EXPERIMENTAL INVESTIGATION OF CAPILLARY ARC PHENOMENA

S. Arai, S. Hamada
Tokyo Denki University, Japan

1 Introduction

The relationships between electrical and physical behaviors of the capillary arc are experimentaly studied to understand the physical mechanism governing the high arc voltage generation during the heavy current operations of current limiting fuses. The arc temperature measurements by the spectroscopical method and pressure measurement by the pressure transducer method were used, these methods have been reported in the area of basic research of fuse operation. [1][2][3]

The high pressure container is mainly made of insulation cylinder and stainless steel disks. The empty space of container is reduced as small as possible. The test sample which consists of a copper wire and a Pyrex capillary, is inserted into the container along its axis.

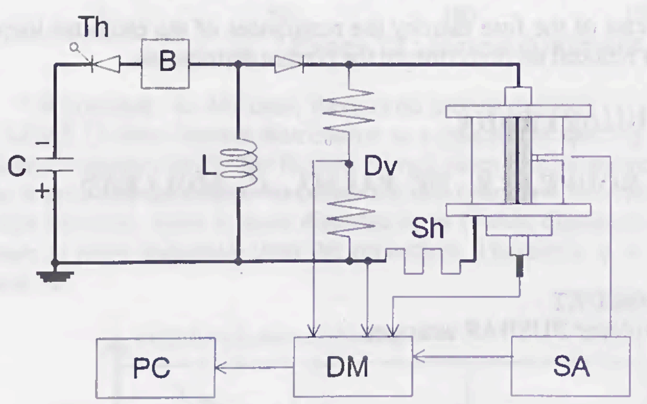
The arc temperature of 6000~10000K and pressure of 0.1~ 0.7MPa were observed at the arc current of 120~300A after completely burned back between electrodes. The trend of growing the arc voltaes is observed according to decreasing diameter of the capillary in the given length under the same test conditions.

It is suggested that the developement of high arc voltage depends on the ratio of vaporizing mass of the inner surfase material of capillary surrounding arc column to the incident arc power.

2 Experimental System

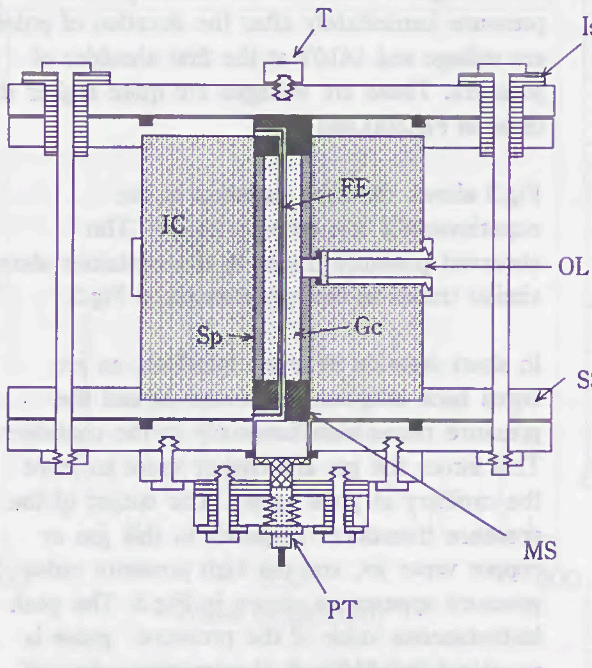
The experimental system arrangement is shown in Fig.1. The operating sequence of the test circuit is as follows.

The capacitor bank C is charged at appropriate voltage, the charge of capacitor bank is discharged through the reactor L, Thyristor Th and breacker B by the closing circuit switch of Thyristor. When total charged energy of the capacitor bank is transfered to the reactor and the capacitor bank voltage is zero, the breacker is open at the instant, and the capaciter bank is isolated. The test circuit changes over from the circuit of capacitor bank and reactor to the circuit of reactor, the pressure container and distributed resisutance. The current commutates into the test sample and the current measurement shunt Sh. Arc energy in the high arc voltage state is easily controlled by this circuit.



