Geometrical Model of Discharge Space in the State of the High Arc Voltage Generation of Capillary Arcs

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Abstract: The paper describes the discharge space in consideration of the capillary arc behavior depending on the arc current density and the diameter of a capillary tube. According to increasing the arc current density or decreasing the diameter of capillary tube, the arc voltage becomes higher and the radiation intensities emitted from the capillary tube changes from the line spectral radiation to the continuous spectral radiation with spectral absorption.

The pressure in the high pressure vessel during arcing time is extremely lower than the estimated pressure due to the completely vaporized element at arc temperature. Therefore droplets and bulks of liquefied element substance remain in the capillary space.

The continuous spectral radiation suggests that the arc column is surrounded by the optical dense vapor layer including droplets, absorbing the radiation from arc column and emitting continuous spectral.

It is supposed that the layer plays an important role in high arc voltage generation by effectively carrying off the energy from the arc column.

1 INTRODUCTION

The study of the capillary arc behavior has been experimentally made to understand the physical mechanism governing the high arc voltage generation during the heavy current operation of current limiting fuses.[1]

The experiment was made to investigate the relation between the arc voltage and the arc temperature, the pressure of arc discharge space and the diameter of a capillary tube in a high pressure vessel. The temperature is measured by the spectroscopic measurement systems.

From experimental results, the arc voltage becomes higher and spectral radiation profile emitted from the capillary tube changes from line spectra to continuous profile with resonant absorption as increasing the arc current density or decreasing the diameter of capillary tube. The temperature in continuous spectral radiation intensity is estimated from fact that the radiation can be coincident with the simulation of the blackbody radiation combined with resonant absorption of sodium.[2]

It is experimentally confirmed that the pressure in the high pressure vessel during arcing time is extremely lower than the estimated pressure due to the completely vaporized element at the arc temperature. These observed results suggest that a quite large proportion of liquefied element substance remain in the capillary tube as droplets and bulks of liquefied element substance. As the cause of the observation of continuous spectral radiation, it is supposed that the optical dense layer mixing vapor and droplets surrounds the arc column and absorbs the radiation from the arc column and radiates the continuous spectral radiation intensity.

It is believed that the layer plays an important role in high arc voltage generation by effectively carrying off the energy from the arc column.

2 EXPERIMENTAL SYSTEM

2.1 Experimental apparatus

The high pressure vessel mainly consists of an insulation cylinder, upper and lower stainless steel circular disk covers and flanges. The pressure measuring unit is installed on the lower cover. The opening is made through at the middle side of the insulation cylinder. A test sample set together a cylindrical spacer is inserted along the axis of the insulation cylinder.[1]

2.2 Pressure measuring unit

The pressure in the high pressure vessel is measured by the pressure measuring unit including the pressure transducer. The piston is pressed down by the pressure in the high pressure vessel, the pressure is transferred to the transducer through the piston-cylinder containing silicon oil.

2.3 Spectroscopic measurement systems

The opening to take out the radiation from the inside of high pressure vessel is holed through at the middle side and perpendicular to the axis of the insulation cylinder. The optical fiber is inserted into the opening to lead the radiation away from arc discharging space.

The two monochromatic spectroscopic system and multi channel spectroscopic analyzer system are used in this study in order to estimate the temperature of the arc discharge space by the spectral intensity measurement method. [1]~[7] The arc column temperature is estimated by the calculation from the 2 line spectral intensities obtained by the 2 monochromatic spectroscopic system under the assumption of local thermal equilibrium.

2.4 Experimental circuit

The arc energy is easily adjusted by the test circuit which consists of the loop circuit including a capacitor bank and a reactor and the loop circuit including the reactor and a test sample. Closing the loop circuit of the capacitor bank and the reactor, charged energy in the capacitor bank is transferred to the reactor. And then the capacitor bank is broken at the moment of completely discharging, so energy in the reactor flows into the test sample.

