Fluctuation phenomena in multi-phase AC arc for nanoparticles fabrication

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Abstract: Temperature measurements by the high-speed camera with the appropriate band-pass filters were performed to understand the fluctuation phenomena in a multi-phase AC arc. The measured temperature in most of arc region was higher than 1.0×10^4 K. The arc temperature fluctuated in the range from 0.8×10^4 to 1.1×10^4 K. The obtained results suggest the multi-phase AC arc has sufficient temperature for the evaporation of refractory materials.

Keywords: thermal plasmas, multi-phase AC arc, fluctuation phenomena

1. Introduction

Thermal plasmas have been widely applied to many fields because of the unique advantages, such as high temperature, high enthalpy to enhance reaction kinetics, rapid quenching capability to produce chemical non equilibrium materials, and selectivity of atmosphere in accordance with required chemical reaction. These advantages have brought advances in plasma chemistry and plasma processing.

Among various thermal plasma reactors, arc plasma as an energy source with high energy efficiency has been applied in welding, cutting, plasma spraying, steel making, fabrication of nanomaterials, and so on. Although most power sources for generating arc plasma are accomplished by DC power supply, it takes more cost in the apparatus for converting AC to DC [1, 2]. The existing single- or three-phase AC power supplies have a characteristic of intermittent discharge due to the polarity transition. This characteristic based on AC power supply limits the application of the arc plasma. To obtain more effective arc plasma reactor, a multi-phase AC power supply was developed and a stable 12-phase AC arc was successfully generated [3]. Compared with other thermal plasmas, the multi-phase AC arc possesses following advantages; high energy efficiency, large plasma volume, low gas velocity, easy scale-up, and low cost.

The multi-phase AC arc has been applied to an innovative in-flight glass melting technology because of the above-mentioned advantages [4-8]. Furthermore, this heat source is expected to be applied to nanomaterial fabrication processes due to its high productivity. However, fluctuation phenomena in the multi-phase AC arc have not been understood yet, although such arc fluctuation must be important to determine the characteristics of the products such as particle size distribution, yields of the desired materials.

The purpose of the present study is to establish the high-speed measurements method of temperature fluctuation using the high-speed camera with band-pass filters. Another purpose is to understand arc fluctuation in the multi-phase AC arc.

2. Experimental and Analysis

2.1 Experimental Setup

A schematic diagram of the experimental setup is shown in Fig. 1. It consisted of 6 electrodes, arc chamber, and AC power supply at 60Hz. Electrodes were made of tungsten (98wt%) and thoria (2wt%) with diameter of 6 mm. Six electrodes were symmetrically arranged by the angle of 60 degree as shown in Fig. 2. These electrodes were positioned at the angle of 5 degree with regard to the horizontal plane to enlarge the plasma volume. Because the melting points of tungsten oxides are lower than that of metal tungsten, 99.99% Ar was injected around the electrode at 5 L/min of gas flow rate to prevent them from the oxidation. As the multi-phase arc discharge was generated under the atmospheric air except of the above mentioned Ar, air is also the plasma forming gas.

Twelve sets of arc welding transformers with single-phase AC (DAIHEN B-300, Japan) were applied to generate the 6-phase AC arc discharge. The applied voltage between each electrode and the neutral point of

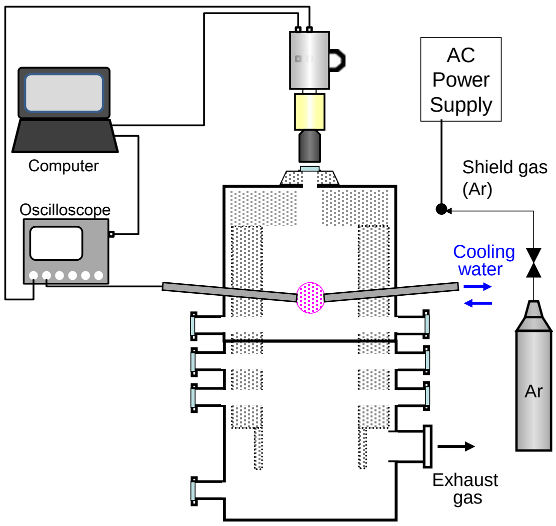

Fig. 1. Experimental setup of the multi-phase AC arc reactor with measurement apparatus.

the coil of the transformer can be calculated by the following equation:

$$V_i = V_m \sin\left[\omega t - \frac{2\pi(i-1)}{12}\right] \quad (i = 1,2,\ldots,12) \qquad (1)$$

where V_i^N indicates the applied non-load voltage for each electrode number i and V_m^N indicates the amplitude of the non-load voltage (about 220 V, AC 60Hz). The voltages were applied to 6 electrodes (No. 1, 3…11) for the 6-phase AC arc while voltages were applied to 12 electrodes (No1, 2, 3…12) for the 12-phase AC arc, as shown in Fig. 2. Arc current, shield gas flow, and electrode gap distance were changed as operating parameters. The number of the phases were also changed.

