Anode Hotspot Temperature Estimation in Vacuum Gaps under 50 Hz Alternating Excitations

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ABSTRACT

This paper presents the computed results of anode hotspot temperature calculations for vacuum gaps subjected to 50 Hz ac excitations. The transient heat diffusion equation governing the heat conduction is solved by a finite difference method. The effects of nonlinear variation of thermal properties with temperature and phase change are also studied by using ANSYS 4.4, a powerful finite element package. The peak temperatures are estimated by a seminumerical method. The methods presented provide a convenient means of anode hotspot temperature estimation and the determination of cool-off time for different electrode materials. The results of a parametric study to examine the effects of electrode material, field intensification factor, and radius of the spot are presented along with a comparative analysis of different available methods. The results obtained for stainless steel, copper and aluminum anodes indicate that the temperature of hot spots can reach the melting point for reasonable values of the field intensification factor. They are therefore the main sources of microparticles. The asymmetry of the experimentally observed prebreakdown current waveform about its own peak, which is caused by thermal instability at the anode, can be attributed to the nonlinear variation of thermal properties with temperature. The methods discussed can be used to estimate the size of microparticles originating from thermally unstable regions at the anode.

1. INTRODUCTION

THE study of electrical properties of vacuum gaps has generated a great deal of interest in connection with increasing applications in a variety of HV apparatus, including protective switchgear installations. Though these devices were primarily developed to protect electrical sys-

tems against short-circuit currents at power frequencies, yet there are only few studies concerning the behavior of vacuum gaps under ac voltages [1-5]. In HV gaps in vacuum, considerable electronic currents (pre-breakdown currents) are found below the breakdown voltage (BDV). Several studies [6-11] on prebreakdown (PBD) conduction under ac voltages indicate that the current magni-

tudes are much higher than under comparable dc stresses and the waveform is asymmetrical about its own peak. Further, PBD currents at 50 Hz voltages are reported [12] to be strongly dependent on the melting point of the anode material. It is also observed that anode phenomena resulting from thermal instabilities could play a significant role in PBD current enhancement under alternating voltages [13]. It has also been shown from studies on electrical breakdown between plane-parallel electrodes under dc voltages that steady evaporation from either electrode due to local heating by PBD current does not produce sufficiently dense vapor in the interelectrode space for significant amplification of field emission current [14]. The attainment of a critical temperature by a region on the anode would lead to the production of electrode vapor by the detachment of a charged microparticle and its subsequent evaporation. This process can take place when the ultimate tensile strength of the microparticle is equal to the force due to the local electric field. It has also been reported that even a subcritical heating (i.e. below the melting point) of a particle could create the necessary conditions for a subsequent breakdown event [15]. Also, the photographic observation of predischARGE phenomena has shown the presence of luminous spots on the anode surface [16–18] which degenerate into locally heated spots.

Generation of microparticles of size $\leq 3 \mu\text{m}$ have been observed under direct voltages [19]. Such phenomena are not clearly understood in the case of alternating and pulsed voltages. It was intuitively believed that the experimentally observed time delay between the voltage and the PBD current peaks was due to a slow phenomenon [12]. The anode thermal time constant was believed to be one of the probable candidates. Therefore, an attempt has been made in this work to compute the thermal time constants. The electron beam originating from cathode microprojections which represents a concentrated source of heat energy plays a crucial role in causing the initial thermal instability in vacuum insulated devices. To obtain realistic solutions for heat flow problems involving anode hot spots, particularly under transient conditions, is nontrivial. Analytical solutions for a variety of problems, including the transient temperature distribution in a semi-infinite body heated by a Gaussian heat source on the surface, have been presented by Martin *et al.* [20]. These solutions are no doubt exact, but need numerical methods for evaluation. Moreover, such solutions are not convenient to handle input energy pulses of arbitrary shape. Increasing availability of economical computational power and the need of a more detailed knowledge of heat transfer in many advanced applications has stimulated the appearance of several codes intended as general purpose tools for thermal computations, for 2 and

3-dimensional problems [22].

