Electric Behavior of Capillary Arcs Ignited at High Current Density Levels in Copper Vapor

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Abstracts: In order to understand the mechanism of the high arc voltage generation of the current limiting fuses, the experimental studies were made by the capillary arc ignited in copper vapor at high current density. The experimental sample consists of a Pyrex glass capillary, a copper wire element and copper electrodes.

The line spectral radiation intensity of copper atom decreases, the continuous component of spectral radiation intensity increases and the mean arc voltage builds up as the inner diameter of capillary is becoming smaller.

During the arcing time in the breaking of high current density, the dynamical movement and geometrical construction of copper medium in the capillary are conjectured by the observation of spectral radiation. The temperature of arc column is estimated by the measured copper spectral lines of 521.8 nm and 510.6 nm in wavelength for the glass tube of 3.5 mm in diameter. The temperature of arc column in this experimental conditions obtained change from 4500 to 19000 K roughly.

Keywords: current limiting fuses, capillary arc, high arc voltage, line spectrum, continuous spectrum, cluster

1. Introduction

The purpose of this research is to understand the phenomenon of high arc voltage generation of current limiting fuses in the breaking heavy current. The sample piece is mainly consisted of a Pyrex glass capillary, a copper wire element and copper electrodes. Two kinds of copper wires with different diameter were used as fuse elements.

It is supposed that the discharge space is axial symmetry and the arc column is surrounded by the layer of copper vapor and clusters after the developing the multi arcing process and fully growing the single arc. Due to the continuous spectral intensity distribution observed in capillaries of the smallest diameter, it is supposed that the layer is at least consisted of two zones. One is the high temperature and optical dense inside zone of layer including copper vapor and clusters closely surrounding the arc column. The other is the low temperature outside zone of layer including vapor and clusters of copper and sodium on the wall of glass tube. These zone construction of layer will be affected by the ratio of arc energy injected until the instant to the mass of copper element.

The inside zone of layer heated high temperature radiates the radiation like blackbody, which is selectively absorbed by the outside zone of layer including the vapor and clusters of copper and sodium. The temperature of inside zone was estimated by considering the continuous spectral intensity distribution observed for the glass tube of 1 mm in diameter as the black body radiation. [1]

The transmissivity of the white light through the sample which was stained by the copper thin film on the inner wall of glass tube for the experiment was measured to investigate the selective spectral absorbing phenomena.

The radiation temperature of arc column was estimated by measuring the two copper spectral lines of 521.8 nm and 510.6 nm in wavelength for the glass tube of 3.5 mm in diameter. The temperature just after ignited arc is from 5000 to 8000 K, then after passing through the minimum temperature about 4500 K, the arc temperature monotonously increases to about 15000 to 19000 K.

2. Experimental equipments and method

2.1. The experimental circuit and apparatus

Fig.1 shows the experimental circuit. A current breaking experiment is carried as follows. The charged capacitor bank C of 0.136 F discharges through the reactor L of 1.96 mH and breaker B interrupts the current of CL loop to disconnect the capacitor bank near the maximum current. Thereafter the current is commutated to flow in the LR discharge circuit which consists of reactor L, the experimental apparatus and current shunt Sh.

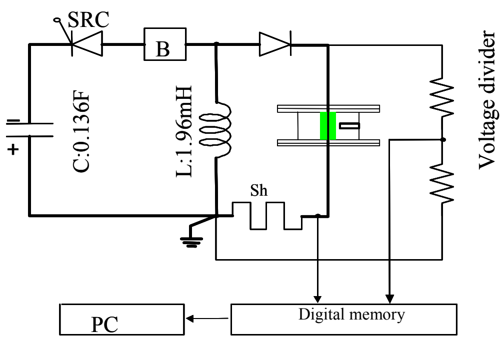


Fig.1 Experimental circuit

The experimental apparatus mainly consists of a pressure container and an experimental sample. The pressure container is constituted with the top and bottom stainless steel circular disks of 15 mm in thickness and a insulation cylinder of 58 mm in length and 80 mm in outer diameter. The experimental sample consists of a copper wire element, a Pyrex glass tube and electrodes which serve to hold elements and to seal the arc burning space of capillary. The dimension of a copper wire is 50 mm in length, 0.18 and 0.26 mm in diameter and the dimension of Pyrex glass tube is 50 mm in length and 1 to 3.5 mm in inner diameter every 0.5 mm.

