Study of Factors Affecting Electric Arc Current in Vacuum Unstable Cathode Composites

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Abstract:

As the arc occurs over a period, it affects the lifespan and safety of the cathode contact surface, reducing the safety of the arc extinguishing chamber of the circuit breaker. This research aims to study the factors that affect arcing in a vacuum. Therefore, the selection of materials and equipment for making the cathode and insulation is crucial in influencing arcing in a vacuum. The purpose of this research is to develop the contact surface of the circuit breaker from composite cathode materials to compare greater efficiency. From studying the parameters that affect the arc factor, the stability of cathode material parameters, and the proportion of ion flow by numerical analysis, it was found that the critical current of the constant current depends on the thermal conductivity of the cathode material, which is a very important result for the development of cathode materials. These results are like the data obtained from other research, which indicates that the analysis by the cathode spot model, used to determine the thermal conductivity in a low-current vacuum arc, may be applied to materials that easily vaporize. Moreover, reducing thermal conductivity could enhance arc stability by minimizing electron backflow from the plasma region.

Keywords: Arc in Vacuum, Low arc Curren, Cathode arc Spot, Copper cathode, Plasma, Instability

Introduction

The objective of this study is to explore and enhance the materials used in the creation of composite cathode materials for the contacts of vacuum circuit breakers. Specifically, it aims to develop and improve these materials to address issues related to unstable arc currents in vacuum circuit breakers.

The expected benefit of this research is to establish guidelines and develop concepts that could lead to the improved production of contact materials. By employing highly precise inspection methods, this study seeks to refine the manufacturing process, resulting in higher-quality contact materials for circuit-breaking devices used in industrial settings.

The research is designed with specific parameters in mind. It will exclusively use

1. Direct current (DC)
2. Maintain arc currents that do not exceed 70 amperes during experiments.
3. The surface arc gap will be adjusted between 1 and 3 millimeters.
4. For the creation of the contact materials, copper will serve as the primary material, with nickel as an additional component.
5. The materials developed through this research are intended for exclusive use within vacuum systems.

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Research Medthodoly

Experimental Circuit

The researcher has assembled the circuit as shown in Figure 1, using four sets of measuring instruments: V1, V2, V3, and V4. These instruments measure cathode potential, cathode temperature, arc voltage, and current. Resistors R1 and R2 are used to limit the current flowing in the circuit, and resistor R2 is connected in parallel with an ammeter to extend the measurement range.

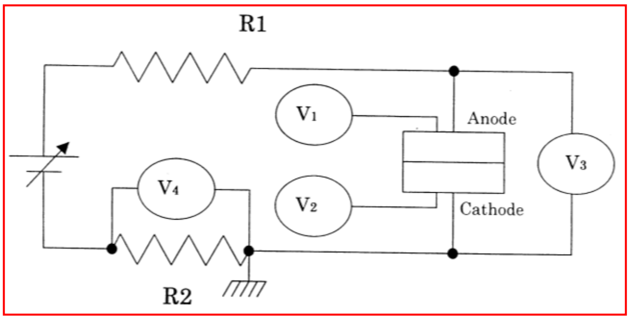

Figure 1: Experimental circuit

For the circuit used in this experiment for aerospace systems, it will be the equipment specifier in this experiment, as shown in Figure 2.2

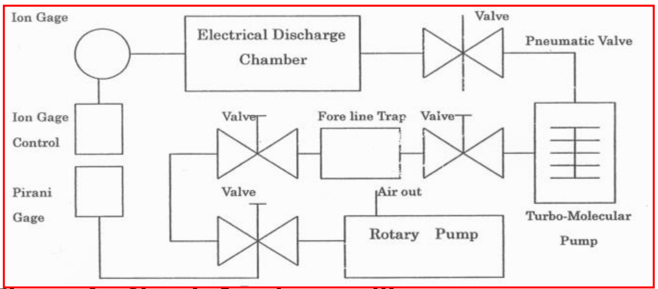

Figure 2 : Circuit for the satellite system

Nomenclature

1. Independent Variable

I Arc current (A)