2.2. Conditions for temperature measurement

Measurement of excitation temperature of atomic Ar in the multi-phase AC arc was carried out by using the high-speed camera system (FASTCAM SA-5, Photron Ltd., Japan). An optical system (MSI-2, Photron Ltd., Japan) including the band-pass filters (Andover Optical Inc., USA) was combined with the high-speed camera, as shown in Fig. 3, to observe synchronized images for different wavelengths. Excitation temperature was then evaluated by atomic-to-atomic line-ratio method from the obtained intensities at different wavelengths. Typical frame rate and shutter speed of the measurements were $1.0\text{x}10^4$ fps and 14.5 μs, respectively. The voltage and current during arc operation were recorded at 1MHz by an oscilloscope (Scope Corder DL 850, Yokogawa, Japan) synchronized with the high-speed camera.

Spectroscopic measurements (iHR550, Horiba Jobin Yvon, Japan) were conducted to select the appropriate band-pass wavelengths. The conventional spectroscopic method was also used to evaluate the excitation temperature of atomic Ar in the multi-phase AC arc from the conventional Boltzmann plot method.

2.3. Sensitivity calibration of measurement system

Sensitivity calibration through the optical system for different wavelengths is required to obtain accurate intensity ratio in the case of camera measurements. Then, the free-burning arc was used as standard line emission source because the temperature distribution is already well-known and also can be measured by several methods [e.g. 9-11]. In the present work, the temperature distribution of free-burning arc was measured by Fowler-Milne method. Then the relationship between the measured temperature and the intensity ratio of line emissions from atomic Ar was used for the sensitivity calibration of the optical system. Finally the excitation temperature of atomic Ar in the multi-phase AC arc was determined by atomic-to-atomic line-ratio method.

3. Results and Discussion

Figure 4 shows the representative emission spectra at a distance of 2 mm from the electrode tip in the cathodic (a) and the anodic period (b). Excitation temperature of atomic Ar at cathodic and anodic periods were evaluated to be 1.2×10^4 K and 0.8×10^4 K, respectively. From these results, the wavelengths for the high-speed camera measurements were selected as 738.4 nm and 763.5 nm because these line emissions were well-separated from neighbour lines with relatively large difference of lower energy levels.

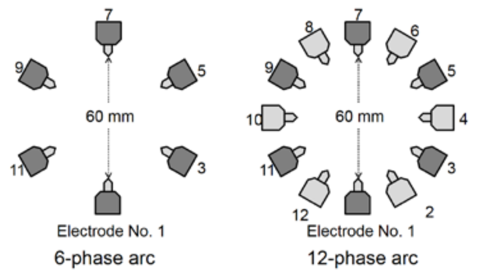

Fig. 2. Top view of the electrode region and corresponding number for each electrode.

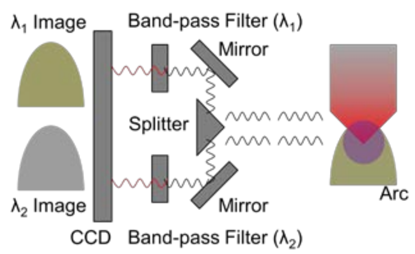

Fig. 3. Conceptual .diagram of high-speed camera system with band-pass filters.

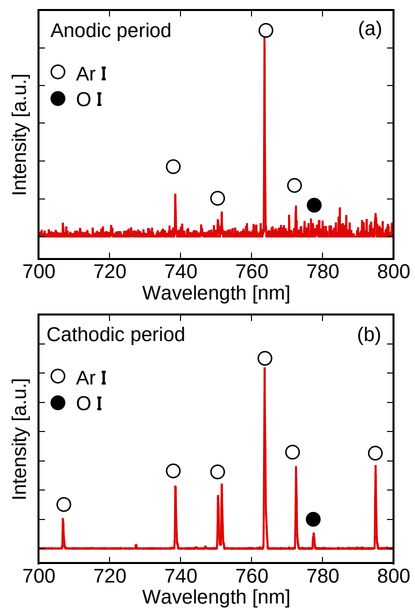

Fig. 4. Representative emission spectra at a distance of 2 mm from the electrode tip in anodic period (a) and cathodic period (b).