2.5 Test samples

The 2 kinds of dimension of copper wire element are 0.18 mm, 0.20 mm in diameter and 50 mm in length. The 6 kinds of dimension of Pyrex capillary tube are 3.5 ~ 1.0 mm every 0.5 mm in inner diameter and 50 mm in length.

3 EXPERIMENTAL RESULTS AND CONSIDERATION

3.1 Arc voltage and spectral radiation intensity characteristics

The arc voltage, current, spectral radiation and pressure were measured according to the current and the diameter of capillary tube. Fig.1 shows the typical relation between the arc voltage, current and the spectral radiation intensity characteristics, for the test sample of the capillary tube of 1.5 mm in inner diameter and the copper wire element of 0.18 mm in diameter. A series of Fig.1 (b) were measured by the multichannel spectroscopic analyzer system at the same time of measurement of the arc voltage and current shown in Fig.1 (a). The sets of sign I and number indicated on the figure indicate the wavelength in nano meter unit of line spectral intensity of copper atom.

As shown in Fig.1 (a), the arc initiating currents are 160 A, 280 A and 350 A. For the arc initiating current of 160 A, the arcing time of 0.63 msec and arc energy of 30J, the arc voltage decreases like the exponential function of time. For the 280A, the arcing time of 0.77 msec and the arc energy of 82 J and 350 A, the arcing time of 0.85 msec and the arc energy of 120 J, the shoulder of arc voltage is observed during the middle of the arcing time.

The voltage of the shoulder increases with the increase of the arc initiating current, apparent arc current density that is calculated by dividing the arc current by the inner cross section of the capillary tube and the arc energy.

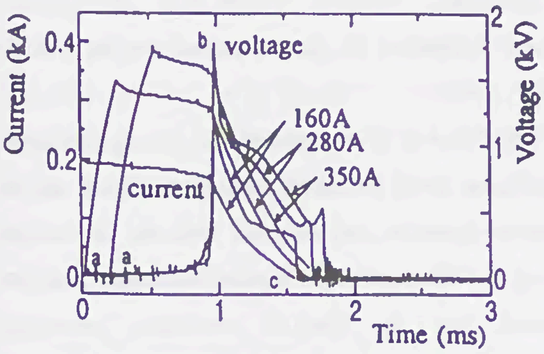


Fig.1 (a) the arc voltages and the currents

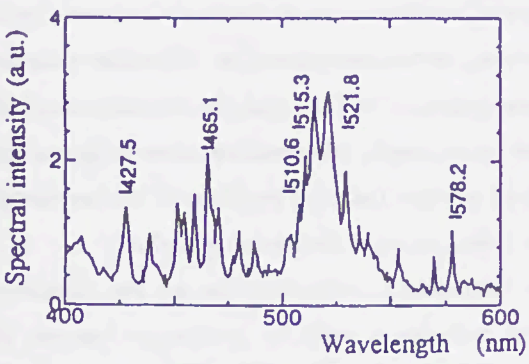


Fig.1 (b - 1) the spectral radiation characteristics for arc initiating current 160A

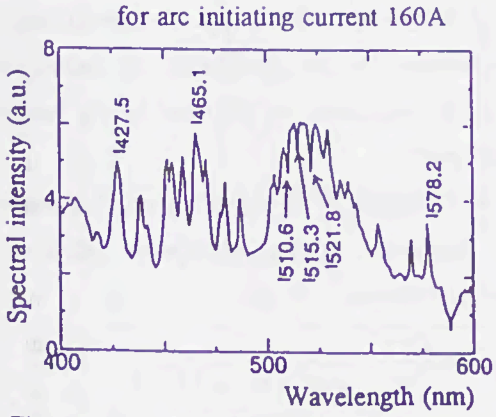


Fig.1 (b - 2) the spectral radiation characteristics for arc initiating current 280A