C :capacitor bank L :reactor
FE :fuse element VD :voltage divider
Sh :shunt Th :thyristor
B :breaker PC :personal computer
DM :degital memory SA :spectorscopic analyzing systems

Fig.1 The experimental system Arrangement



SS :stainless steel
T :terminal
FE :fuse element
Gc :glass capillary
OL :opening for optical cable
PT :pressure transducer
IC :insulation cylinder
Is :insulator
Sp :spacer
MS :metal spacer

Fig.2 A high pressure container

Fig.2 shows the high pressure container which has a pressure transducer at the bottom and a opening at the side of insulation cylinder. The optical fiber is inserted into the opening to take out the light from arc column. A quartz glass window at the toe of the opening protects against the leakage of gas and shields against the heat and mechanical damage of optical fiber.

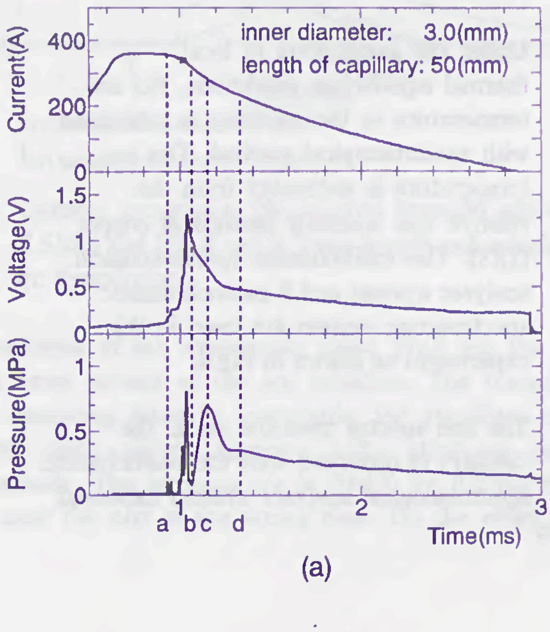
Since the pressure measuring transducer is set back to avoid any deleterious heating effects due to the arc jet, the piston−cylinder including silicon oil is used to communicate the pressure in the container to the transducer. A pressure transducer is a piezoresistive transducer which is semiconductor resistance strain gauges. The resistance change is measured as an output voltage of a bridge circuit. The pressure transducer have a frequency response of about 100kHz.

The test sample is consisted of a copper wire fuse element of 0.18mm in diameter and a Pyrex glass capillary.

3 Experimental Observation

3.1 Arc Voltage and Pressure

Fig.3 shows the typical arc voltages obtained under the same test conditions. The arc voltage of Fig.3(a) is obtained for the capillary diameter of 3mm, arc initiating current 340A, arcing time 2.04ms. Transient process including burn back process of element has completed in 0.14ms with pulse arc voltage after arc initiation. Arc voltage is 690V at the second peak of pressure and 465V at the first shoulder of pressure after the begining quasi−steady arc burning.



(a)

The arc voltage of Fig.3(b) is obtained for the capillary diameter of 2mm, arc initiating current of 298A, arcing time of 1.29ms. The duration of pulse arc voltage is about 0.11ms after arc initiation. Arc voltage is 810V at the second peak of pressure and 535V at the first shoulder of pressure. Those arc voltages are higher than those of Fig.3(a).

The arc voltage of Fig.3(c) is obtained for the capillary diameter of 1mm, arc initiating current of 336A, arcing time of 0.50ms. The duration of pulse arc voltage is about 0.075ms after arc initiation.

