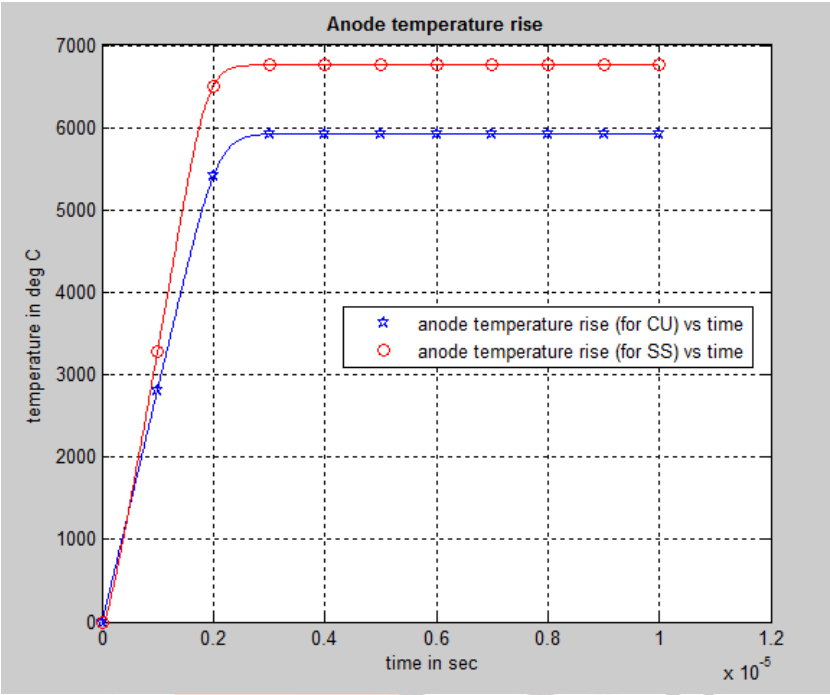

Fig.1 Anode temperature rise for copper and stainless steel materials

The temperature of the anode reduces to pre-breakdown temperature as the applied pulse ceases. This decay is due to vaporization of electrode during the initial period as well as cooling of the electrode. This temperature decay at the surface and at specific points within the contact material can be calculated using the equation of

$$T_d = \frac{0.239(S - WE(T))\Delta\tau}{\rho c\sqrt{\pi\alpha\tau}} .e^{-(\frac{x^2}{4\alpha\tau})} \quad \ldots. (13)$$

Where, WE (T) is an empirical relation for anode temperature decay flux of the vaporization in time Δτ and the values are taken from and modified for atmospheric pressure conditions as follows.

WE (T) = $16200\ [T / 2595]_{9.91}$ for copper electrodes
= $19970\ [T / 2960]_{10.5}$ for stainless steel electrodes

Table 1. Thermal data for Cu and Stainless Steel materials

Parameters	Copper	Stainless Steel
Specific heat flux in W/cm_2	$5.82*10_7$	$5.82*10_7$
Density in gram/cm_3	8.92	7.85
Specific heat in Cal/gram-K	0.0923	0.38
Thermal diffusivity in cm_2 sec	1.12	0.042

Once the anode temperature decayed to their respective vaporization temperature, the spark gap has assumed to be recovered. The vaporization temperature for copper and stainless steel at atmospheric conditions are 2868K and 3233K respectively. Fig.2 shows the anode temperature decay for copper and stainless steel materials.The temperature decay is exponential for temperatures greater than 3273K for Cu and 3773K for SS.