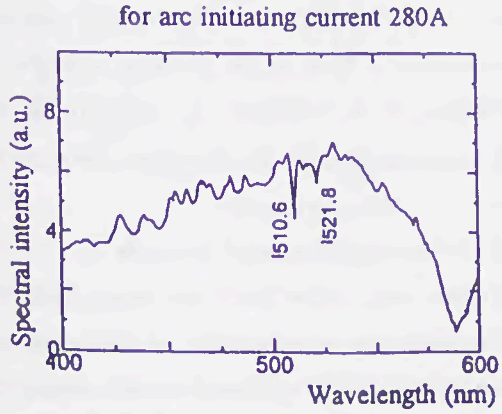


Fig.1 (b - 3) the spectral radiation characteristics for arc initiating current 350A

the capillary tube is 1.5 mm in inner diameter and 50 mm in length

Fig.1 Relation between arc voltage and spectral radiation characteristics depending on current

As shown in Fig.1 (b - 1) that is correspondent with the arc initiating instant of 160A in figure 1(a), the line spectra from copper atom are clearly recognized.

As shown in Fig.1(b - 2) corresponding with the arc initiating instant of 280A, the line spectra of 427.5nm, 465.1nm, 578.2nm in the wavelength for copper atom are clearly recognized, on the other hand spectral absorption is observed at the 510.6 nm, 515.3 nm, 521.8 nm in wavelength.

Showing in Fig.1(b - 3) that is correspondent with the arc initiating instant of 350A, the spectral radiation profile like continuous spectral radiation and spectral absorption occurs at 510.6 nm, 521.8 nm in central wavelength. And furthermore, it is observed that the significant spectral absorption occurs at 587 nm of central wavelength.

3.2 Partial vaporization of element

The arc process during arcing time can be divided into 3 steps for heavy current operation. The first step is the process that multi arcs ignite and each burns back along element to join together a single arc. The second step is the single arc burning process, and the last is small current conduction and recovery of dielectric strength in post arc space around current zero.

Depending on the diameter of element and the rate of flowing energy into the element, the state of the element at the instant of arc initiation may be liquid state heated up a little above melting temperature in the range of heavy current. It is observed that the arcs initiate successively along the wire element, and immediately after multi arcs are constituted, each burns back along the element to join together a single arc in a short time.[8] The input energy into the high pressure vessel during the first step mainly concentrates on the regions of arc dynamic action because of each high arc voltage, so that the consuming energy by enclosing surroundings and the segment of element is comparatively small.

Showing in Fig.1(a), the energy flowing into the high pressure vessel during arcing time is 120J for the arc initiating current of 350 A, on the other hand, the energy of about 27J is necessary for the whole copper element to vaporize completely from liquid state of melting temperature. However part of the input energy into the high pressure vessel is spent to heat up the liquefied element substance, but the energy shared out to heat the liquefied element may not be enough to vaporize whole element at any instant during arcing time.

The reason is as follows, for the sample of the copper element of 0.18mm in diameter and 50mm in length, and the capillary tube of 3.0mm in diameter and 50 mm in length, and pressure of 1.0 MPa, temperature of 9000 K in the discharge space, the rate of number of copper atom to produce the pressure in the capillary tube to number of atom including the original wire element is about 0.3 %.

Therefore it is supposed that a large amount of liquefied element substance exist as droplets and lumps of liquid in the capillary tube during arcing time.

4 ARC DISCHARGE SPACE MODEL IN HIGH CURRENT DENSITY

Under the experimental condition of the low apparent arc current density under about $90\times10^6 A/m^2$ in the vicinity of the arc initiation and the Pyrex capillary tube inner diameter of 3.5~1.5 mm, the arc voltage is exponentially monotonous decreasing. And the temperature of arc column of about 7000~10000K during arcing time is estimated by the relative line spectral intensity method.[1][2]

For the heavy arc current over the apparent arc current density of about $260\times10^8 A/m^{-2}$ in the vicinity of the arc initiation and the capillary tube inner diameter of 1 mm, the arc voltage is high rectangle as shown in Fig.2(a), the spectral radiation profile is continuos as the blackbody radiation except the distinguished resonant absorption of spectra caused by the sodium vapor.