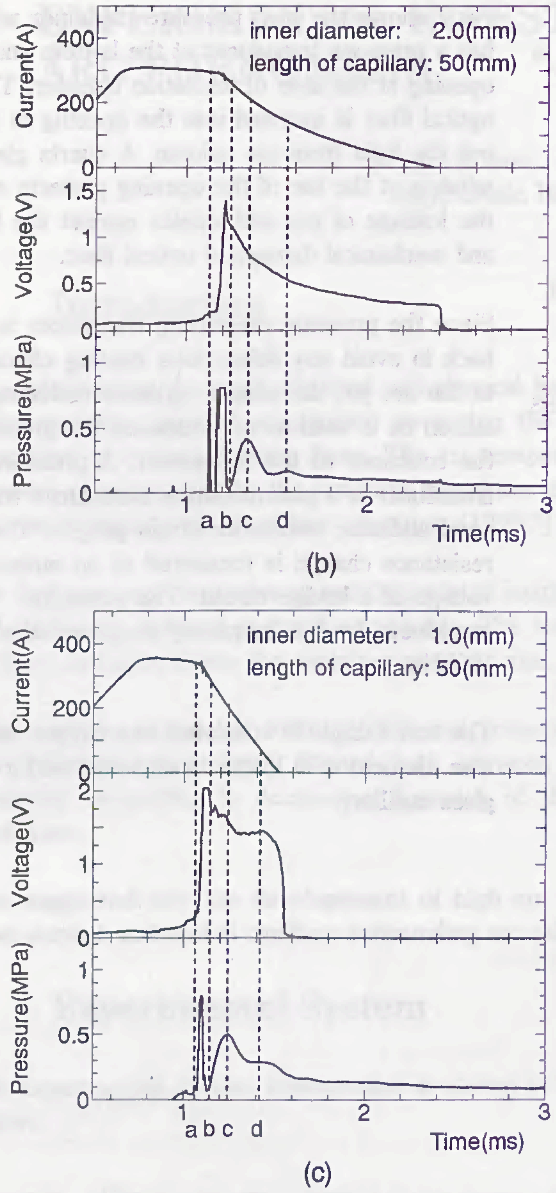


Fig.3 Arc voltages, current and Pressure

Arc voltage is 1600V at the second peak of pressure immediately after the duration of pulse arc voltage and 1410V at the first shoulder of pressure. Those arc voltages are quite higher than those of Fig.3(a) and (b).

Fig.3 shows the time variation of the experimentally measured pressure. The observed pressure traces in the container show similar trends to the appearances on Fig.3.

In short duration after arc initiation, an arc burns back between the terminals and the pressure raises simultaneously in the container. This forces the gas and copper vapor to leave the capillary at great speed. The output of the pressure transducer responds to this gas or copper vapor jet, and the high pressure pulse pressure appears as shown in Fig.3. The peak instantaneous value of the pressure pulse is roughly 0.7~0.8MPa at the instantaneous arc current of 290~240A. After the peak pressure pulse, the pressure pulse falls rapidly. Then the pressure elevation appears again due to arc developed in the capillary. The second peak pressure is about 0.5~0.7MPa, which is lower than the first peak pressure pulse. Then pressure goes on decreasing to the shoulder roughly 0.3MPa and thereafter keeps the similar decrement to the arc current.

3.2 Temperature

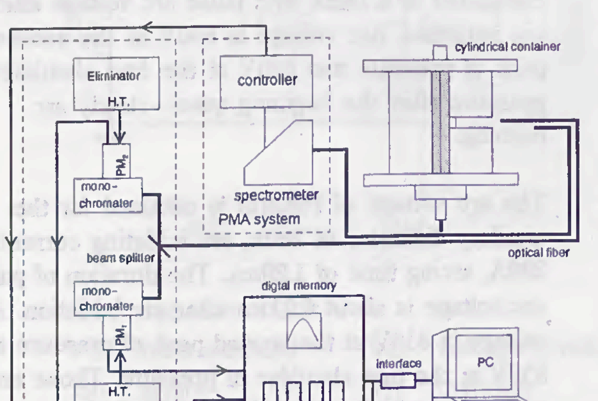


Fig.4 The multichannel spectroscopical analyzer system and 2 monochromatic spectroscope system

Under the assumption of local thermal equilibrium conditions, the arc temperature in the capillary is calculated with spectroscopical method. The arc temperature is estimated from the relative line intensity method of copper [1][2]. The multichannel spectroscopical analyzer system and 2 monochromatic spectroscope system are used in this experiment as shown in Fig.4.