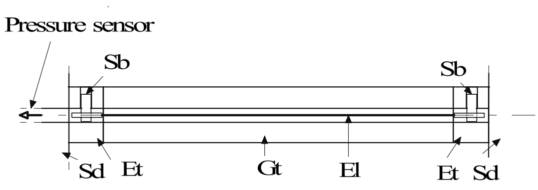


Fig.2 The experimental sample

2.2. Spectral measurement systems

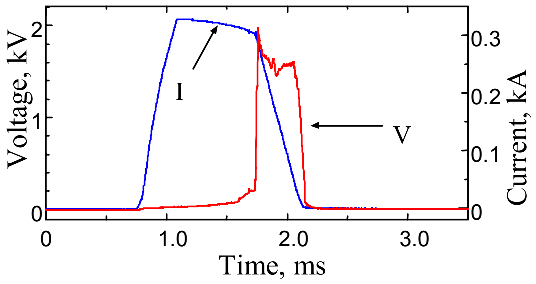
The 2 spectral measurement systems were used to make measurement of the radiation spectrum from the inside of glass tube. One called PMA (Photonic Multichannel Analyzer) consists of the multichannel spectral equipment and the controller of optical system. The PMA measures simultaneously the spectral intensity of time integral during 25 msec in the range of 300 to 800 nm in wavelength. The other measures 2 line spectral intensities with time. The radiation conducted by the single optical fiber is equally divided on the way of optical channel and then each divided radiation is conducted to a monochromatic spectrometer.

3. Experimental Results

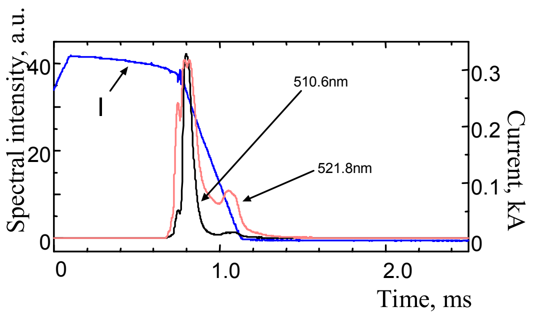
3.1. Spectrum in the glass tube of 1 mm in inner diameter

The experiment was made to obtain arc current and voltage, line spectral intensities of 510.6 nm and 521.8 nm to time and spectral intensity distribution to spectral wavelength using experimental samples. The samples made up by a copper wire element of 0.18 mm or 0.26 mm in diameter and a Pyrex glass tube of 1 mm in inner diameter. The breaking current was same in pre-arcing time.

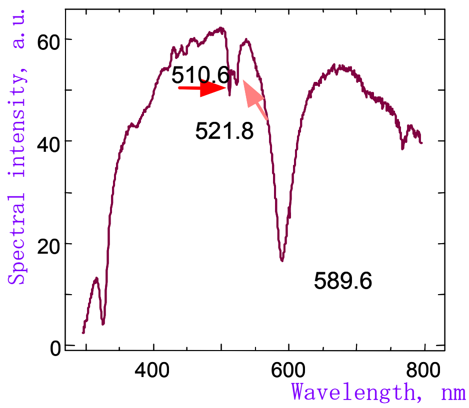
Fig.3 shows current and voltage in Fig.3(a), spectrum intensities of 521.8 nm and 510.6 nm in wavelength observed by the 2 spectrometer system in Fig.3(b), and spectral intensity distribution obtained by PMA in Fig.3(c) for the copper wire element of 0.18 mm in diameter.