As stated above, it is supposed that the optical dense copper vapor layer including droplets surrounds the arc column and absorbs the radiation from the arc column and radiates the continuous spectral radiation. And it is supposed that the spectral absorbing membrane including sodium is outside the layer and on the inner surface of capillary tube, because of the possibility of vaporizing the sodium vapor from Pyrex tube including the component of sodium and the coincidence of the central wavelength of resonant absorption on the observed spectral radiation profile with the wavelength of the strong resonant absorption of sodium.

The temperature estimation due to the continuous spectral radiation is made by comparison between the measured radiation intensity characteristics and the theoretical blackbody radiation. At the same time, the some parameters for the distribution of sodium and copper in the membrane are obtained by the resonant absorption profile.

These are estimated by the following set of equations. Spectral brightness of the blackbody radiation is expressed as follows

$$B_\nu = \frac{2h\nu^3}{c^2}\frac{1}{\exp(h\nu/\kappa T)-1} \qquad (1)$$

where h is Planck's constant, ν is frequency of radiation, c is speed of light, κ is Boltzmann's constant. The monochromatic beam of the radiation impinges on the membrane of l_{Na} thickness. An intensity of the beam of I_ν passing through the membrane is expressed as follows

$$I_\nu = B_\nu \exp[-(\alpha_{\nu Na1} + \alpha_{\nu Na2}) l_{Na}] \qquad (2)$$

where $\alpha_{\nu Na1}$ and $\alpha_{\nu Na2}$ are the monochromatic absorption coefficient of wavelength of 589.0 nm and 589.6 nm of sodium. The monochromatic absorption coefficient $\alpha_{\nu Na}$ is expressed as follows

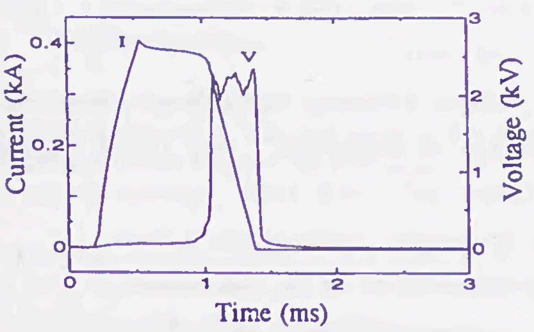
$$\alpha_{\nu Na} = \frac{\pi e^2}{mc} \quad (3)$$

where e is the electron charge, m is mass of electron, N is atom density, f_{Na} is absorptive oscillator strength of sodium, $f_{Na1}=0.655$ at the wavelength of 589.0 nm and $f_{Na2}=0.327$ at the wavelength of 589.6 nm,[9] p_ν is normalized profile of radiation. Under assuming Lorentz's type expression, p_ν is given as follows

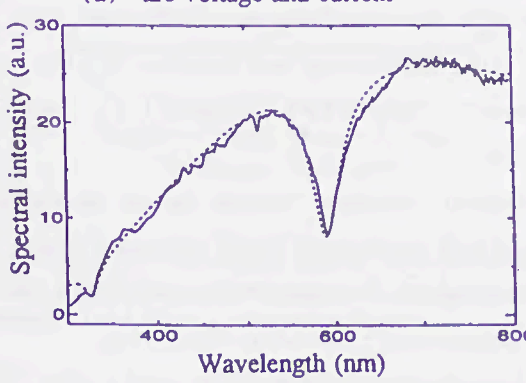
$$p_\nu = \frac{1}{\pi}\frac{\gamma/2}{(\nu-\nu_0)^2+(\gamma/2)^2} \quad (4)$$

where γ is the width of curve at the half depth of central wavelength of absorption curve given by Margenau and Watson,[10] ν_0 is the central wavelength of resonant absorption curve. γ is given as follows

$$\gamma = \frac{e^2 f_{Na} N}{2\pi m \nu_0} \quad (5)$$



(a) arc voltage and current



(b) the observed and calculated spectral radiation

Fig.2 the observed arc voltage and current, the observed and calculated spectral radiation profiles for the capillary tube is 1mm in inner diameter, the element is 0.20 mm in diameter

