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# Measurement of cathode surface temperature using the method of CCD imaging in arc discharge

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**Abstract** A two-wavelength pyrometry device using ordinary array CCD (charge coupled device) to collect the radiation data in the horizontal and vertical directions has been developed for measuring the cathode surface temperature during the arc discharge. Analyses of experimental results show that the device can make the measurement of the cathode surface temperature feasible. The cathode surface temperatures measured are lower than the melting point of tungsten (3653 K), and the arc current, cathode diameter, and the cathode length are the main influencing factors of the cathode surface temperature.

**Key words** Cathode surface temperature, Arc discharge, Charge coupled device，Two-wavelength pyrometry technique

**CLC numbers** O536, O539

## 1 Introduction

The cathode surface temperature of high-current arc is an important parameter for studying the mechanism of cathode erosion and cathode electron emission. And especially for numerical calculations of arc discharge, the cathode surface temperatures that are measured provide certain good boundary conditions. Hence, a measurement method of the cathode surface temperature has to be developed. During the arc discharge, both infrared radiation and the modulated photothermal effect can be used to measure the cathode surface temperature [1-5]. Although these methods do not disturb the arc discharge, the measurements are affected by the radiation of plasma, and accurate experimental results are difficult to obtain. A two-wavelength pyrometry technique has been developed [6,7]. This technique can solve the problem associated with the radiation from the arc plasma and does not perturb the arc. In this article, the experimental device consisting of the ordinary array CCD and the cathode surface temperature's measurement are described.

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## 2 Experimental device

The arrangement of the experimental device is shown in Fig. 1(a). The device mainly includes a DC-arc discharge system, an optical system, and a monitor. The optical system consists of a diaphragm, a lens, interference filters, an array CCD receiver, and a PC. A DC arc is struck between a water-cooled copper anode and a cylindrical rod tungsten cathode, and the arc length is about 5 mm. The cathode is cone-shaped (cone angle is about 60°) on one end termed as the cathode tip, and the other end is cooled by water. The total optical radiation from the cathode and the arc plasma is imaged on the CMOS chip of the CCD using a lens system, and the data are acquired using a PC. The CMOS chip of the array CCD is $795 \times 596$ pixels. One of the advantages of using an ordinary array CCD is that the radiation data in the horizontal and vertical directions can be obtained simultaneously. The distance between the cathode and the diaphragm is about 2.0 m, and the diaphragm is placed before the lens. The optical system is calibrated using a standard tungsten ribbon lamp.

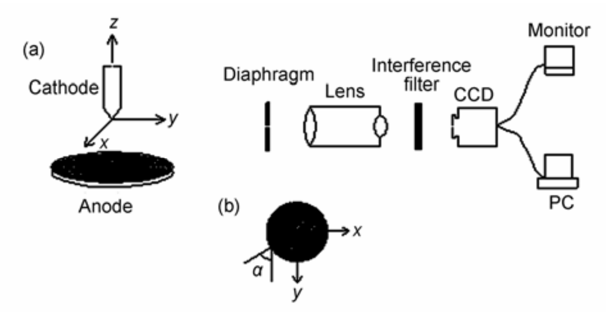


**Fig. 1** (a) Structure of the device. (b) Horizontal cross-section of the cathode at the $Z$ level of the scan.

## 3 Theory of two-wavelength pyrometry technique

The total radiation intensity $F_m(x, \alpha, \lambda, T)$, which is acquired using an array CCD, consists of the sum of the radiation intensity $F_p(x, \lambda)$ emitted by the arc plasma, the radiation intensity $F_e(x, \alpha, \lambda, T)$ emitted by the cathode at surface temperature $T$, and the radiation intensity $F_r(x, \alpha, \lambda, T)$ resulting from the plasma radiation reflected by the cathode , thus [6]

$$F_m(x,\alpha,\lambda,T)= \\ F_p(x,\lambda)+F_e(x,\alpha,\lambda,T)+F_r(x,\alpha,\lambda,T) \qquad (1)$$

where $\alpha$ is the angle between the line of sight (paralleled to $y$ axis) and the horizontal component of the normal to the cathode surface (Fig. 1(b)), $\lambda$ denotes the wavelength of the measured radiation, and $T$ the cathode surface temperature .

The horizontal scan of $F_m(x, \alpha, \lambda, T)$ is taken from the edge of the arc to the center of the cathode (Fig. 2 ). Moreover, $F_e(x, \alpha, \lambda, T)$ and $F_r(x, \alpha, \lambda, T)$ are equal to zero in the region characterized by $|x| > r_e$ where, $r_e$ is the cathode radius at the $z$ coordinate of the scan, so $F_p(|x| > r_e , \lambda)$ is equal to $F_m(|x| > r_e , \alpha, \lambda, T)$. If the plasma radiation is assumed to have cylindrical symmetry, the plasma emission coefficient $f(r)$ for $r > r_e$ can be calculated using the Abel integral equation [8]:

$$f(r) = -\frac{1}{\pi}\int_r^R \frac{F_P^{'}(|x| > r_e, \lambda)\mathrm{d}x}{(x^2 - r^2)^{1/2}} \qquad (2)$$

where $r$ is the radial position, $R$ the plasma radius, and $F_p^{'}(|x| > r_e, \lambda)$ the differential of $F_p$ with respect to $x$.