(a) Current and voltage



(b) Current and spectral intensities of 521.8 nm and 510.6 nm in wavelength to time

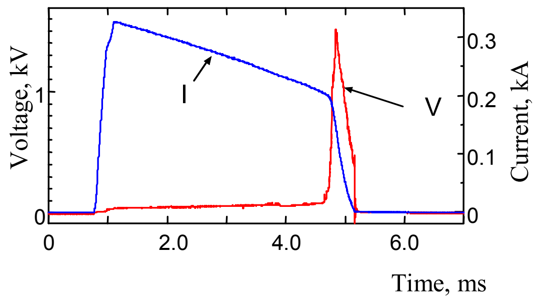


(c) Spectral intensity to spectral wavelength

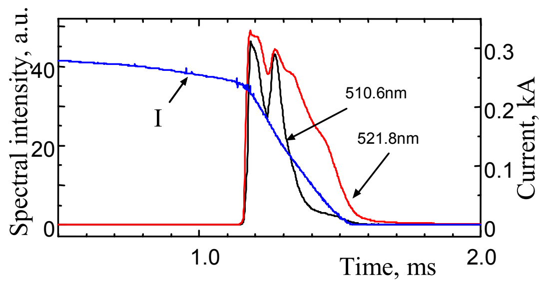
Fig.3 Current, voltage, line spectral intensities and spectral intensity distribution for the element diameter of 0.18 mm and the glass tube inner diameter of 1.0 mm

Fig.4 shows current and voltage, line spectral intensities to time and the spectral intensity distribution to spectral wavelength obtained for copper wire elements of 0.26 mm in diameter, and Pyrex glass tubes of 1 mm in inner diameter.

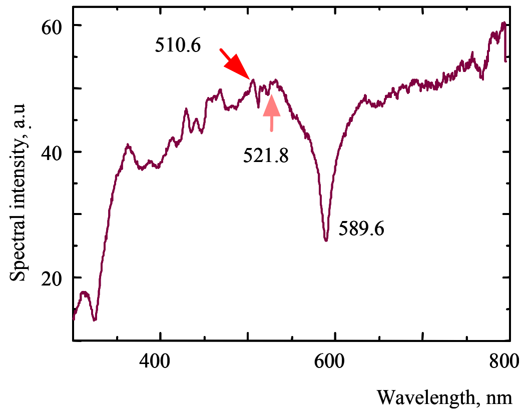
As seen in Fig.3(a) the current wave form is roughly rectangular during prearcing time of 1.0 ms. An arc voltage builds up rapidly to the maximum voltage of 2.0 kV just after arc initiation and decreases 1.55 kV.



(a) Current and voltage



(b) Current and spectral intensities of 521.8 nm and 510.6 nm to time



(c) Spectral intensity to spectral wavelength

Fig.4 Current and voltage, line spectral intensities and spectral intensity distribution for the element diameter of 0.26 mm and the glass tube inner diameter of 1.0 mm

As seen in Fig.4(a) the current during the pre-arcing time is same wave form as that in Fig.3(a), but the pre-arcing time of 4.1 ms is longer because of the larger diameter of element. According to the lower arc ignition current, the arc voltage decreases linearly from the maximum of 1.5 kV at arc initiation to the minimum of 0.4 kV just before an arc current zero and instantly rises 0.5 kV at the current zero.

Fig.3(b) shows the line spectral radiation intensities of 521.8 and 510.6 nm in spectral wavelength for copper atoms. Both intensities very quickly increase after the ignition of arc, the intensity of 521.8 nm is larger than that of 510.6 nm for 115 μ s before the maximum intensity, and the intensities inverse each other around the maximum intensity, that is, the intensity of 510.6 nm is larger than that of 521.8 nm. And the intensities again inverse each other and decrease with time, the intensity of 521.8 nm swells before arc current zero.

