Electrode temperature measurements of multi-phase AC arc by high-speed video camera

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Abstract. The multi-phase AC arc plasma has been applied in the glass melting technology as a promising heat source. The electrode erosion of the multi-phase arc is one of the most important issues to be solved. In the present work, the theory of the two-colour pyrometry by using the high-speed video camera with band-pass filters was applied to the electrode temperature measurements. First, the spectroscopic measurements of the electrode region in the multi-phase arc were conducted to select the appropriate wavelengths of band-pass filters. Then, the electrode temperatures of 2-phase, 6-phase, and 12-phase arcs were measured. The electrode tip temperature and the molten area were evaluated from the obtained 2-dimensional temperature distributions. Results indicated that the increase of the number of the phases leads to the lower tip temperature and the larger molten area. Observation of the multiple arcs further revealed the particular characteristics of the multi-phase arc, such as the periodical arc motion has important role on the electrode molten state.

1. Introduction
The glass industry is a large global industry that annually produces more than 100 million tons of glass products such as sheet glass, container glass, fiber glass, optical glass, and so on. Most glass has been produced by typical Siemens-type melter fired in air with heavy oil or natural gas as the fuel. This type of melter has been used for more than 140 years because of its good large-scale performance and continuous melting system. In the air-fuel fired furnace, the heat transfer from above burner flame to glass melt is so low that the conventional melting technology is energy intensive and time consuming, especially in the melting and the refining processes. With the rapid growth of glass usage and the increased energy and environment issues, it is crucial to develop a new glass melting technology to solve these problems.

An innovative in-flight glass melting technology with thermal plasmas was developed to solve above problems [1-3]. The granulated raw material with small diameter is dispersed in thermal plasmas and the powders contact fully with the plasma and/or burner flame. The high heat-transfer and temperatures of the plasma will melt the raw material quickly. In addition, the decomposed gas of carbonates is removed during the in-flight treatment to reduce the fining time considerably. Compared with the traditional glass production, the total vitrification time is evaluated only 2-3 h at the same productivity as the fuel-fired melter.

Arc plasmas as an energy source with high energy efficiency have been applied to the in-flight glass production. In particular, the multi-phase AC arc is one of the most suitable heat sources for the in-flight glass melting because it possesses many advantages such as high energy efficiency, large...
plasma volume (about 100 mm in diameter), low velocity (5-20 m/s) [4, 5]. In spite of the recent experimental works, which revealed the importance of the number of the phases on the discharge characteristics and the arc stability of the multi-phase arc, it remains to be explored. Electrode erosion is one of the considerable issues for the practical use of the multi-phase arc system in glass melting process.

Electrode temperature is important to understand erosion phenomena of the electrode material and the interactions between the arc and the electrodes. Two-colour pyrometry is a useful tool to measure the surface temperature of solid and/or liquid. Therefore, some experimental works have been reported to evaluate the electrode surface temperature of the DC [8] or AC arcs [9]. In the present work, the combination between the two-colour pyrometry and the high-speed camera observation was applied to investigate the dynamic behaviour of the molten electrode on the millisecond time scale. The purpose of the present study is to measure the electrode temperature by the high-speed camera and to investigate the influence of the number of the phases on the electrode temperature and the molten state in the multi-phase arc.

2. Experimental Procedure
2.1. Experimental setup
The schematic diagram of the experimental setup is shown in figure 1 (a). It consisted of 12 electrodes, arc chamber, and AC power supply. The electrodes were symmetrically arranged by the angle of 30 degree and were divided two layers, upper six electrodes and lower six electrodes. The electrodes were made of tungsten (98wt%) and thoria (2wt%) with diameter of 6 mm. City water was used to cool the electrodes at 3 slpm of water flow rate for each electrode and 99.99% argon was injected around electrodes to prevent them from oxidation at 5 slpm of gas flow rate. The arc chamber was made of stainless steel and cooled by water. 24 Sets of arc welding transformers with single-phase AC (DAIHEN B-300, Japan) were used to generate the multi-phase AC arc discharge. The more detail about the power supply for the generation of the multi-phase AC arc discharge was explained [4]. In the present work, arc current was adjusted at AC 100 A for each electrode.