This paper presents the results of anode hotspot temperature calculations in electrodes subjected to pulsed electron beam heating, particularly under 50 Hz ac excitations. A sufficiently accurate numerical solution for the transient temperature distribution in a cylindrical disc heated by a circular source at the surface using a finite difference method is presented. This computer code was validated by comparison with an analytical solution in our earlier work [23]. The effect of nonlinear variation of thermal properties with temperature and phase change (solid to liquid) is studied by computing the temperature distribution using ANSYS 4.4, a powerful finite element package. For further comparison, the results from a semi-numerical method are also presented for stainless steel, copper and aluminum anodes. The effect of important parameters such as the field intensification factor (β -factor), cathode work function and radius of the hot spot on the peak temperatures are also examined. A comparative study of the above methods is made in order to arrive at reasonable compromises between accuracy, computing time and memory requirement. The temperature calculations involving non-linear variation of material property with temperature indicate that the temporal variation of temperature is asymmetrical about its peak. The PBD current growth which is caused by thermal instability at the anode is also asymmetrical about its peak, thereby indicating that there appears to be a one to one correspondence between the two. The above argument is supported by an excellent agreement of the experimentally recorded PBD current waveshape and the corresponding temperature profile.

2. METHODS OF ANODE HOTSPOT TEMPERATURE ESTIMATION UNDER ac EXCITATION

THE most widely used numerical methods for the solution of transient heat diffusion equation such as the one encountered in the present case are the finite difference method (FDM) and the finite element method (FEM). In addition to these two methods, seminumerical methods, which make use of available analytical solutions, can also be used, but they have some limitations.

2.1 PROBLEM FORMULATION

In the present analysis the anode hotspot is modeled as a cylindrical disc heated by the electron beam at its

center. The electron beam flux q_e is assumed to be uniform within the beam radius r_e . Neglecting convection and radiation losses, the governing equations [20] in the cylindrical coordinate system takes the following form

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (1)$$

The boundary conditions for Equation 1 are

$$\begin{aligned} \frac{\partial T}{\partial z} &= 0 \quad \text{at } r = 0, z = z_{max} \\ T &= T_{\infty} \quad \text{at } r = r_{max} \\ T &= T_{\infty} \quad \text{at } z = z_{max} \\ -k \frac{\partial T}{\partial z} &= \begin{cases} q_e & r \leq r_e, z = 0 \\ 0 & r > r_e, z = 0 \end{cases} \end{aligned} \quad (2)$$

where r_e is the electron beam radius (m), T is the temperature ($^{\circ}\text{C}$), t is the time (s), α is the thermal diffusivity (m^2/s), k is the thermal conductivity (W/Km), q_e is the heat flux (W/m^2), T_{∞} is the ambient temperature ($^{\circ}\text{C}$), and r and z have their usual meaning in cylindrical coordinate system.

In all practical vacuum gaps, under alternating voltages, there is an obvious reversal of polarity in each half cycle of the applied voltage. It will suffice if the temperature distribution is calculated for one half cycle of the 50 Hz sinusoidal voltage pulse, where the grounded electrode is considered as the cathode and the HV electrode as anode. The electron beam power input at any instant is given by $P(t) = V(t)I(t)$ where $V(t)$ and $I(t)$ are instantaneous values of voltage and current. The current-voltage relationship is governed by the well known Fowler-Nordheim (FN) equation [24]. The heat flux q_e which is a non-linear function of time is given by

$$\begin{aligned} q_e(t) &= \frac{p(t)}{\pi r_e^2} \\ p(t) &= K_1 \beta^2 V_{max}^3 \sin^3(\omega t) d^2 \exp\left(\frac{-K_2 d}{\beta V_{max} \sin \omega t}\right) \end{aligned} \quad (3)$$

where $K_1 = 1.54 \times 10^{-6} A_e / \phi$ and $K_2 = 6.83 \times 10^9 \phi^{1.5}$, V_{max} is the applied voltage (peak) (V), d is the gap distance (m), β is the field intensification factor, and ϕ the work function (eV).

The effective values of β and A_e are obtained from the slope and intercept of the FN plots for a constant value (4.5 eV) of work function. For anode materials like stainless steel, copper and aluminum, β are in the range of 150 to 250 for 1 mm gap under ac excitation [12]. The present analysis shows that the electron beam power density and hence the hotspot temperature is highly sensitive to the β values.

2.2 THE FINITE DIFFERENCE METHOD

The use of finite difference method (FDM) for the numerical solution of such transient heat flow problems has been reviewed in detail in [31]. In the present work the computational domain is discretized into control volumes of nonuniform size. The high temperature gradients near the heat source are handled by using a 'staggered grid' arrangement (smaller grids are used near the heat source). The time steps are done by the 'alternating direction implicit' (ADI) scheme. This computer code has been validated by comparison with the analytical solution for a semiinfinite solid heated by a circular source [20]. This method has been discussed in greater detail in one of our previous papers [23]. The solution at the origin [20] can be written as

$$T(t) - T_{\infty} = \frac{q_e r_e}{k} \left[\frac{r_e}{2\sqrt{\pi\alpha t}} \left(1 - \exp\left(\frac{-r_e^2}{4\alpha t}\right) \right) + \text{erfc}\left(\frac{r_e}{2\sqrt{\alpha t}}\right) \right] \quad (4)$$

The numerical and the analytical solutions are found to agree well for a single pulse (Figure 1).