The dotted line curve on Fig.2 shows the spectral radiation profile calculated by using the set of equations from (1) to (5). Physical parameter of the membrane is given by the calculation.

The calculated blackbody radiation curve particularly depends on the temperature of the layer. In the resonant absorption, the depth of resonant absorption curve at the central wavelength of 590 nm depends on both sodium vapor density and optical length of the membrane. And the width of curve at half depth of resonant absorption curve depends on the sodium atom density in the membrane. For the capillary tube diameter of 1.0 mm, the calculated temperature is 4300K according to the coincidence with the theoretical blackbody radiation. The optical length of the membrane of sodium is 2.7×10^{-8} m and of copper is 1.4×10^{-8} m. The particle density of sodium in the membrane is $8\times10^{26}m^{-3}$ and of copper is $420\times10^{26}m^{-3}$. Fig.3 shows the proposed qualitative model of arc space in heavy current by the above considerations.

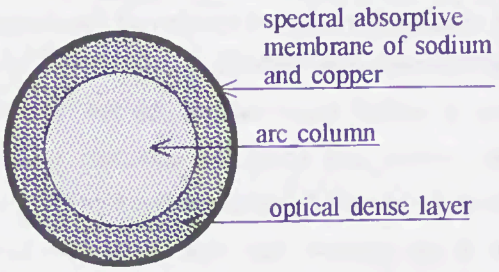


Fig.3 The basic model of the arc discharge space in the capillary tube for high current density

The model is the constitution of coaxial configuration. The arc column occupies the central section. The layer surrounding arc column contains copper vapor and droplets of liquefied element substance and is optical dense, so the layer absorbs the radiation from the arc column and emits continuos radiation. The membrane on the inner surface of the capillary tube absorbs resonantly spectra emitted by the layer.

5 CONCLUSION

Decreasing diameter of capillary tube or increasing the arc current density, the shoulder of voltage grows, and the rectangular attains at last. On the other hand, the spectral radiation changes from line to continuos profile.

For capillary tube diameter of 3.5 ~ 1.5 mm, temperature of arc column of 7000 ~ 10000K is clearly estimated by the relative spectral line intensity method. And for the capillary tube diameter of 1.0 mm and the apparent arc current density over about $2.6\times10^{8}A/m^{2}$ in the vicinity of the arc initiation, the temperatures of 4000~5000K is estimated by comparing the measured continuos spectral radiation characteristics with the theoretical blackbody radiation.

Flowing energy into the element is not enough to vaporize the element completely, the lump of liquids and droplets of element substance remain in the arc discharge space. It is supposed that the multi arcs develops into a single arc of coaxial construction in the capillary tube in the first step, the arc column burns in the center along the axis of capillary tube, and the layer of mixture of vapor and droplets of the element substance surrounds arc column in the second step. The layer is optical dense and absorbs the radiation from arc column and emits the continuos spectral radiation as the blackbody radiation. The membrane on the wall of the capillary tube and outside the layer includes the sodium vaporized from the capillary tube.

From the experimental results, it is believed that the high arc voltage generation is the cause of the high current density, the layer containing the vapor and droplets of element substance between arc column and the capillary wall and the membrane on the wall of capillary tube. It is considered that the layer and the membrane carries effectively off the energy from arc column. The distance between arc column and wall of capillary tube becomes shorter by decreasing the capillary tube diameter, cooling the arc column by the above construction between arc column and the wall is more effective.

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