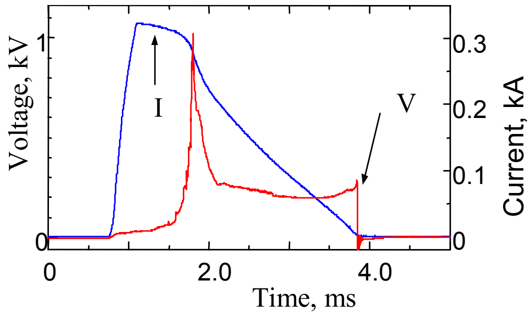
Fig.4(b) shows the same behavior of line spectral intensities as Fig.3(b). Both intensities very quickly increase after the ignition of arc, the intensity of 521.8 nm is larger than that of 510.6nm for 47 μ s before the maximum intensity. Both intensities have a deep dent around the maximum intensity. Then both intensities decrease with time, and the intensity of 521.8 nm is kept over and decreases slower than that of 510.6 nm until arc current zero.

As seen in Fig.3(c) and Fig.4(c), the spectral intensity distribution to the spectral wavelength is roughly continuous and strong spectral absorption is clearly recognized at two portions around 325 to 327 nm and 590 nm of wavelength for the glass tube of 1 mm in inner diameter. It is supposed that the spectral absorption around 325 to 327 nm is brought on the copper clusters and vapor, absorption around 590 nm is brought on sodium clusters and vapor.

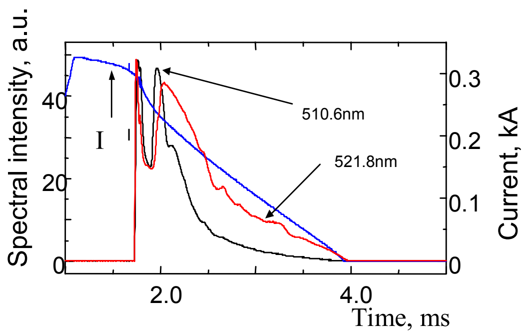
3.2. Spectrum in the glass tube of 3.5 mm in inner diameter

The same experiment as the section 3.1. was made except using Pyrex glass tubes of 3.5 mm in inner diameter as parts of experimental samples. The breaking current was same in prearcing time.

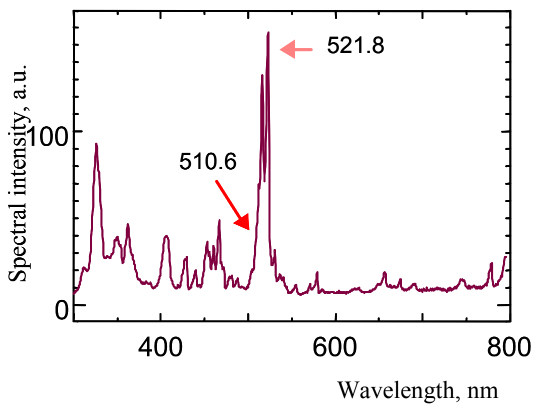
Fig.5 shows current and arc voltage, line spectral intensities and spectrum distributions obtained by a experimental sample made of a copper wire of 0.18 mm in diameter as the element.



(a) Current and voltage



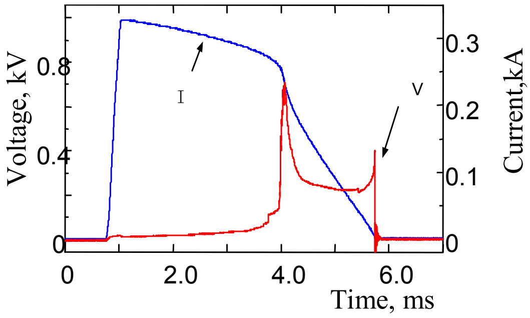
(b) Current and spectral intensities of 521.8 nm and 510.6 nm to time



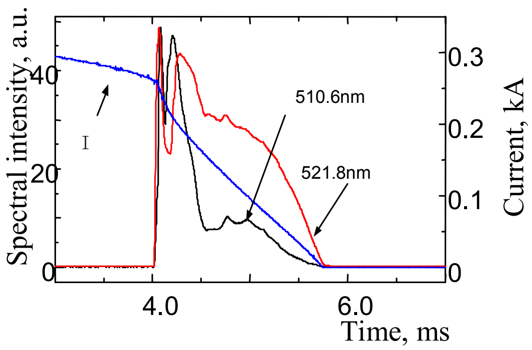
(c) Spectral intensity to spectral wavelength

Fig.5 Current and voltage, line spectral intensities to time and spectral intensity distribution to spectral wavelength for the element diameter of 0.18 mm and the glass tube inner diameter of 3.5 mm.