Figure 1.

Heating of semi-infinite solid. Comparison of FDM with exact solution.

2.3 THE FINITE ELEMENT METHOD

Temperature distributions are calculated by heat transfer analysis as a first step in the selection of materials that may experience abnormal temperatures during their service life. Therefore, there is a strong need for realistic modeling of boundary conditions, representing complicated geometry, and analyzing materials (solids and fluids) with anisotropic properties. FDM approach cannot meet these challenges adequately. In addition to the ability to treat irregular geometry, finite element methods (FEM) can offer improved accuracy and in some cases higher efficiency for the same accuracy as compared to FDM. FEM,

by its nature, leads to unstructured meshes i.e., an analyst can place finite elements anywhere. In addition to these advantages FEM is robust and has a strong mathematical foundation. The advantages and disadvantages and the applicability of FEM to heat conduction problems are discussed in [25,26].

The present problem of electron beam heating is modeled in 2-d domain with symmetry about the z -axis in the cylindrical coordinate system (r, ϕ, z) . The thermal properties are independent of ϕ , and temperature is a function of only r and z , and the domain is represented by axisymmetric ring elements. The region of interest is confined to $r \leq r_e$. Therefore, five nodal points inside the domain (electron beam impact area) were sufficient to achieve a fair degree of accuracy. The overall modeling of the electrode requires large number of elements and consequent increase in memory and computer time. The heat inputs to the different nodes were calculated using the relations given in [25]. The outer boundary ($T = T_{amb}$) was varied and it was found that it did not affect the accuracy of the results appreciably at points beyond $10\times$ the beam radius. Therefore it is assumed that the temperature, $T = T_{amb}$ at all points beyond this limit. The non-linear material property data given by Toloukin [27] for the respective materials was used in the ANSYS program. The phase change (solid-liquid) in the electron beam impact area has been modeled by a step change in specific heat over the zone (i.e. $T_{solid} < T < T_{liquid}$) and the new value of specific heat C'_p is determined from the relationship $(C'_p - C_p)(T_{liquid} - T_{solid}) = \text{latent heat}$. Further, guidelines given in the user manual [22] was used to incorporate phase change in the computations.

2.4 SEMI-NUMERICAL METHOD

Semi-numerical methods essentially use analytical solutions. Functions which can be conveniently represented mathematically are discretized and analytical solutions are used to obtain the solution at the end of each interval. The final solution is obtained by superposing these individual solutions. This procedure is based on Duhamel's theorem. Myers [30] has discussed the applicability of this method to obtain solutions to transient heat conduction problems. The analytical solution given in Equation (4) above has been used to compute the temperature distribution for one half cycle of the sinusoidal pulse. The results obtained agree well with those obtained by FDM and FEM. The peak temperature (i.e. at $r = 0$) for one half cycle of the ac pulse is given in Table 1. The complete analytical solution requires use of numerical methods, and the temperature calculations at other points along the r and z direction are complicated. However, these methods

Table 1.

Table showing effect of β on T_{max} estimated by different methods for different anode materials for 1 mm gap at 90% of breakdown voltage (peak ac voltages are 45, 27 and 16 kV for stainless steel, copper and aluminum anodes, respectively).

Anode	Work	β -Value	T_{max} in °C (at $r=0$)		
Material	Fun		Const Mat	Nonlinear Mat	
	(ev)		Properties	Prop&Phase Change	
			+	++	***
			FDM	SNM	FEM
St. Steel	4.5	200	497	518	563
		220	1126	1175	1082
		230	1626	1698	1420
		240	2290	2393	1819
Copper	3.2	200	107	109	104
		250	508	572	554
		275	1015	1144	1166
		300	1856	2089	3365
Aluminum	2.6	225	113	122	104
		280	661	728	615
		290	876	965	1052

Note: * - Finite Difference Method.

** - Semi-numerical Method.

*** - Finite Element Method(Ansys 4.4).

The values of the emitter area for the three materials are: (a) St. Steel = $9.6 \times 10^{-11} \text{ cm}^2$, (b) Copper = $9.2 \times 10^{-12} \text{ cm}^2$, (c) Aluminum = $3.5 \times 10^{-11} \text{ cm}^2$.

can be used conveniently to estimate peak temperature values.