Figure 5 shows the high-speed snapshots of the 6-phase AC arc filtered at 738 nm in wavelength during one AC cycle of 16.7 ms. Maximum electric field was applied between the opposite electrodes. Two discharge patterns can be observed periodically. One is characterized with parallel long arcs across the central, as shown in 0.0 ms and 13.3 ms. Another pattern can be characterised by the existence of one main arc as shown in 6.7 ms and 15.0 ms. Although such characterization is important to understand the discharge characteristics of multi-phase AC arc, it is insufficient to understand how the arc fluctuation affect to the materials processing quantitatively. Therefore, the accurate measurement of temperature fluctuation is desired. Then, the temperature distribution was evaluated from these high-speed images filtered at 738 nm and 763 nm.

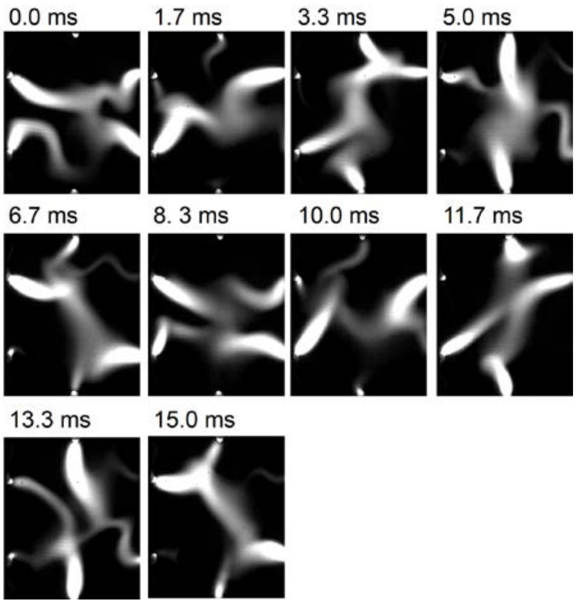

Fig. 5. High-speed camera images of multi-phase arc behaviour observed from upper window of the plasma reactor: Wavelength of band-pass filter was 738 nm for Ar atomic line emission.

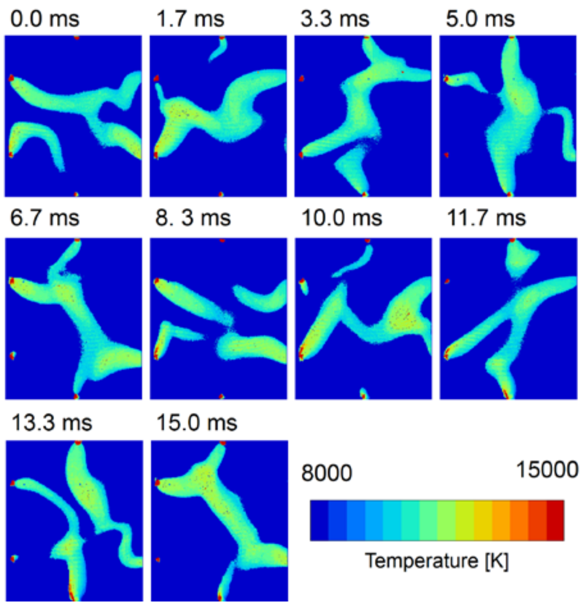

Fig. 6. Temperature distribution of the multi-phase AC arc during one AC period of 60 Hz measured by the high-speed camera observation.

Figure 6 shows the temperature distributions during one discharge cycle of 16.7 ms. Excitation temperature of atomic Ar in most of arc region was higher than 0.8×10^4 K. These results clearly indicate that the arc temperature is sufficient high to treat refractory metals and/or ceramics powders. Although it was difficult to measure the temperature distribution of multi-phase AC arc by the conventional method because of its unique and complicated motion and its asymmetric configuration, the temperature fluctuation during an AC cycle was successfully observed by the high-speed camera system with band-pass filters.

