

anode were applied to obtain the solution of an equation in eight dependent variables.

A. Nomenclature

1. Independent Variable

I Arc current (A)

2. Experimental Data

$V_{eff}(I)$ Effective cathode heating voltage (V)

$\delta(I)$ Ion current fraction flowing towards the anode

3. Dependent Variables

V_p Sheath voltage (V)

a Cathode spot radius (m)

J Current density (A/m²)

S Electron current fraction

T Temperature of cathode spot surface (K)

F_o Cathode electric field (V/m)

N_o Plasma density (1/m³)

T_e Electron temperature (K)

4. Physical Properties and Constant

Γ_{ev} Evaporation rate (kg/m²s)

P_{ev} Evaporation energy (W/m²s)

$H_o(T)$ Heat of evaporation per atom (J/atom)

K Thermal conductivity (W/mK)

V_i Ionization voltage of Copper (eV)

Φ_o Work function of Copper (eV)

A Richardson's constant 1.20×10^6 (A/m²K²)

$\Phi(F_o, T)$ 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)

B. Sheath Region Equation

1. Current Equation

The relationship between arc current, current density, and cathode spot radius is expressed as

$$I = \pi a^2 J. \quad (1)$$

2. Equation of Mass Flow and Ion Current

$$\Gamma_{ev}(T) - N_o M \left[\frac{kT_e}{2\pi M} \right]^{\frac{1}{2}} = \frac{\delta J}{q} M \quad (2)$$

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 space charge sheath is assumed to be equal to the ion saturation current density of collisional plasma. Thus, equation (3) is obtained as

$$(1-S)J = q N_o \left[\frac{kT_e}{2\pi M} \right]^{\frac{1}{2}} \quad (3)$$

3. Electron Current

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

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

4. Electric Field of the Cathode Surface

The equation for the electric field of the cathode surface is given by the Mackeown equation, which includes the effect of the space charge of the electrons returning from the collisional Plasma to the sheath

$$F_o^2 =$$

$$\frac{4}{\epsilon_o} \left\{ \left[\sqrt{\frac{M}{2q}} (1-S)J - \sqrt{\frac{m}{2q}} SJ \right] \sqrt{V_p} - \frac{2kT_e N_o}{\epsilon_o} \left[1 - \exp \left[\frac{-qV_p}{kT_e} \right] \right] \right\} \quad (5)$$

5. Energy Balance at the Cathode spot Surface

The solution of the heat equation with $\nabla(K\nabla T) = 0$ at the boundary is given by

$$-K \frac{\partial T}{\partial X} = J V_{eff} \quad r \leq a \quad \text{At } X=0$$

$$K_o(0.45T + 348) = \frac{8a}{3\pi} J V_{eff} \quad (6)$$

where K_o is the thermal conductivity at room temperature and X is the normal direction to the cathode surface as shown in Fig.1. The temperature dependence of the thermal conductivity of Copper mix nickel is considered [5]. Heat loss due to thermal conduction into the cathode is

$$J V_{eff} (1-S)J(V_p - V_i - \Phi_o + H_o(T) - S\Phi(F_o T) - P_{ev}(T)) \quad (7)$$

where 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.

C. Equation of the Plasma Region

1. Particle conservation

The equation of particle conservation is same with equation (2)

2. Energy conservation of the collisional Plasma

The energy loss by transport flow of ions and electrons is equal to the acquired energy due to the electric field. This will be considered. By integrating over the entire collision Plasma, the energy conservation equation is expressed as follows:

$$2nkTe[\nabla \cdot \mathbf{V}dv = \int E \cdot \mathbf{J}dv$$

By considering the physical meaning of $2nkTe[\nabla \cdot \mathbf{V}dv$ and approximating the solution of $\int E \cdot \mathbf{J}dv$, the equation of plasma energy conservation is expressed as

$$\frac{kTe}{q}J(2+2\delta-S)+qV_t\frac{\Gamma_{ev}}{M}=0.851\eta J^2 \quad (8)$$

where the first term of the left hand-side of equation (8) is 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, which is the plasma resistance expressed by Spitzer formula.

III. EXPERIMENTAL DATA

The effective cathode heating voltage, V_{eff} is the experimentally obtained using the calorimetric method [3], and the ion current fraction $\delta(I)$ flowing toward the anode is set to 10% of arc current [13].