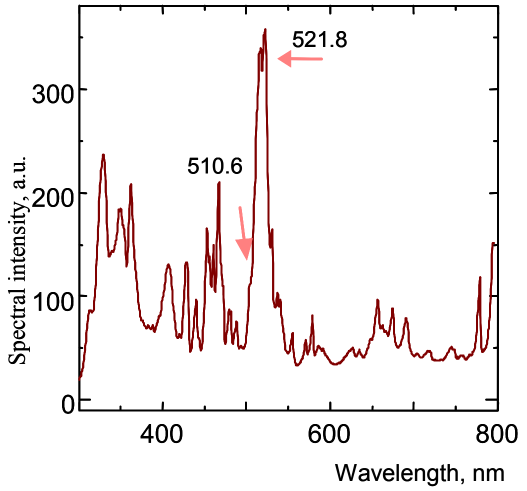
Fig.6 shows current and arc voltage, spectral intensities to time and spectral intensity distribution to wavelength obtained by a experimental sample made of a copper wire of 0.26 mm in diameter as elements.



(a) Current and voltage



(b) Current and spectral intensities of 521.8 nm and 510.6 nm to time



(c) Spectral intensity distribution to spectral wavelength

Fig.6 Current and voltage, line spectral intensities to time and spectral intensity distribution to spectral wavelength for the element diameter of 0.26 mm and the glass tube inner diameter of 3.5 mm.

As seen in Fig.5(a) the current wave form is roughly rectangular during prearcing time of 0.85 ms. An arc voltage builds up rapidly to the maximum voltage of 1.0 kV after arc initiation and decreases 0.25 kV for 0.3 ms and is kept from 0.2 to 0.25 kV.

As seen in Fig.6(a) the current is the same wave form as that of Fig.5(a) except for pre-arcing time of 3.3 ms. Since the arc ignition current is lower than that of Fig.5(a), the arc voltage decreases linearly from the maximum of 0.7 kV at arc initiation to 0.35 kV and the minimum of 0.2 kV just before an arc current zero and quickly rises the peak voltage of 0.4 kV at the current zero.

Fig.5(b) and Fig.6(b) show the distribution of line spectral radiation intensities of copper atom for the glass tube of 3.5 mm in inner diameter.

The both line spectral intensities on each figure from the arc discharge space suddenly build up at the same time of arc ignition and reach the peak values in a few micro seconds. After reaching the peak intensity, the both spectra collapse and return in 0.2 to 0.3 msec. The spectral intensity of 510.6 nm in wavelength is larger than that of 521.8 nm for this duration.

Thereafter both spectral intensities change each other, that is, the spectral intensities of 521.8 nm is larger than that of 510.6 nm and the spectral intensity of 510.6 nm collapses more quickly than that of 521.8 nm. Both spectral intensities mostly disappear at the same time near arc current extinction.

Fig.5(c) and Fig.6(c) show the spectral intensity distribution to the spectral wavelength for the glass tube of 3.5 mm in inner diameter. The spectral intensity distribution is mostly line spectrum.

The spectral radiation intensity in the glass tube of 3.5 mm in inner diameter is about 7 times larger than that of 1 mm for the values around 515 to 520 nm of spectral wavelength.

The remarkable difference for the distribution of spectral intensity to the wavelength is observed for the inner diameter difference of glass tube. The continuous spectral intensity distribution was observed by PMA for the glass tube of narrow inner diameter and the line spectral intensity distribution was observed on the large inner diameter of glass tube. The result suggests that the higher density of copper layer surrounding arc is as the diameter of glass tube is smaller, the weaker spectral intensity pass out through the glass tube.