The line spectra from the arc in the capillary is observed with the multichannel spectroscopical analyzer system expessed

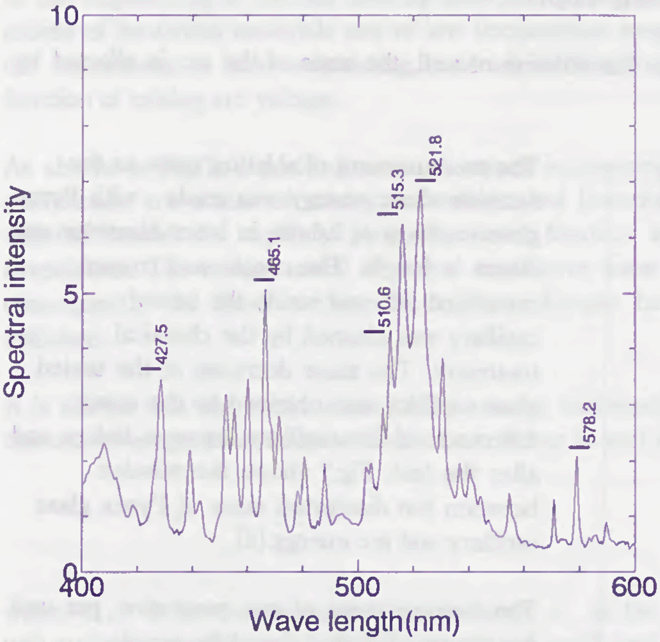


Fig.5 Typical spectrogram of the arc taken by the multichannel spectroscopical system

in PMA system in Fig.4 in order to select the effective line spectra for the relative line intensity method.

The 2 monochromatic spectroscope system is used to obtain the 2 spectral line intensities from the arc in the capillary. The light guided by an optical fiber from the arc is divided equaly, and sent to each monochromatic spectroscope.

The typical spectrogram of the arc taken by the multichannel spectroscopical system is shown in Fig.5, the spectrogram was obtained under the experimental conditions of the tube diameter of 3mm, the arc initiation current of 345A and the arcing time of 1.8ms. The copper line spectra were observed at the wave length of 427.5, 465.1, 510.6, 515.3, 521.8, 578.2nm.

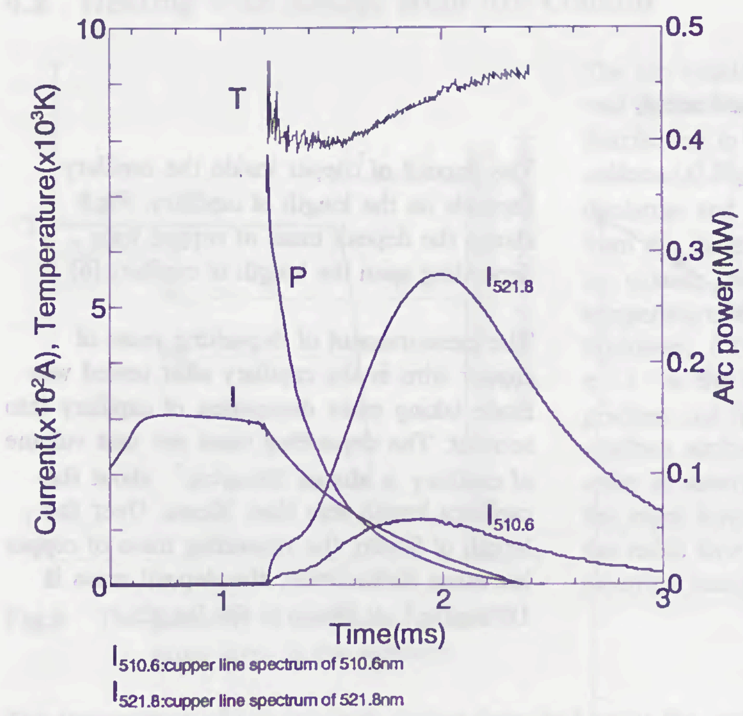


Fig.6 Current, arc power, line spectral intensity curves of 510.6 and 521.8 nm in wave length and calculated arc temperature

To ensure the correct interpretation of obtained spectral data, it is necessary to existence of local thermodynamic equilibrium in the arc, so that this condition is checkd with the Boltzmann plot.[5] Accordingly, it made certain that 4 CuI lines of 510.6, 515.3, 521.8, 578.2nm from the spectrogram were linearly plotted with the upper energy level with regard to the given arc temperature on the semi−logarithmic section paper.