Figure 1 (b) shows the cross-sectional view of the electrode tips for the multi-phase AC arc. The applied voltage between each electrode and the neutral point of the coil of the transformer can be calculated by the following equation:

\[ V_i^N = V_m^N \sin \left[ \frac{2\pi(i-1)}{12} \right], \quad (i = 1, 2 \ldots 12) \]  

where \( V_i^N \) indicates the applied non-load voltage for each electrode number \( i \) and \( V_m \) indicates the amplitude of the non-load voltage (about 220 V). The voltage was applied to only electrode No. 1 and No. 7 for the 2-phase arc discharge. In the case of the 12-phase arc discharge, the voltage was applied to electrode No. 1, 2…12.

2.2. Temperature measurements by high-speed video camera
According to the Wien’s approximation of Planck’s law, the spectrum of thermal radiation from a blackbody is used to determine the electrode temperature at the applied wavelengths. A real body that emits less thermal radiation than the blackbody has surface emissivity \( \varepsilon \) less than 1. Since the emissivity is unknown for many applications, the grey body assumption \( \varepsilon(\lambda_1) = \varepsilon(\lambda_2) \) is used where it is hypothesized that the surface emissivity is independent of wavelength.

\[ TR_{\lambda_1} = Ke(\lambda) d^2 \lambda_1^{-5} \left( e^{d^2/\lambda_1 T} - 1 \right)^{-1} \]

(2)

Based on these approximations, the electrode temperature \( T \) is obtained from the ratio of the radiation intensity,
where $K_2$ is the second radiation constant in Planck’s law which value is $1.439 \times 10^{-2}$ m·K, $TR_{\lambda_1}$ and $TR_{\lambda_2}$ are the thermal radiations emitted by the electrode at $\lambda_1$ and $\lambda_2$, respectively.

Spectroscopic measurements (iHR550, Horiba Jobin Yvon) were conducted to determine appropriate wavelengths for two-colour radiations. Electrode temperature of the multi-phase arc was then measured from the thermal radiation at the two wavelengths which determined by the spectroscopic results. High-speed video camera (FASTCAM SA-WTI, Photron) with the band-pass filter system was used to measure the radiation intensities as shown in figure 2. Frame rate and exposure time of the measurements were 10,000 fps and 20 $\mu$s, respectively. The voltage of each electrode was recorded at 1 MHz by an oscilloscope (Scope Corder DL 850, Yokogawa).
3. Results and Discussion

Figure 3 shows the emission spectrum of the multi-phase arc at electrode tip. Line emissions from argon and oxygen atoms were observed while continuum emission from the electrode surface was detected. From this spectrum, two wavelengths, 785 nm and 880 nm, were selected for the temperature measurements in order to avoid the direct plasma emission.

The surface temperature of the electrode for the multi-phase arc was measured with above selected wavelengths. Figure 4 shows the snapshot of the electrode obtained by the high-speed camera and the calculated temperature distribution of the electrode for the 12-phase arc. The temperature around the electrode tip was higher than the melting point of tungsten (3,695 K). The electrode tip temperature and the molten area were estimated from the obtained temperature distributions.

Figure 5 shows the time dependence of the electrode tip temperature for the 2-phase and the 12-phase AC arcs in a cycle (20 ms). Each plot corresponds to the averaged value more than three data. Two peaks of the tip temperature were found in both cases for the 2-phase and the 12-phase arcs. These peaks originated in the sinusoidal current waveform in AC cycle, resulting in the peak values of the heat transfer from the arc to the electrode. The temperature variation range of the 12-phase arc was smaller than that of the 2-phase arc. This could originate in the existence of the multiple arcs at the same time in the case of the 12-phase arc, while only single arc exists in the case of the 2-phase arc.