4. Consideration and investigation

4.1. Optical state of copper vapor surrounding arc column estimated by spectral radiation intensity distribution

Using the PMA, the distributions of continuous spectral and line spectral intensity are observed by the measurement of spectrum emitted through the glass tube during arcing time. It is supposed that the different distribution of spectral intensity emitted through the glass tube during arcing time depends on the state of medium generated from the dispersed and decomposed wire element and surrounding the arc discharged space.

As previously reported about the continuous distribution of spectral intensity, [1] it is estimated that the arc column is surrounded by the layer of optical dense medium, this layer absorbs the some spectral radiation from the arc depending on the optical density. The medium includes copper vapor, copper clusters which consist of many kinds of assembly of copper atoms and radiate the continuous spectra.[2]

On the other hand, the medium surrounding arc column becomes optically thinner and the line spectral radiation intensity through the glass tube is stronger as inner diameter of glass tube is larger.

4.2. The arc column temperature estimated by the line spectral radiation measurement

It is supposed that the line spectral radiation through the glass tube of larger inner diameter is directly emitted from the arc column. If the local area thermal equilibrium is maintained in an arc column, the temperature of arc column is estimated by the ratio of 2 line spectral intensities as given by the following equation for copper atoms.[3]

$$T = \frac{11975}{2.05 - ln\dfrac{I_{521.8}}{I_{510.6}}} \quad [K] \qquad (1)$$

where T is the absolute temperature of arc column, $I_{521.8}$ and $I_{510.6}$ are the spectral intensities of 521.8 nm and 510.6 nm in wavelength respectively.

The temperature of arc column was calculated by the equation (1) about the data of line spectral intensities shown in Fig.5(b) and Fig.6(b). The calculated results are shown in Fig.7 and Fig.8.

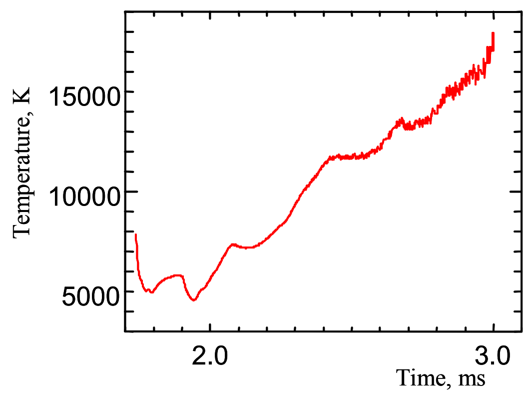


Fig.7 the temperature of arc column obtained from the data of Fig.5(b) for the sample made of the element of

0.18mm in diameter and the glass tube of 3.5mm in inner diameter

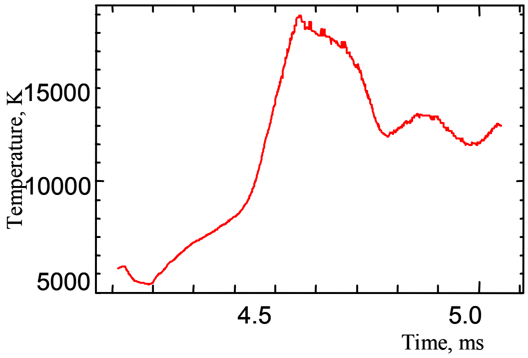


Fig.8 the temperature of arc column obtained from the data of Fig.6(b) for the sample made of the element of 0.26mm in diameter and the glass tube of 3.5mm in inner diameter

The change of arc temperature is shown in Fig.7 obtained for the sample made of the element of 0.18mm in diameter and the glass tube of 3.5mm in inner diameter. The temperature is 8000 K at the arc ignition, and decreases to the minimum value of 4950 K, and then increases monotonously to 18000 K for 1 msec.

Fig.8 shows the change of arc temperature obtained by using the sample made of the element of 0.26mm in diameter and the glass tube of 3.5mm in inner diameter. The temperature is 5500 K at the arc ignition, and decreases to the minimum value of 4950 K, and then increases monotonously for 0.35 msec to the maximum value of 19000 K, and again decreases to the mean value of 13000 K.