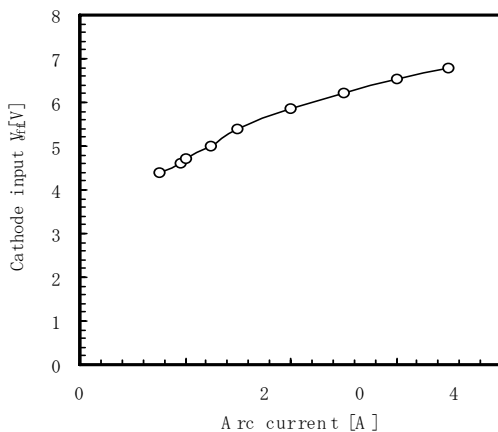


Fig. 2 Cathode input

IV. CALCULATION OF THERMAL CONDUCTIVITY

Pure copper Cu and Cu-Ni alloys were made using a vacuum melting process. The thermal conductivity for Cu-Ni alloys has been calculated from Wienemamn-Franz's law [14].

V. NUMERICAL METHOD

In order to predict instability arc current and transient recovery voltage, simultaneous algebraic equations (1)-(8) are solved numerically by a bisection method. The real solutions are restricted using the equation of cathode electric field of cathode surface.

VI. NUMERICAL RESULTS

The dependent variable is obtained for arc currents ranging from 10-70 A, as shown in Figs. 4-11. At the difference ratio of copper and nickel were conducted at 1%, 2% and 4% of nickel. The thermal conductivity was calculated as 401 W/mk, 225 W/mk and 162 W/mk, respectively. The numerical result is obtained for arc current to analyze eight dependent variables. Therefore, cathode surface temperature, electron current ratio, electron temperature of plasma, current density, plasma density, cathode electric field, decreases below consistent. When the arc current increases, the part of sheath voltage decrease below and the arc current increases as the voltage becomes stable. Cathode spot radius increases when the arc current increases.

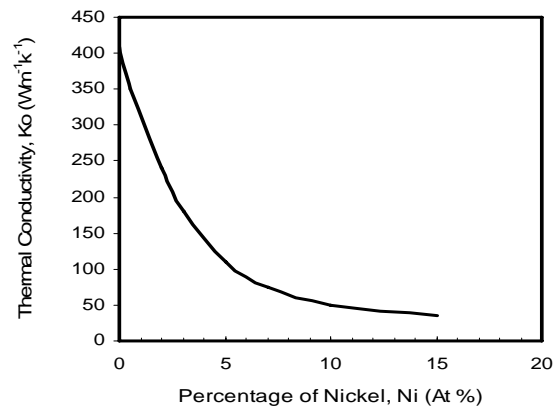


Fig. 3 Dependence of percent nickel on thermal conductivity

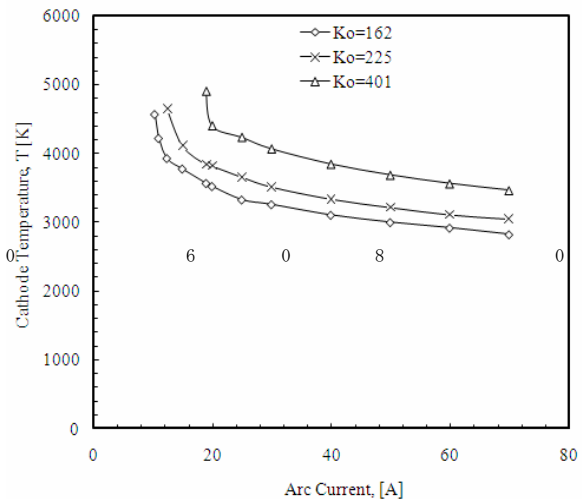


Fig. 4 Dependence of thermal conductivity on cathode temperature and instability - initiation arc current

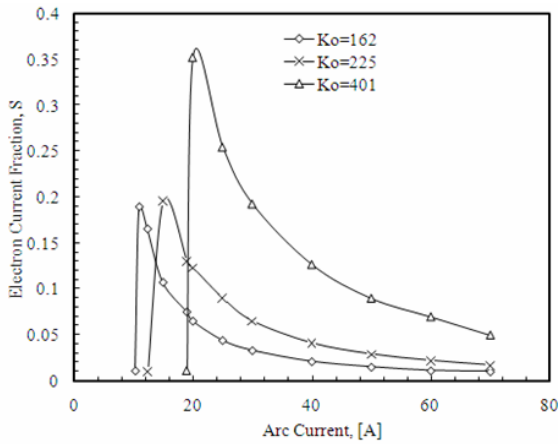


Fig. 5 Dependence of thermal conductivity on electron current ratio and instability - initiation arc current