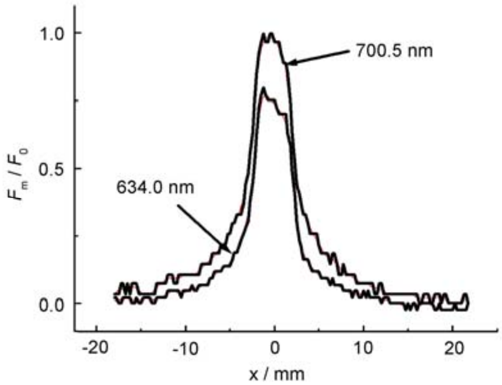


**Fig. 2** Radial profiles of the total radiation intensity $F_m/F_0$ for the wavelengths 634.0 nm and 700.5 nm at $z = 4.0$ mm. (Arc current is plasma 170 A, cathode diameter is 4.0 mm, argon gas flow is 5 L·min$^{-1}$, and $F_0$ is the maximum of the total radiation intensity).

$F_p(|x| \le r_e , \lambda)$ can be worked out using the plasma coefficient $f(r)$.[8] Hence, it is possible to eliminate $F_p(x,\lambda)$ from $F_m(x, \lambda)$ (Fig. 3). Fig. 3 shows the measurements at wavelengths 634.0 and 700.5 nm. The radiation intensity increases as the distance increases from the arc plasma to the edge of the cathode. The radiation intensity then slowly increases owing to a continuous increase in the radiation reflected by cathode surface when the radial distance increases from the edge to the center of the cathode. However, the radiation reflected by the cathode surface is difficult to measure.

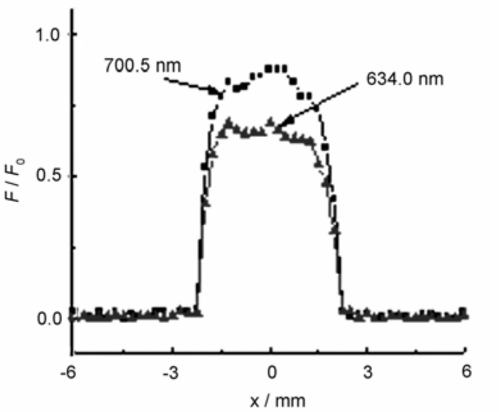


**Fig. 3** Radial profiles of the radiation intensity $F/F_0$ for the wavelengths 634.0 nm and 700. 5 nm, the subtracted arc plasma radiation intensity $F_p/F_0$ from the total radiation intensity $F_m/F_0$ at $z = 4.0$ mm (with the same conditions as in Fig. 2).

At the edge of the cathode ($\alpha \approx 90°$), the radiation reflected by the cathode surface tends to be zero and can be neglected [3]. Hence, $F_e(\lambda,T)$ is easily obtained from Eq. (1) at the end of the cathode. Moreover, the cathode surface temperature can be calculated from Eq.

(3) [6,9] :

$$\frac{F_e(\lambda_1,T)}{F_e(\lambda_2,T)}=\frac{\varepsilon(\lambda_1,T)}{\varepsilon(\lambda_2,T)}\left(\frac{\lambda_2}{\lambda_1}\right)^5\left(\frac{1-e^{c_2/\lambda_2 T}}{1-e^{c_2/\lambda_1 T}}\right) \quad (3)$$

where $\lambda_1$ and $\lambda_2$ are continuum wavelengths chosen for measurement, $c_2 = 1.4388\times10^{-2}$ m·K ,[6] $\varepsilon(\lambda_1, T)$ and $\varepsilon(\lambda_2 , T)$ are the hemispherical emissivity of the cathode at wavelengths $\lambda_1$ and $\lambda_2$ [10] , respectively.

## 4 Analysis of experimental results

In the experiment, the continuum wavelengths used to perform the cathode surface temperature measurement are 634.0 and 700.5 nm. Hence, the wavelengths of the interference filters are 634.0 and 700.5 nm, and their bandwidth is 1.0 nm. The cathode surface temperature is related to the arc current, cathode diameter, cathode length, and so on. In the following paragraph, the arc current, cathode diameter, and cathode length are discussed.