4.3. Development of medium surrounding the arc column

In the breaking current level of the experimental circuit adapted for this research,[4] just a little before the arc ignition, the element changes from a cylindrical liquid of uniform cross section to one of variable cross section constricted at many points along the length of element. The constrictions in the cross section of element develop at many points along the length of wire element as the result of current pinch effect. It is estimated that the temperature of element at that instant may be slightly higher than the melting temperature by the value of specific Joule integral.

At last the multi-arc starts along the length of element following the development of constriction of element cross section in very short time. Each arc burns back and joins together, and single arc is formed in very short time duration.

For the short duration after the ignition of multi-arc, the energy flowing into the experimental sample increases abruptly according to the generation of high arc voltage, but most energy may concentrate into the zones of arc burning points, so that a smaller amount of energy supplies to a layer of decomposed copper wire element diffused outside the arc burning space. Therefore a copper layer outside the arc space may consist of copper vapor and clusters mixed up various sizes.

4.4. Line and continuous spectral radiations depending on the glass tube diameter

In early arcing time, the arc discharge space is surrounded by the layer consisting of copper vapor and various size clusters. The spectra emitted from the arc discharge space may be affected by the density of layer which depends on the inner diameter of glass tube.

The lower density of layer surrounding arc discharge space is and also the thinner optical thickness of the layer is, the larger inner diameter of glass tube is. The absorption of emission from arc discharge space decreases and the line spectral intensity observed outside the glass tube is stronger as the inner diameter of glass tube is larger. It is supposed that the line spectral intensity observed outside the glass tube of larger inner diameter may directly come through from the arc discharge space.

The density of layer surrounding arc discharge space is denser and the optical thickness of the layer is also thicker as the inner diameter of glass tube is smaller. The absorption of emission from the arc discharge space by the layer increases and the line spectral intensity attenuates and at last the only continuous spectral distribution observes outside the glass tube as the inner diameter of glass tube is furthermore smaller. The mechanism of continuous spectral radiation observed in the smallest inner diameter of glass tube is supposed as follows. The clusters which absorb the emission from arc discharge space radiate the continuous spectrum within the longest limited wavelength depending on the size of cluster.

5. Conclusions

Using samples stretched a copper wire element in the capillary of glass tube, and in the region of current limiting level for the prearcing time of a few milli-seconds order, the formation of medium distribution in the arc discharging space was considered by the spectral radiation during arcing time. And the temperature of arc column was observed by two lines spectral intensities emitted from the copper atom in an arc column.

After the multi arcs ignite along the wire element at the start of arcing time, the single arc is formed by each arc burning back for the duration of quite short time.

The line spectral distribution was observed in the glass tube of larger inner diameter, the continuous spectral distribution was observed in glass tubes of the smallest diameter.

The process of distribution of arc space media of the element material in relatively short arcing time is supposed from the spectral observation as follows. Each arc is surrounded by the vapor and clusters of the element material in the duration of multi arc, multi arcs grow up into the single arc between the electrodes, the arc column is surrounded by the layer of copper vapor and clusters.

On the observation of line spectral distribution in the glass tube of larger inner diameter, spectral radiation of arc column directly comes through the glass tube because of the thin density of clusters in the layer. On the continuous spectral distribution in the smallest inner diameter, the spectral radiation of arc column is absorbed by the inside zone of optical dense layer and then the continuous radiation form the dense cluster zone in the layer comes out through the glass tube because of thick density of clusters in the layer.

The continuous radiation emitted by the inside zone of the layer of high temperature is absorbed the outside zone of the layer including copper and sodium clusters. The sodium may be supplied by the ablation of inside wall surface of Pyrex glass tube.

It was made certain that the thin membrane of copper adhered to the glass tube wall after experiment absorved selectively little line spectral radiation.

The line spectra of arc column directly come out through the glass tube, so that the temperature of arc column is obtained by the two line spectra of copper atom assuming the local area thermal equilibrium. The temperature of arc column changes from 4500K to 19000K.

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