Molten area was evaluated from the obtained temperature distribution to characterize the molten state of the electrode surface quantitatively. Number of the pixels, in where the temperature was more than melting point, was counted and then converted into area. Figure 6 shows the time variation of the molten area for 2-phase and 12-phase AC arcs. The variation range of the molten area of the 12-phase arc was larger than that of the 2-phase arc. This result will be discussed in the following paragraph.
Figure 5. Time variation of the electrode tip temperature for the 2-phase and the 12-phase arcs in a cycle (20 ms).

Figure 6. Time variation of the molten surface area for the 2-phase and the 12-phase arcs in a cycle (20 ms).

Figure 7 shows the relationship between the number of the phases and the electrode tip temperature. An increase of the number of the phases leads to the decrease of the electrode tip temperature. Figure 8 shows the relationship between the number of the phases and the molten area. In contrast to the tip temperature, an increase of the number of the phases leads to the increase of the molten area. The molten area at anodic period was larger than that at cathodic period. This is because the total heat transfer from the arc to the electrode at anodic period was larger than that at cathodic period, resulting from the electron condensation.

In order to investigate the effects of the number of the phases on the tip temperature and the electrode molten state, the movement of the arc spot was considered. Figures 9 and 10 represent the snapshots of the high-speed video images without band-pass filters for the 2-phase arc and the 12-phase arc, respectively. The 2-phase arc spot only moves slightly, whereas the arc spot for the 12-phase arc moves from the right to the left and then returns to the right side. This periodic swinging motion would be attributed to the rotational electro-magnetic field of the multi-phase ac arc.

Because of the periodical motion of the arc spot, the molten state of the electrodes can be predicted as indicated in the figure 11, which shows the model images of the electrode cross sections. These model images imply the following characteristics of the molten state; (a) the molten surface area for the 12-phase arc is larger than that for the 2-phase arc and (b) the molten depth for the 2-phase arc is deeper than that for the 12-phase arc. Note that the molten volume of the electrodes for the 2-phase
and the 12-phase arcs were assumed to be almost the same because the total input powers for each electrode were adjusted to the same level.

![Figure 7](image1.png)  **Figure 7.** The relationship between the electrode tip temperature and the number of the phases.

![Figure 8](image2.png)  **Figure 8.** The relationship between the electrode molten surface area and the number of the phases.

The obtained experimental results can be explained by the above model. Wider area of the arc spot motion in the 12-phase arc leads to the larger molten surface area, resulting in the lower tip temperature. Wide and shallow molten region for the 12-phase arc compared with the 2-phase arc leads to the larger boundary area between the solid phase and the liquid phase inside the electrode, resulting in the rapid solidification of the molten electrode for the 12-phase arc. These characteristics of the electrode molten state would have important role on the electrode erosion of the multi-phase arc. Further experimental studies are needed to understand the electrode erosion mechanism of the multi-phase AC arc.

4. **Conclusions**

The temperature measurements system by using the high-speed video camera with the band-pass filters was established. From the surface temperature distributions of the electrodes, the time variation of the tip temperature and the molten area were obtained to investigate the effects of the number of the phases on the electrode molten state. Results indicated that the increase of the number of the phases leads to the decrease of the tip temperature and the increase of the molten surface area. These results were also explained by the periodical arc spot motion, resulting in the different molten state between the 2-phase arc and the multi-phase arc. The obtained results suggest that the particular characteristics of the multi-phase arc, such as arc motion, have the strong effects on the electrode erosion mechanism.

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Figure 9. The snapshots of the high-speed video images for the 2-phase arc at electrode region.

Figure 10. The snapshots of the high-speed video images for the 12-phase arc at electrode region.

Figure 11. Cross sectional images of the electrodes for the 2-phase and the 12-phase arcs.
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