3. RESULTS AND DISCUSSION

COMPUTATIONS are carried out to determine the cool-off time and the variation of anode hotspot temperature in one half cycle of the 50 Hz ac applied voltage (half-cycle time 10 ms). The results obtained by the FDM for a 45 kV electron beam impacting over a $2.5 \mu\text{m}$ stainless steel target assuming constant thermal properties are shown in Figures 2 to 4. The results indicate that the

Figure 2.
Temperature history at the origin for 45 kV
(peak) 10 ms ac half-wave pulse.

Figure 3.
Surface temperature distribution at pulse peak (5 ms).

Figure 4. Isotherms at pulse peak (5 ms).

'cool-off time' (i.e. time taken for the temperature to reduce to 10% of its peak) is $< 10 \mu\text{s}$ for the three electrode materials, stainless steel, OFHC copper and commercial aluminum (Figure 5). This was verified from the computed temperature decay characteristics for short pulses of $10 \mu\text{s}$ duration. The results indicated that the time for attainment of stable temperature during cool-off is $< 10 \mu\text{s}$ and therefore much smaller than the experimentally observed time delays of 0.2 to 0.5 ms between the peaks of PBD current and voltage. Therefore, the delayed

Figure 5.
Cool-off time for stainless steel, copper and aluminum anodes.

phenomena associated with the prebreakdown current is not due to the cool-off time in contrast to the earlier intuitive belief. The time interval between successive half cycles of the same polarity is 10 ms in case of 50 Hz ac, which is much longer than the cool-off time and therefore, the residual temperature of the anode hot-spot almost reaches the ambient at the end of the pulse. However, even a small residual temperature can contribute to the final steady-state temperature of the electrode which was warm when removed for observation. This is understandable because the only mode of heat dissipation is by way of conduction through the shanks (radiation losses being neglected).

The FDM used in the present computation uses a grid containing 1600 (40×40) control volumes. The computational domain is taken $r_{\text{max}}/r_e = z_{\text{max}}/z_e = 8$. A time step of $10 \mu\text{s}$ is found to be satisfactory.

The FEM package can deal with the effect of variation of material properties like thermal conductivity and specific heat with temperature. The peak temperature in one half cycle of the ac wave for a $2.5 \mu\text{m}$ radius hotspot for a range of β values are shown in Table 1. The temperature variation in a half-cycle time estimated by the FEM for typical values of β for the three materials are shown in Figures 6(a) to (c). The difference in the values of peak temperatures estimated by the FEM (compared

Figure 6.

Temperature history plots for typical β values obtained by the FEM (Ansys 4.4) package at 90% BDV - Nonlinear material properties and phase change included. Electron beam radius 2.5 μm , Gap distance 1 mm (a) Stainless steel anode (45 kV peak), (b) Copper anode (27 kV peak), (c) Aluminum anode (16 kV peak).

with the other two methods) shown in Table 1 are due to the combined effects of change in specific heat due to phase change and change in thermal conductivity at elevated temperatures. Comparison of the experimentally recorded voltage and current oscillograms shown in Figure 7 with the temperature profile shown in Figure 6(a) indicates that the value of the ratio $\frac{\partial T_1}{\partial t_2}$ obtained from the

PBD current waveform is equal to that obtained from the temperature profile. This similarity of the temperature profile with the PBD current wave form indicates an apparent one to one correspondence between the initial thermal instability at the anode and the temporal growth of PBD current. Zeitoun Fakiris [28] has used spectroscopic methods to measure anode hotspot temperature and

Figure 7.

Experimentally recorded PBD current and voltage oscillogram traces for 45 kV peak ac voltage across a 1 mm gap (plane parallel stainless steel electrodes of 30 mm diameter). Sensitivities: Voltage (V) 20 kV/div, Current (I) 100 μ A/div.

concluded that melting temperatures are reached under dc conditions.

Figure 8.

Peak temperature (at $r = 0$, $z = 0$) variation with β values for typical cathode work functions (values are indicated on the curves) for different materials. The peak temperatures are estimated for ac peak voltages of 45, 27 and 16 kV for the three materials.

Nevroviski et al. [32] have attempted to calculate the anode hotspot temperatures and have commented that hydrodynamic instability is a possible cause for breakdown in vacuum gaps under dc stresses. The applied voltage in the present case is alternating and the electrodes are subject to polarity reversal. Under alternating

Figure 9.