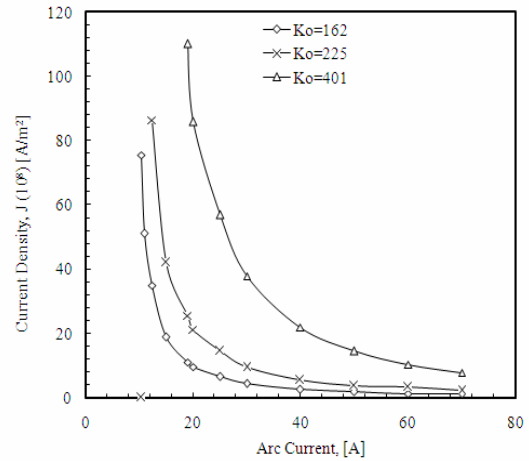


Fig. 8 Dependence of thermal conductivity on current density and instability - initiation arc current

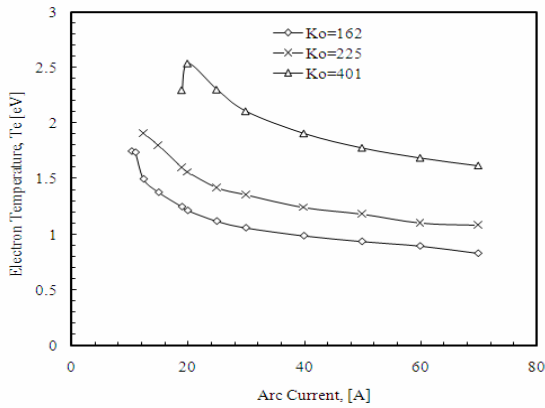


Fig. 6 Dependence of thermal conductivity on plasma temperature and instability - initiation arc current

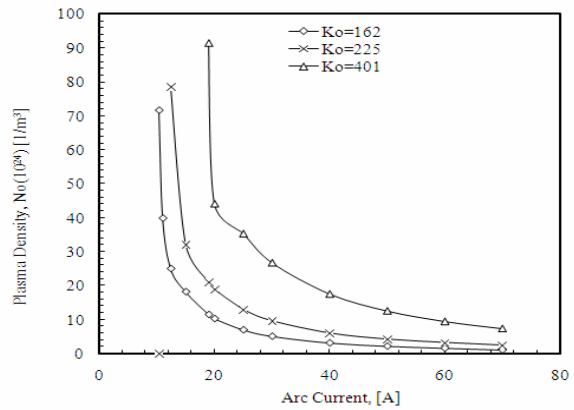


Fig. 9 Dependence of thermal conductivity on plasma density and instability - initiation arc current

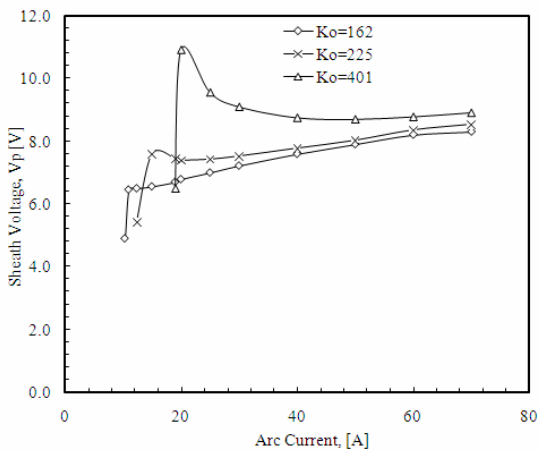


Fig. 7 Dependence of thermal conductivity on sheath voltage and instability - initiation arc current

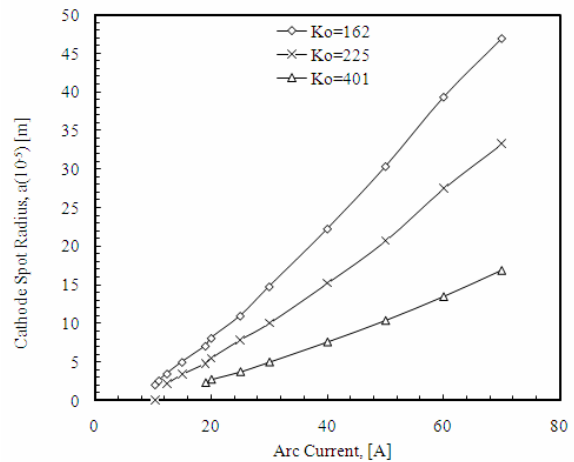


Fig. 10 Dependence of thermal conductivity on cathode spot radius and instability - initiation arc current