Fig.6 shows current I, arc power P, line spectral intensity curves of 510.6 and 521.8 nm in wave length taken by the 2 monochromatic spectroscope system and temperature T calculated from these spectral intensity data obtained during the arcing time.

The conditions of the experiment about Fig.6 are the same as Fig.3(b). The line spectral intensity curves start at same instant of the arc initiation. The traces of both line spectral intensities are mostly similar pattern excepting intensity magnitude, the shoulders of the curves appear for 0.2 msec after the starting, thereafter both curves increase and attain to maximum intensity in 0.7∼0.8ms, then decrease monotonously. The temperature is 7900K for 0.27ms from the begin, then increases gradually and goes up 9200K near the end of the arcing time. On the other hand, arc power goes down monotonously for arcing time.

3.3 Tube Mass Dissipation and Remaining Copper

The arc discharge constricted by the capillary causes the ablation of wall, the state of the arc is affected by the generated gas by the ablation.

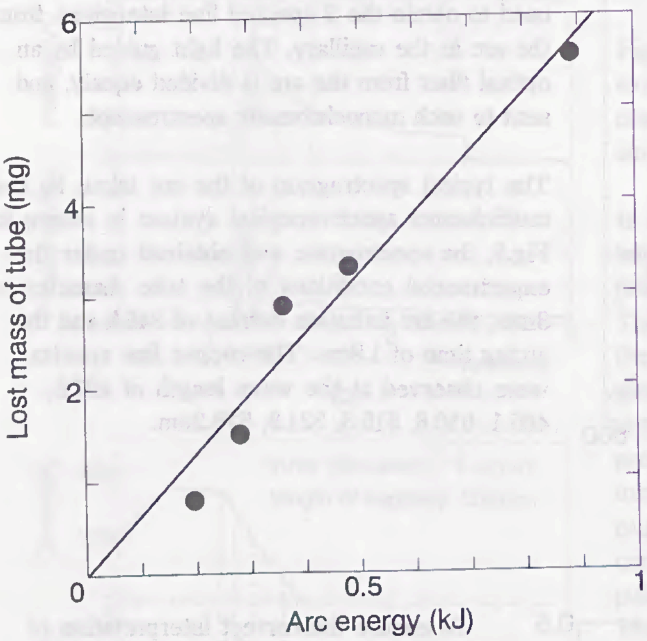


Fig.7 The dissipated mass of capillary and arc energy

The measurement of ablating mass as the function of arc energy was made with Pyrex glass capillary of 2.0mm in inner diameter and 20mm in length. The copper and copper compound adhered inside the tested capillary was cleaned by the chemical treatment. The mass decrease of the tested glass capillary was obtained by the mass difference of the capillary between before and after the test. Fig.7 shows the relasion between the dissipated mass of Pyrex glass capillary and arc energy.[6]

The average mass of gas generation per unit arc energy of Pyrex glass tube equals approximately to 6.6 mg/kJ.

