An Investigation of The Parameters Effecting to the Instability Vacuum Arc Current

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Abstract- **To investigate the parameters effecting to the stability arc current of silver cathode, the cathode spot model is applied. It was concluded that the current below that no real solution is instability arc current region. It is considered that the electron returning to the sheath region from the plasma one dominates over positive ions. As a result, electric field at cathode surface becomes imaginary solution.**

To study the parameters effecting to the stability arc factors, the parameter scan of cathode materials and ion current fraction by numerical analysis, it was found that the critical current of the stable current is highly dependent on the thermal conductivity of the cathode material. This is a very important result for the development of cathode materials for low-surge vacuum interrupters.

I. INTRODUCTION

In reality, however, the arc current flow is interrupted prior to this moment at actual current values ranging 2-10 A. Failure to carry the arc current gradually to zero is called current chopping. In this way, overvoltages are generated, caused by the magnetic energy still trapped in the circuit's main inductance. Chopping current strongly depends on the contact material of vacuum switching devices [1]-[2]. Prior to the chopping current of a metal vacuum arc shortly before the natural sinusoidal current zero, the instability phenomena characterized by noise occurs on the current trace.

It is generally considered that the instability of low-current arc and resultant chopping phenomena are strongly related to the ionized vapor generated from the electrode. The current instability phenomena depends on the physical properties of cathode material but does not depend on the circuit parameters. In modern vacuum switching circuit device, however, overvoltages due to current chopping are minimized by careful selection of the contact compound, and can be handled by low-surge-type vacuum switching device contact material [1].

In order to clarify the parameters effecting to the instability phenomena for low-current vacuum arc, the cathode spot model is proposed as shown in Fig. 1. The cathode spot region is considered to be the collisionless space charge sheath connected directly by singly ionized collisional plasmas neglecting the transition region as reported in [3]-[4].

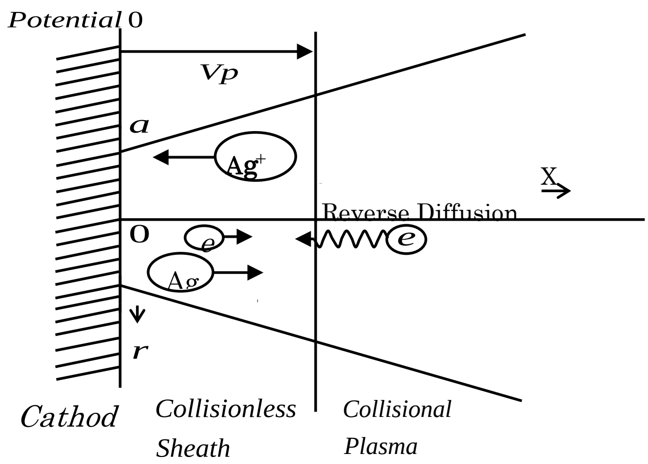

Fig. 1. Cathode spot model

II. Variables and Their Governing Equations [3][4]

The following eight dependent variables are normally treated as dependent variables in cathode spot studies in vapor arcs:

Vp, Sheath voltage (V); a ,Cathode spot radius (m); J, Current density (A/m^2); s, Electron current fraction ; T, Temperature of cathode spot surface (K); Fo, Cathode electric field (V/m); No, Plasma density ($1/m^3$); Te, Electron temperature (K). All of the dependent variables have been treated as averaged values over the spot area, $r \leq a$.

The independent variable is the arc current I. The physical constants of the cathode material are the following:

Γ_{ev} ,Evaporation rate (kg/m^{2}s); P_{ev} ,Evaporation energy (W/m^{2}s); $H_o(T)$,Heat of evaporation per atom (J/atom); K ,Thermal conductivity (W/mK); V_i ,Ionization voltage of Copper ; Φo ,Work function of Copper (eV); A , Richardson's constant (A/m^{2}K^2); $\Phi(F_o,T)$,Cooling effect of electron emission (eV); M , Mass of atom and ion of Copper (kg); m ,Electronic mass (kg); q ,Electronic charge(C); k ,Boltzmann's constant (J/K); ε_o ,Vacuum permittivity (F/m).