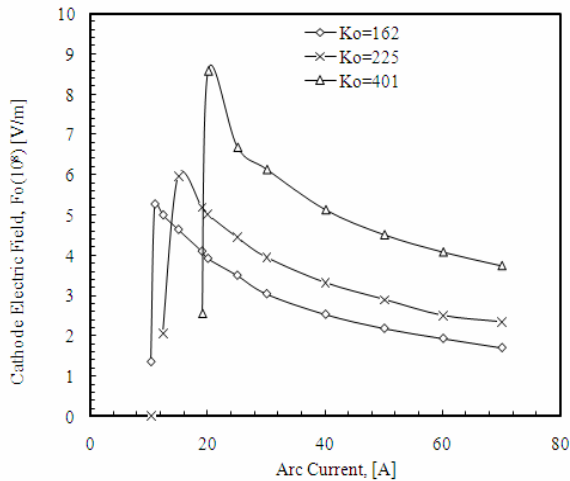


Fig. 11 Dependence of thermal conductivity on cathode electric field and instability - initiation arc current

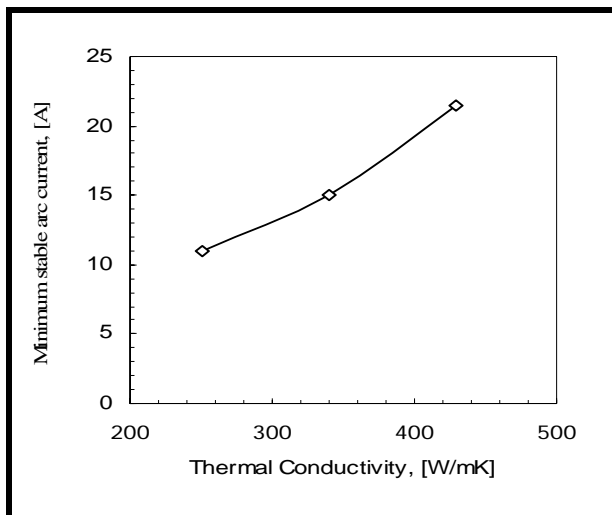


Fig. 12 Dependence of thermal conductivity on minimum stable arc current

VII. THERMAL CONDUCTIVITY SCAN

In order to study thermal conductivity effect on stability arc, the thermal conductivity is performed. Figs.4-12 shows plasma parameters with various values of thermal conductivity. The left hand side of last point of each line shows instability arc current region. The minimum stable arc current of each thermal conductivity is plotted in Fig. 12.

VIII. TRANSIENT RECOVERY VOLTAGE PREDICTION

As previously mentioned, it is believed that the parameters of the instabilities directly reflect the interruption characteristics of the contact material. These investigations are very important for the development of low-surge-type vacuum interrupter

contact materials. As Fig. 12, the minimum stable arc current decreases with decreasing thermal conductivity. These results reflect directly to chopping current level. The maximum value of transient recovery voltage (V_p) is expressed as follows: [15]-[17].

$$V_p \cong \sqrt{\frac{L}{C}} \cdot I_c \quad (9)$$

According to the equation above, if circuit parameters in all cases are equal, then the value of V_p is directly proportional to chopping current I_c . In case the minimum stable arc current is reduced, the chopping current is also reduced.

IX. CONCLUSION

When the current decreases below 21 A, the electrons returning to the sheath region from the plasma region were found to dominate over positive ions, and thus the cathode electric field has an imaginary solution. When the arc current was decreased below the stable region, the electrons returning to the sheath region from the plasma region were found to be dominant over positive ions. As a result, the cathode electric field by Mackeown's equation yields an imaginary solution, and consequently, the stable ion sheath criterion is not satisfied. This results show the physical explanation for the initiation of arc current stability due to the effect of reverse diffusion electrons from the plasma region. 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.

In order to predict the maximum value of transient voltage, the value is calculated using equation (9). These show that if the chopping current is reduced then the peak of transient recovery voltage will be reduced. It was found that the instability arc current depends upon cathode characteristic. This is a very important result for the development of cathode materials for low – surge vacuum interrupters.

Finally, it can be concluded that the results obtained by this study clearly demonstrate the physical mechanism of current instability and transient recovery voltage occurrence. If the minimum stable arc current is low value then the chopping current also become low value.

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