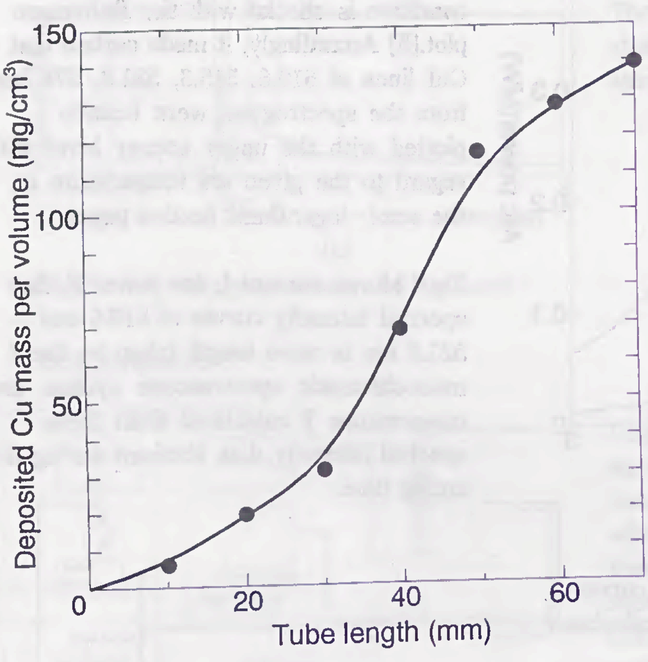


Fig.8 The deposit mass of copper and the length of capillary

The deposit of copper inside the capillary depends on the length of capillary. Fig.8 shows the deposit mass of copper wire depending upon the length of capillary.[6]

The measurement of depositing mass of copper wire in the capillary after tested was made taking mass dissipation of capillary into account. The depositing mass per unit volume of capillary is almost 28mg/cm^3 about the capillary length less than 30mm. Over the length of 50mm, the remaining mass of copper increases distinctively, the deposit mass is 128mg/cm^3 at 60mm in the length.

4 Consideration to the Causes of Lowering Arc Conductivity

4.1 Effect of Depositing Copper

In the engineering of current limiting fuses, the appearance of dangerous high arc voltage is well known by means of insulation materials use of low temperature evaporation for the filler. Pyrex glass capillary used in the experiment is hard evapolating material, so that it may be difficult to plays an important part in the function of raising arc voltage.

As shown in Fig.7, depositing mass of copper increases appreciably over 30 mm in capillary length. These phenomena are a hint of raising arc voltage and lowering arc conductivity. It is supposed that the copper adhered inside the capillary plays the same function as the filler of the materials of low temperature evapolation. The molten metal of copper may cover some area of capillary inner surface like the shin sheet, consequently the inner surface of capillary changes hard to ease evaparation materimals after the arc initiation.

It is shown that the temperature of arc column surrounded by the ablating wall is inversely proportional to the rate of evaporation mass to incident arc power in unit surface area of the wall.[7] It is given by

$$T_a = \frac{C}{\omega} \tag{1}$$

where T_a is the temperature of arc column, ω is the rate of evaporation mass to incident arc power in unit surface area of the wall, C is proportional coefficient. It follows that the temperature of arc column goes down as the rate of evaporation mass increases.

4.2 Heating Wall Energy from Arc Column

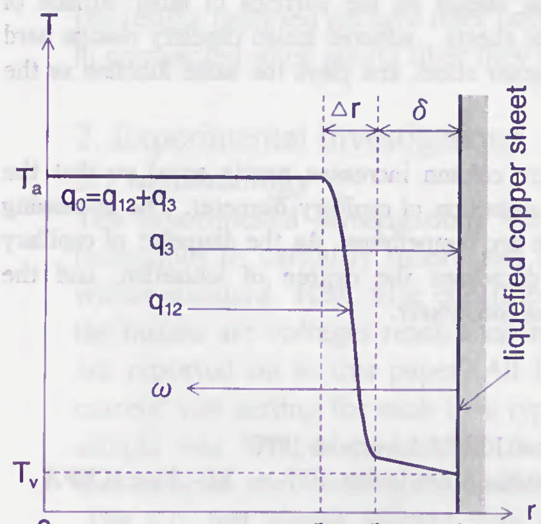


Fig.9 The geometry of arc discharge and vapor layer in the capillary.

The arc constricted by evaporating wall materials has a well defined boundary, and the arc temperature distribution in the cross section of arc column is mostly uniform.[4] Fig.9 shows the suppositive geometry of arc discharge and vapor layer which separates the arc column from the inner surface of capillaryin the capillary. T_a is arc column temperature, T_v is the evaporating temperature of copper, r_1 to r_3 is the vapor layer thickness, Δr is the region of steep temperature gradient, q_{12} is the input power density in steep temperature gradient and q_3 is the input power density on the capillary surface. Therefore temperature gradient of the order of several thousand degrees per millimeter exists in the vapor layer. Temperature gradient must be enough for the radial flow of heat which keeps the balance of the total electrical energy developed in the arc column.