The measurements of the cathode surface temperature are made after the arc is ignited approximately thrice. As the array CCD is used as the receiver, the images of the cathode and the arc plasma at the wavelengths 634.0 and 700.5 nm are easily obtained within 30 seconds. It is found through analysis of the successive images that radiations from the cathode or the arc plasma hardly vary within 30 seconds.

When the arc current is larger, the quantity of heat transferred to the cathode is larger; therefore, the cathode surface temperature is higher than that operated with low arc current (Fig. 4). Moreover, the cathode surface temperature decreases as the axial distance from the cathode tip increases. However, the temperature of the cathode tip cannot be measured in the experiments, and the edges of the cathode tip cannot be identified well because the cathode tips often eroded and their shapes start to change as the experiments progress (Fig. 5). If the measurement is made away from the edge of the cathode, the experimental error of the cathode temperature can be as high as 1000 K [6].

The temperature of tungsten cathode operating with 3.0 mm diameter is higher than that operating with 4.0 mm diameter (Fig. 6). The change in the cathode length also affects the profiles of the cathode surface temperature (Fig. 7). The cathode surface temperature decreased more rapidly in case of short cathodes compared to that in case of long cathodes as the axial distance from the cathode tip increases. The reason is that heat transfers rapidly from the cathode tip to the water-cooled end of the cathode when the length of cathode is short. It should be pointed out that in the experiments, the measured cathode surface temperatures are all lower than the melting point of tungsten (3653 K).

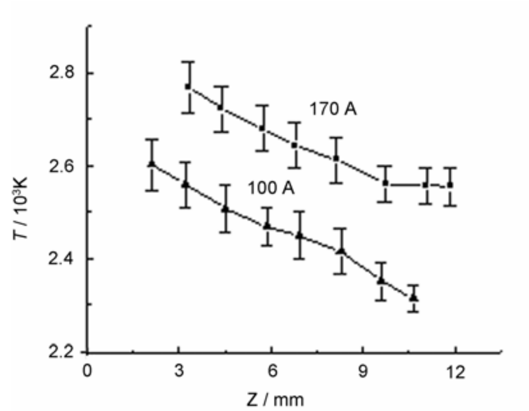


**Fig. 4** Axial cathode surface temperature profiles for different arc currents. (Length of cathode is 63.0 mm, cathode diameter is 4.0 mm, argon gas flow is 5 L·min$^{-1}$).

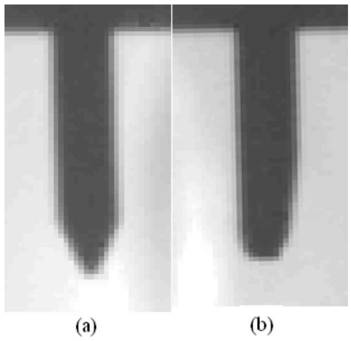


**Fig. 5** Pictures of cone-shaped cathodes: (a) A noneroded cathode, (b) An eroded cathode.

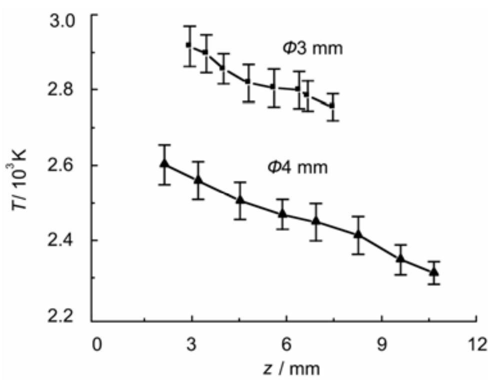


**Fig. 6** Axial cathode surface temperature profiles for different tungsten cathode diameters. Arc current is 100 A, cathode length is 63.0 mm, and argon gas flow is 5 L·min$^{-1}$.

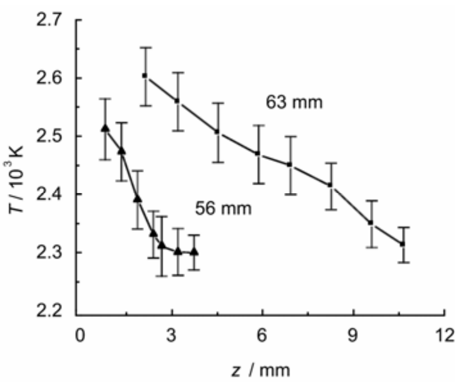


**Fig. 7** Axial cathode surface temperature profiles for different cathode lengths. Arc current is 100 A, cathode diameter is 4.0 mm, and argon gas flow is 5 L·min$^{-1}$.

## 5 Conclusions

From the above-mentioned analysis, the method using ordinary CCD to collect the radiation data can make the measurement of the cathode surface temperature feasible in the arc discharge. The cathode surface temperatures that are measured are under the melting point of tungsten, and the arc current, cathode diameter, and cathode length are the main factors that influence the cathode surface temperature.

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