Eight equations are required in order to determine the eight dependent variables. For the lack of a closed set of equations led to determine the sheath voltage Vp, some other means is required. In the present study, the experimental data of cathode input V_{eff} and ion current fraction $\delta(I)$ flowing toward the anode are applied so as to obtain the solution of an equation in eight dependent variables.

III. SHEATH REGION EQUATION

1) Current Equation

$$I = \pi a^2 J \tag{1}$$

2) Equation of Mass Flow and Ion Current
3)

$$\Gamma_{ev}(T) - N_0 M\left(\frac{kT_e}{2\pi M}\right)^{\frac{1}{2}} = \frac{\delta J}{q} M \tag{2}$$

The right hand-side of equation (2) is the mass flow to the anode provided by the ion current. The ion current density (1-S)J in the pace charge sheath is assumed to be equal to the ion saturation current density of collisional plasma. Thus, equation (3) is concluded as

$$(1-S)J = qN_o\left(\frac{kT_e}{2\pi M}\right)^{\frac{1}{2}} \tag{3}$$

3) Electron Current

The electron current from the cathode is determined primarily via by the thermionic mechanism, together with the Shottky effect.

$$SJ = AT^2 \exp\frac{-q\left(\Phi_o - \sqrt{\dfrac{qF_o}{4\pi\varepsilon_o}}\right)}{kT} \tag{4}$$

4) Electric Field of the Cathode Surface

The equation of the electric field of the cathode surface is given by the Mackeown equation, including the effect of the space charge of the electrons returning from the collisional plasma to the sheath.

$$F_0^2 = \frac{4}{\varepsilon_0}\left\{\left[\sqrt{\frac{M}{2q}}(1-S)J - \sqrt{\frac{m}{2q}}SJ\right]\sqrt{V_p} - \frac{2kT_eN_o}{\varepsilon_o}\left[1-\exp\left[\frac{-qV_p}{kT_e}\right]\right]\right\} \tag{5}$$

5) Energy Balance at the Cathode Spot Surface

$$K_o(0.48T+164) = \frac{8a}{3\pi} JV_{eff} \tag{6}$$

$$JV_{eff} = (1-S)J\left(V_p + V_i - \Phi_o + H_o(T)\right) - SJ\Phi(F_0,T) - P_{ev}(T) \tag{7}$$

The first term of the right-hand side of equation (7) is the input due to the ion bombardment, the second term is the power dissipated by the electron emission, and the third term is the power dissipated by vaporization.

IV. EQUATION OF THE PLASMA REGION

1) Particle Conservation

The equation of particle conservation is the same as that for equation (2).

2) Energy Conservation of the Collision al Plasma.

The energy loss due to the flow of ions and electrons is equal to the acquired energy due to the electric field.

$$\frac{kT_e}{q} J(2+2\delta-S) + qV_i\frac{\Gamma ev}{M} = 0.851a\eta J^2 \tag{8}$$

The first term of the left hand–side of equation (8) represents the energy flow into the cathode and the anode, and the second term is the power required by ionization. The right-hand side is the input power to the plasma by joule heating.

III. CALCULATION

3.1 Experimental data

The effective cathode heating voltage, V_{eff} is experimentally obtained using the calorimetric method [4], and the ion current fraction $\delta(I)$ flowing toward the anode is set to 10 % of arc current [5].

3.2 Calculation method

To determine the eight dependent variables, the simultaneous algebraic equations (1) – (8) together with bisection method are used, and I, V_{eff} , $\delta(I)$ and the physical constants of cathode material, are assigned. The real solutions are restricted using the equation of cathode electric field of cathode surface (1).

3.3 Numerical results

The dependent variables are obtained for arc currents ranging from 24-70 A, as shown in Figs.2-5. At the arc current of 24 A, the values of the dependent variable such as the cathode electric field, Fo, current density, J, plasma density, No, and sheath voltage, V_P change rapidly. When the arc current decreases below 24 A, no real solution exists. The current of 24 A may correspond to the instability onset current, as previously proposed.