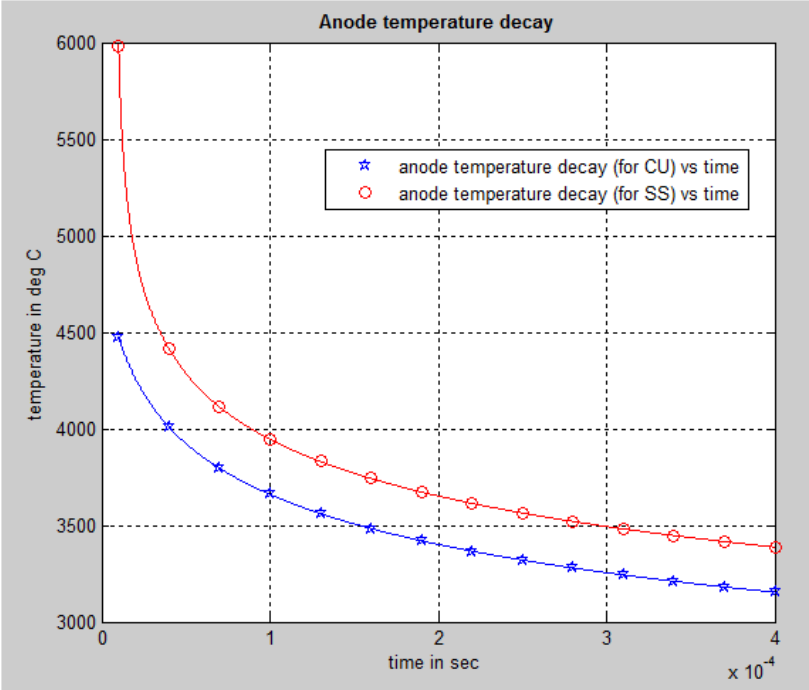

Fig.2 Anode temperature Decay for copper and stainless steel materials

This changes from exponential to linear and become invariant for temperatures less than 3273K for Cu and 3773K for SS. The initial exponential decay is due to metal vaporization and after this decay is due to only cooling of anode. The decay time to vaporization temperature is around 300µs and is closely matching with the experimental results of G.Frind. In his measurements, recovery time increases slowly and reaches 40µs at 4kA. Then the curve attains a value of 630µs for 12kA current.

3. SIMULATION METHOD

A heat transient simulation model is developed using FEM based software to study the temperature decay in copper, stainless steel, silver, tungsten and graphite materials. The total recovery time is not possible to estimate by the anode temperature decay method for temperatures less than vaporization temperature. The temperature decay model of the switch following the equations below:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u_{trans} \cdot \nabla T = \nabla \cdot (K \nabla T) + Q \quad \ldots\ldots (14)$$

$$-n \cdot (-K \nabla T) = h \cdot (T_{ext} - T) \quad \ldots\ldots (15)$$

$$-n \cdot (-K \nabla T) = \varepsilon \sigma (T_{amb}^4 - T^4) \quad \ldots\ldots (16)$$

Where, K = Thermal conductivity (W/m-K)
P = Density (kg/m_3)
C_p= Heat capacity at constant pressure (J/kg-K)
h = Heat transfer co-efficient (W/m_2-K)
T_{ext} = External temperature (K)
ε = Surface emissivity
T_{amb}= Ambient temperature (K).

Equation (14) is Heat transfer equation in solids; (15) is convective cooling equation; (16) is surface to ambient radiation equation. Physics controlled and very fine meshing is used in the simulation

The complete recovery time is not possible to estimate by the anode temperature decay method for temperatures less than vaporization temperature due to metal vaporization not possible below these temperatures . For study of anode temperature decay in both copper and stainless steel materials a heat transient model is developed using FEM based software. Specific heat flux of 5.82*10_{11}w/m_2 is calculated by the formula of for a pulse having 10µs pulse width and current of 30kA and applied to the surface of the anode. The decay time of the anode temperature will increase with pulse width since the thermal gradient at the surface is a decreasing function of pulse width. Fig.3 shows the temperature decay curves for copper and stainless steel materials. It shows that the temperature of the copper electrodes decays much faster than that with stainless steel.

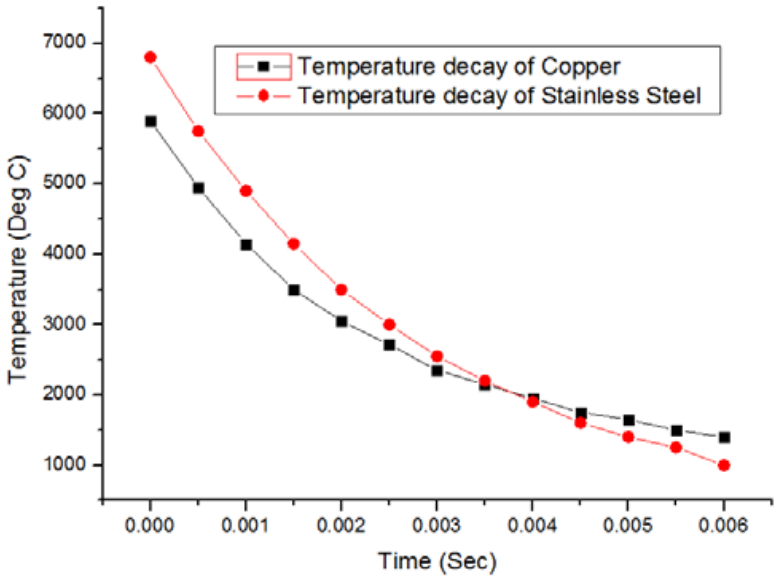

Fig. 3 the temperature decay curves for copper and stainless steel materials.

The simulation decay curve is linear compare to the theoretical model curve, because the simulation did not consider the initial temperature decay due to metal vaporization. Since in actual sparkgap recovery involves electrodes as well as gas temperature recovery, the obtained recovery time may differ with the experimental values.

4. CONCLUSION

Copper electrodes are having faster decaying time than that of stainless steel electrodes. The evaporative losses in this model are comparable to input higher flux density only at higher temperatures. The recovery process of sparkgaps not only depends on the temperature recovery of anode but the dielectric medium recovery between the electrodes also plays a vital role. The anode temperature recovery method is only effective above vaporization temperatures. Below these temperature levels recovery can be estimated by gas temperature recovery methods.

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