2. Experimental Data

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

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

3. Dependent Variables

V_p 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)

F_o Cathode electric field (V/m)

N_o Plasma density (1/m^3)

T_e Electron temperature (K)

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4. Physical Properties and Constant

Γ_{ev} Evaporation rate (kg/m^2s)

P_{ev} Evaporation energy (W/m^2s)

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

K Thermal conductivity (W/mK)

V_i Ionization voltage of Copper 7.73 (eV)

Φo Work function of Copper 4.5 (eV)

A Richardson's constant 1.20×10^6 (A/m^2K^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)

Equation of the Plasma Region

1) Particle Conservation

The equation of particle conservation is the same as that for equation Current Equation $I = \pi a^2 J$.

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.

$$\frac{kT_e}{q} J(2+2\delta-S)+qV_i\frac{\Gamma ev}{M}=0.851a\eta J^2 \quad (1)$$

The first term of the left hand–side of equation (1) 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.

Result and discussion

The current values used in the experiment ranged from 18 to 70 amperes, with an additional arc current range of approximately 16 to 18 amperes. The voltage drops across the cathode ranged from 5.25 to 6.45 volts. The voltage drop across the cathode is shown in Table 3.1 and Figure 3.1.

Table 1 : Voltage Drop Across the Cathode and Anode

Arc current	Arc voltage	Cathode voltage	Anode voltage
16.16	15.91	5.26	10.65
17.00	15.96	5.28	10.69
18.00	16.03	5.30	10.74
25.20	16.55	5.51	11.04
32.04	16.97	5.66	11.32
35.00	17.20	5.80	11.40
42.00	17.77	6.03	11.74
57.00	18.32	6.32	12.00
65.29	18.48	6.38	12.10
83.40	19.14	6.45	12.69

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when the arc current is less than 35 amps, the proportion of electron current, voltage across the sheath, current density, plasma density, and electric field at the cathode change rapidly. The change in plasma temperature and the temperature of the arc cathode spot varies slightly. At arc currents of 14.35 to 18.80 amps, all variable values will change and will change faster as the arc current decreases. The radius of the arc cathode spot decreases rapidly due to the rapid decrease in current density. As a result of the increase in temperature at the arc cathode, plasma temperature and plasma density, the current density of the cathode and electron current will decrease. In cases where the electric field at the negative terminal increases the plasma temperature similar to Equation.

$$\left[E_0^2\right]=\frac{4}{\varepsilon_o}\left[\left[\sqrt{\frac{M}{2q}}(1-S)J-\sqrt{\frac{m}{2q}}SJ\right]\sqrt{V_p}-\frac{kT_e n_0}{\varepsilon_0}\left[1-\exp\left\{\frac{-qV_p}{kT_e}\right\}\right]\right]$$

The rapid increase in the cathode electric field can be explained by the principle of physics that when electrons from the plasma area travel back to the sheath area and influence the negative charge, which is the anode, causing instability of the charge surrounding the sheath.

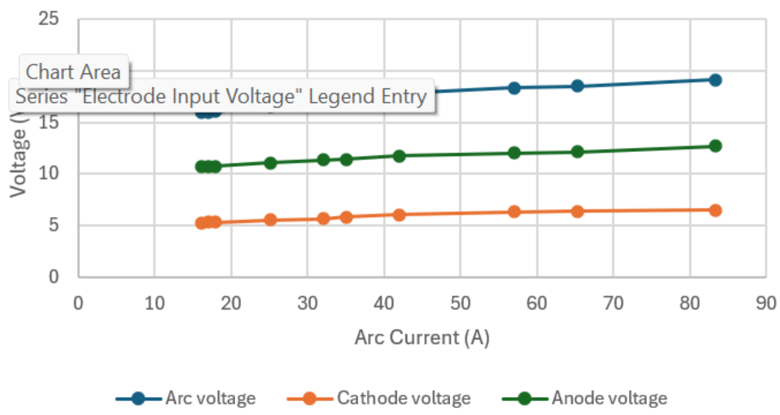

Figure 3 : Graph showing the voltage of the arc with the voltage drop across the cathode and anode.