Peak temperature (at $r = 0$, $z = 0$) variation with radius of the hotspot for different materials at 90% BDV (peak voltages are indicated on curves).

voltages we have observed a significant deviation of the FN plots from linearity at anode hotspot temperatures of 80 to 90% of the melting point. The computations carried out by including 'phase change' also show that the hotspot temperature is highly sensitive to the β value. Therefore, with only a slight increase in β , the temperature can reach the melting point. It is difficult to say that the melting temperature is not attained before the detachment of a microparticle, but it is probable that detachment can take place at 80 to 90% of the anode melting temperature. The demarcation line between the solid and liquid phase cannot be determined precisely especially in case of alloys like stainless steel. At 90% of melting temperature even a small variation in the beam flux can cause phase change. Further, single crystal thermal property values should be used for the temperature calculations where the beam impact area is less than or comparable with the grain size of the metal. However, it is presumed that this does not introduce any appreciable error in the temperature estimation because, the overall domain of interest covers an area larger than the grain size. The peak temperatures are sensitive to the emitter area and the work function of the cathode. Computations were done for a range of work functions and emitter areas (obtained from the y -intercept of the Fowler Nordheim plot) and the values shown in Table 1 were found

to be reasonable. The values of work function for copper and aluminum in Table 1 are 3.2 and 2.6. Such low work function spots are to result from the presence of oxide and semiconducting layers. Figure 8 shows the peak temperature variation with β value for typical work function values. The dependence of hot spot temperature on the radius of the electron beam is shown in Figure 9. At the specified voltage levels, the radius of the beam is $\leq 3 \mu\text{m}$ for peak temperatures to reach close to the melting point, thereby indicating that the size of microparticles released is $< 3 \mu\text{m}$ in radius. This is in agreement with the findings of earlier work [19] where particles of $< 3 \mu\text{m}$ were observed under direct voltages. From Table 1 it is seen that the peak anode hotspot temperature reaches 80 to 90% of the melting point for β values in the range 220 to 230 for stainless steel, 260 to 270 for copper, and 270 to 280 for aluminum, which are reasonable. The results obtained for stainless steel for a 45 kV (peak) electron beam impinging on a $2.5 \mu\text{m}$ radius spot for a gap distance of 1 mm are consistent with those of Vine and Einstein [29] for a 60 kV dc beam of $3 \mu\text{m}$ diameter where the maximum anode temperature was found to be 1400°C . Our results indicate that a lower value of beam flux ($q_e = 2.1 \times 10^{10} \text{ W/m}^2$) is sufficient to drive hot spot temperature to the melting point whereas a higher value ($q_e = 8.4 \times 10^{10} \text{ W/m}^2$) is required in case of dc voltages used by Vine *et al.* [29]. This difference possibly is due to the different pulse shape and the difference in area of impact. Further, Vine *et al.* [29] have considered a Gaussian distribution of electron beam energy within the impact area and applied correction factors for penetration and backscatter.

The numerical techniques used in the present analysis can be used as diagnostic tools to estimate the anode hotspot temperatures in many electrode materials subjected to pulsed electron beam heating in vacuum where experimental methods become extremely complex. The accuracy of the results also depend on the knowledge of material properties at high temperatures. The methods discussed above can also be used to estimate the size of microparticles originating from anode hot spots. The FDM approach requires lesser computation time and memory requirement compared to the FEM. The advantage with the use of ANSYS 4.4 (FEM package) is the incorporation of non-linear material properties and phase change. However, seminumerical methods can be used to estimate the peak temperatures at the origin, but the solution for the entire domain of interest becomes complex.

4. CONCLUSIONS

THE transient temperature distribution in a cylindrical disc heated by a pulsed heat source (electron beam)

such as those encountered in vacuum gaps stressed by ac voltages is solved by numerical and semi-numerical methods. The results can be used to estimate the cool-off time, peak temperatures and the size of microparticles originating from thermally unstable regions in vacuum insulated HV devices such as vacuum interrupters, particle accelerators and separators *etc.* The cool-off time is found to be $< 10 \mu\text{s}$ for stainless steel, copper and aluminum anodes. The results indicate that at voltages close to breakdown (90% BDV) the temperature reaches the melting point for reasonable values of β . The anode hot spot temperatures are also influenced by the emitter work function. The present computations predict lower work function for aluminum and copper which is caused by the presence of oxide layers. The FDM provides the advantage of lesser memory requirement whereas the FEM package has the advantage of incorporating the nonlinear material property variation with temperature and irregular boundaries and the phase change. The asymmetry of the PBD current waveform about its peak observed experimentally may be attributed to the nonlinear thermal properties of the anode material because the PBD current development is dependent upon the initial thermal instability at the anode. In addition to the above two numerical techniques, seminumerical methods can be used to estimate the peak temperature values of hot spots subjected to pulsed electron beam heating in vacuum.

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