The temperature of copper sheet surface deposited inside the capillary may keep the evaporating temperature of copper. The specific enthalpy of copper vapor ejected from copper sheet surface is given by the evaporating temperature of copper and local pressure on the sheet surface of copper.

As mention in section 4.1, the temperature of arc column depends mainly upon the rate of migrating vapor mass to the arc column. A fraction of the ohmic power production in the arc column per unit length is spent to evaporat copper or the inner surface material of capillary. The ratio of the fraction of the ohmic power producting the migrating vapor mass to ohmic power is expressed by λ and in case of copper dominant evaporation, the following relationship as shown in Fig.9 is given

$$\lambda \frac{I^2}{\pi r_1{}^2 \sigma} = \varepsilon_c 2\pi r_3 \omega [h_1(T_1) - h_v] \tag{2}$$

where I is arc current, ε_c is ratio of the copper sheet area to the inner surface area of unit length of capillary, $h_1(T_1)$ is the specific enthalpy of arc column, h_v is the specific enthalpy of copper evaporation, σ is a arc column conductivity.
The inflow rate of evapolating mass into the arc column is given by

$$\omega = \gamma \frac{I^2}{2\pi 2\sigma r_1^2 r_3} \frac{1}{[h_1(T_1) - h_v]} \tag{3}$$

where γ is constant including λ and ε_c.

As the inner diameter of capillary is decreased, the inflow rate of evapolating mass may be greatly incleasing, because the right side of Eq.(3) increases inversely proportional to 3 powers of capillary inner radius because of a thin vapor layer. The $h_1(T_1)$ goes down according to the decrease of arc temperature because of the superheated copper vapor in arc column. The increasing mass inflow rate into the arc column plays the important function to lower the temperature of arc column owing to Eq.(1).

It is qualitatively supposed that vapor or gas ejected from the wall sorrounding the arc column may essentially increase by means of reducing capillary diameter, the inflowing vapor into the arc column accordingly increases, the arc temperature is lowered. Lowering the arc temperature, the conductivity of the arc column becomes low. Consequently arc voltage goes up according to the decreasing the diameter of capillary.

5 Conclusion

The copper metal used as fuse elements adhers like copper sheets on the portions of inner surface of capillary in the short time after arc initiation. The copper metal sheets adhered inside capillary change hard evaporating surface of Pyrex to easy evaporating surface of copper sheet, and plays the same function as the filler of the low temperature evapolation materials.

The inflowing copper vapor into and outflowing from the arc column increases nearly equal so that the pressure of arc column changes modelately according to the reduction of capillary diameter. The increasing rate of copper vapor inflowing into the arc column lowers the arc temperature. As the diameter of capillary decreases, the lowering arc temperature correspondingly decreases the degree of ionization, and the conductivity of arc column goes down also, the arc voltage rises conversely.

References

[1] M.R.Barrault: Pressure in Enclosed Fuses, P110 ~ 113 Proc.ICEFA Liverpool 1976

[2] L.J.Cao, A.D.Stokes: Spectrum Analysis of an Ablation−Stabilised Arc in Ice, P27 ~ 32 Proc.ICEFA Nottingham 1991

[3] D.R.Barrow, A.F.Howe: The Use of Optical Spectroscopy in the Analysis of Electric Fuse Arcing, P221 ~ 225 Proc.ICEFA Nottingham 1991

[4] L.Niemeyer: Evaporation Dominated High Current Arcs in Narrow Channels, IEEE Trans. Power Appar. Syst., vol.PAS−97, pp.950−958 1978

[5] G.R.Jones: High Pressure Arcs in Industrial Devices,(book) P158 ~ 161 Combridge U. Press 1988

[6] H.Oishi, S.Arai: Characteristics of Arc Voltage and Metallic Vapor Pressure in the Enclosed Capillary,(Japanese) P75 ~ 82 T.IEE Japan Vol.113- B No,1 '93

[7] J.Ren, S.Arai, S.Hamada: Symmetrical Gas Flow in a Tube and Pressure in a Pressure Chamber Caused by Ablation Arcs,(Japanese) P24 ~ 29 T.IEE Japan Vol.115- B No,1 '95