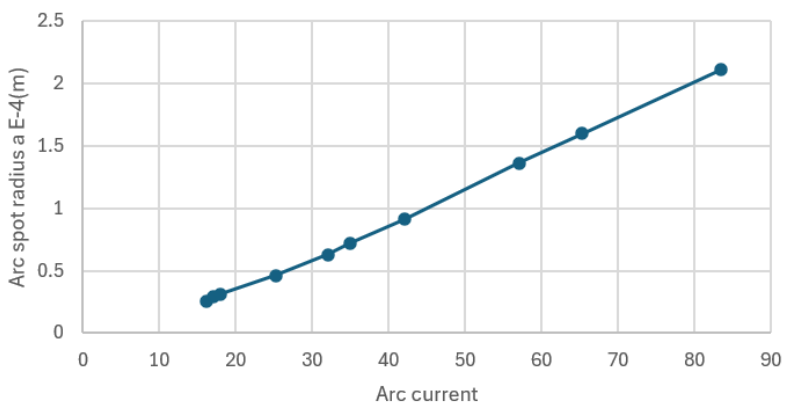

Figure 4: Relation between arc spot radius and arc current

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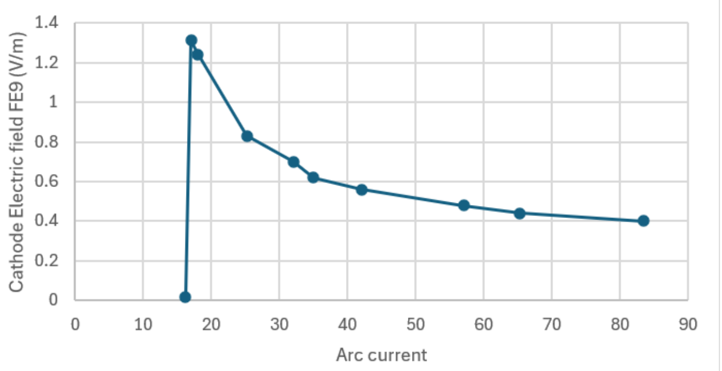

Figure 5 : Relation between cathode electric field and arc current

Parameter effect to stable arc current

In this study, the effects of the cathode material's physical properties namely work function, thermal conductivity and the experimental data on the ion current fraction reaching the anode are examined.

1. Work function impact

The value of work function is set ranging from 4.16 to 4.40 eV for checking the effect to minimum stable arc current. It was found that the cathode electric field at minimum stable arc current region as same value of the set point.

2 Ion current fraction

The value of ion current fraction is set ranging from 0.05 to 0.15 for checking the effect to minimum stable arc current. It was found that the cathode temperature at minimum stable arc current region as same value of the set point as shown in Figure 6.

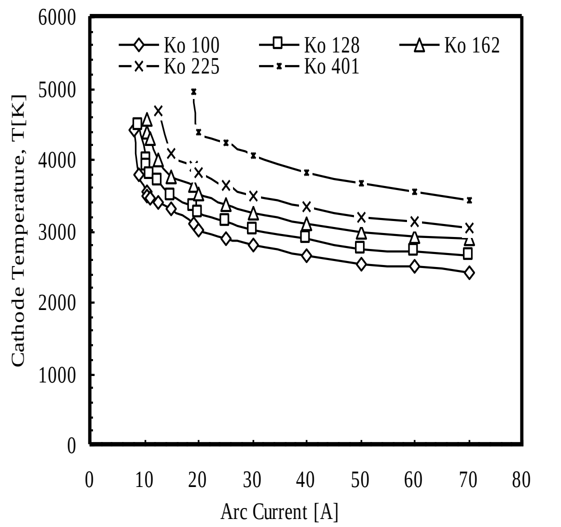

Figure 6 : Relation between cathode temperature and arc current

3 Thermal conductivity impact

The minimum stable arc current was decreased when the cathode thermal conductivity was decreased.results are shown in Figure 7.