IV. CALCULATION RESULTS

The simultaneous algebraic equations (1)-(8) are determined numerically by a bisection method. The numerical results are obtained for arc currents ranging from 21.5-70 A, as shown in Figs. 2-5. At the arc current of 21.5 A, the cathode electric field, Fo, the plasma density, No and the current density, J change rapidly. When the arc current decreases below 21.5 A, no real solution exists. The current level below which no real solution exists is proposed as the current instability region.

In unstable region, the electrons returning to the sheath region from the plasma region were found to be dominant over positive ions. Mackeown`s equation of the cathode electric field has an imaginary solution, and consequently, the stable ion sheath criterion which ensures the stable arc is not satisfied. This is the physical explanation for the initiation of arc current instability as reported in [3][4].

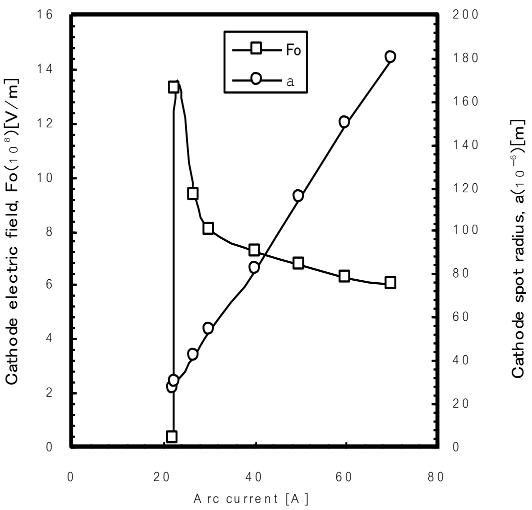

Fig.2. Cathode electric field and cathode spot radius

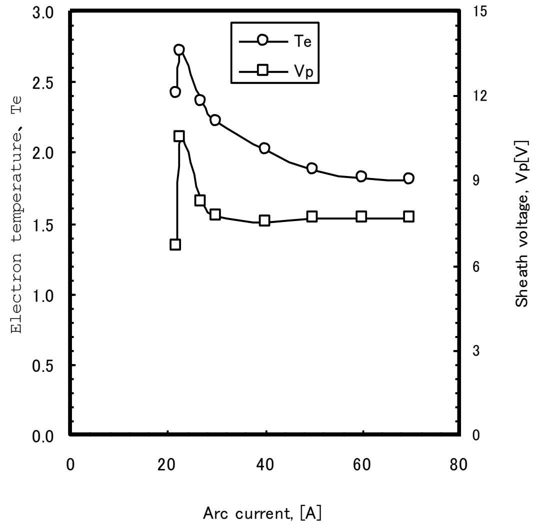

Fig.3 Electron temperature and sheath voltage

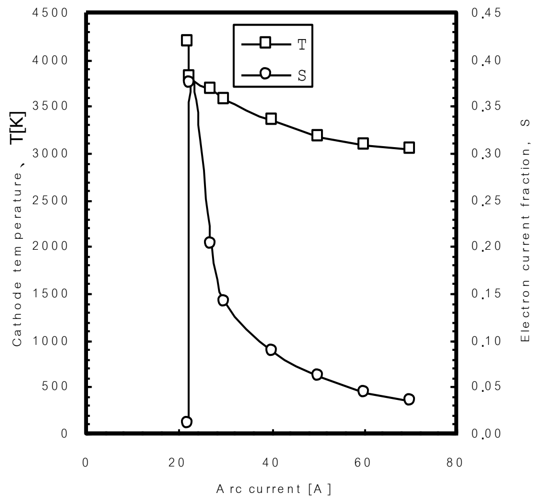

Fig.4. Cathode temperature and electron current fraction

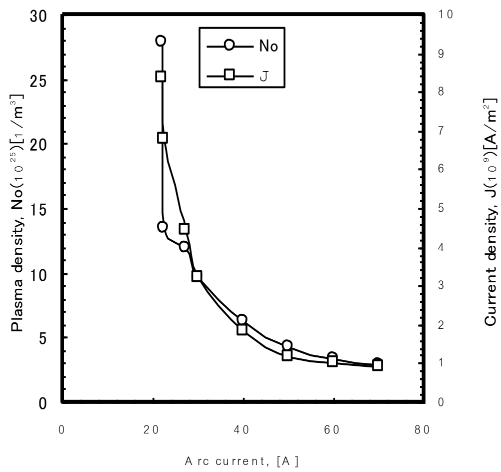

Fig.5. Current density and plasma density

V. Parameters Effect to Stable Arc Current

In this study, the effect of the physical characteristics of the cathode material, work function, thermal conductivity and the experimental data, ion current fraction flowing to anode are considered.

5.1 Ion current fraction effect

The value of ion current fraction is set ranging from 0.05 to 0.15 for checking the effect to minimum stable arc current. The calculation results are shown in Fig. 6.

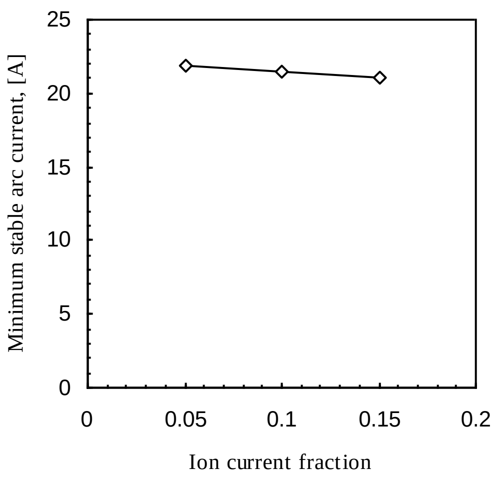

Fig.6. Stable arc current vs Ion current fraction

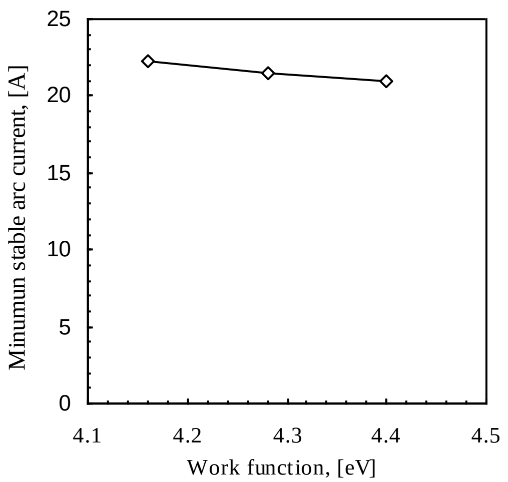

Fig.7. Stable arc current vs Work function

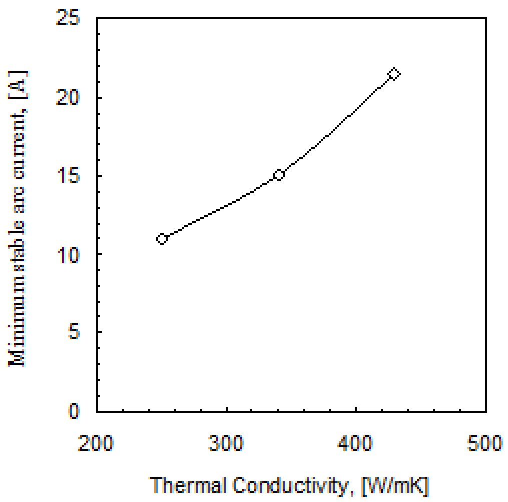

Fig. 8. Thermal conductivity vs Stable arc current

5.2 Work function effect

5.3

The value of work function is set ranging from 4.16 to 4.40 eV for checking the effect to minimum stable arc current. The calculation results are shown in Fig. 7.

5.3 Thermal conductivity effect

The thermal conductivity is set ranging from 250 to 429 W/mK for checking the effect to minimum stable arc current. The calculation results are shown in Fig. 8.

VI. CONCLUSION

The instability arc phenomena are explained that the electrons returning to the sheath region from the plasma one dominate over positive ions then the stable ion sheath criterion does not satisfied. This is the physical explanation for the initiation of arc current instability.

To study the parameters effecting to the stability arc factors, the parameter scan of cathode materials and the experimental data by numerical analysis, it was found that the critical current of the stable current is relatively insensitive to the work function and ion current fraction. However, it is highly dependent on the thermal conductivity of the cathode material. This is a very important result for the development of cathode materials for low-surge vacuum interrupters.

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