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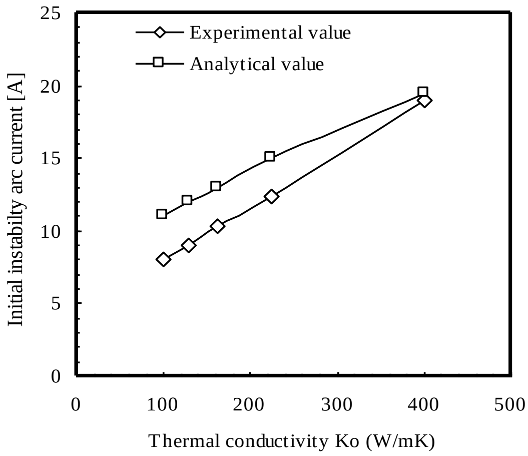

Figure 7 : Relation between Initial instability arc current and thermal conductivity

Conclusion

The relationship between thermal conductivity andelectrical conductivity in cathode materials, particularly copper, is critical in vacuum arc stability. An increase in thermal conductivity leads to a rise in electrical resistance and surface temperature of the cathode, while the radius of the arc cathode spot decreases. This interplay affects the stability of the arc current, with thermal conductivity being a key factor. A decrease in thermal conductivity can enhance arc current stability by reducing the number of returning electrons from the plasma region. Conversely, as the area of stable arc current increases, thermal conductivity decreases, leading to a lower current density and, consequently, a reduced cathode temperature. This decrease in temperature further diminishes the electron current, which correlates with findings suggesting that analyzing thermal conductivity impacts in low-current vacuum arcs may be relevant for evaporative materials

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References

1. Narong Mungkung, 2003, "Probe Measurenment of a Sing Cathode Spot Arc Plasma",
2. International Conference on Phenomena in Ionized Gass, 15 Jul 2003, Germany, pp.183-184. 2 M. McVey,2017, cigre-usnc[Online], Available: https://cigre-usnc.org/wp-content/uploads/2017/10/2-GOTF-Mark-McVey.pdf [20 May 2023].
3. H.Bahirat, M.Ali and P.KK, Electrical Engineering Portal[Online], Available: https://electrical-engineering-portal.com/download-center/books-and guides/electrical-engineering/transient-recovery-voltage-circuit-breakers[20 May 2023].4. M. Yano, Y. Osaki, O. Morimiya, and Y. Nakano,1970, "Experimental study of the current chopping phenomena in vacuum circuit breakers", Elec. Eng. Japan, Vol. 90, pp. 73-83.
4. G. Ecker, 1980, "Theoretical aspects of the vacuum arc in Vacuum Arcs", John Wiley & Sons, pp. 250-259.
5. O. Morimiya and S. ikeno, 1982, "An Analysis of a stationary copper cathode spot using power input to the cathode", Elec. Eng. Japan, Vol. 102-A, No. 1, pp.9-16.

DOI: 10.48141/sci-arch-36.4.24.13 ISSN:1005-1538

6. O. Morimiya, S. Suzuki and K. Watanabe, 1999, "An analysis of the in-stability phenomena of a low current vacuum arc", Elec. Eng. Japan, vol. 119-A, No. 2.
7. S. Suzuki, T. Okutomi, and O. Morimiya, 1988, "Measurement of instability initiation current in vacuum arc", Japanese J. Appl. Phys., Vol 27, No. 1, pp.157-158.
8. I.I.Beilis, 1974, Analysis of the cathode spot in a vacuum arc, Sov. Phys., pp. 19, 2, 251-257.
9. I.I.Beilis, 1996, Current continuity and instability of the mercury vacuum arc cathode spot, IEEE, Trans. On Plasma Sci., Vol.24, No.4, pp.1259-1270.
10. I.I.Beilis, 1999, Application of vacuum arc cathode spot model to graphite cathode, IEEE, Trans. On Plasma Sci., Vol. 27, No.4, pp.821-826.

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