The temperature fluctuation at fixed position was analysed from the obtained temperature distributions. The fluctuation of excitation temperature at a distance of 2 mm from the tip of No. 1 electrode is shown in Fig. 7 (a) and the synchronized voltage waveform is shown in Fig. 7 (b). No. 1 electrode was in at the anodic period at the first half period, while the second half period corresponds to the cathodic period. Two peaks of the excitation temperature were found during one AC cycle of 60Hz. These two peaks were originated in the peaks of the sinusoidal current waveform, resulting in the peak values of the current density in the arc region. Results also indicated that the maximum temperature during the cathodic period was higher than that during the anodic period. This can be explained by the different current density in the arc. Arc near the electrode at the cathodic period was more constricted than that at the anodic period. Therefore, higher Joule heating at the cathodic period leads to higher arc temperature.

The conventional spectroscopic method can provide accurate temperature although the time-resolution of the conventional method is insufficient to observe the arc fluctuation. Therefore, the time-averaged temperature estimated from the present method and the temperature measured by the conventional spectroscopic method were compared to validate the accuracy of the present method. Figure 8 shows the comparison of the time-averaged temperature estimated from the present method and the temperature measured by the conventional spectroscopic method. Here, the temperature measured by the present method at the anodic period was averaged from 3.5 to 7.5 ms, which range was determined from the exposure time of 4 ms in the conventional method. On the other hand, the temperature at at the cathodic period was averaged from 11.8 to 15.8 ms. This comparison shown in Fig. 8

indicated that the time-averaged temperature estimated from the present method showed well agreement with the conventional method.

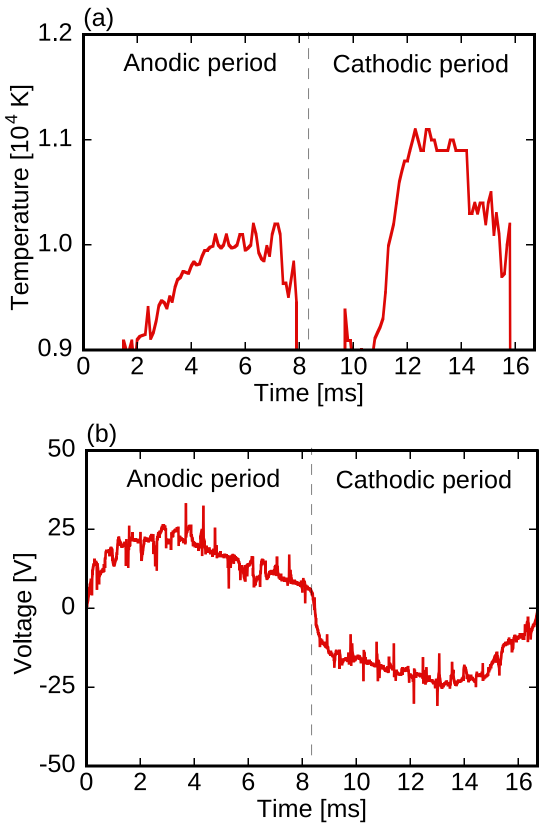

Fig. 7. Time transient of excitation temperature of argon atom at the electrode region with 2 mm from the electrode tip (a) and synchronized voltage waveform (b).

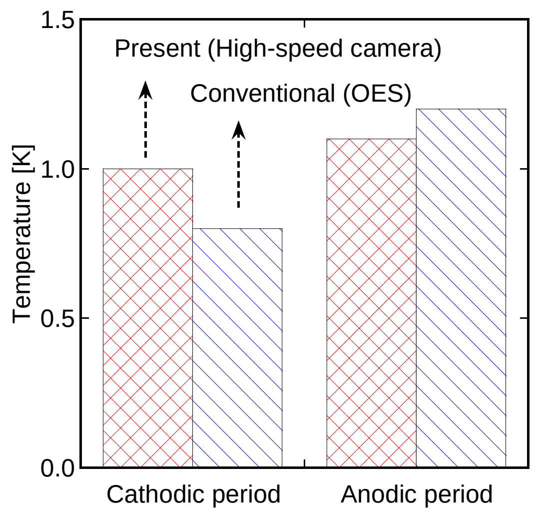

Fig. 8. Comparison between measured temperature by the present method and the conventional spectroscopic method.

In the present paper, the high-speed camera observations with the appropriate band-pass filters were performed to measure the temperature fluctuation in the multi-phase AC arc. In the nanoparticles fabrication processes, to control the fluctuation of temperature and precursor concentration is of great importance to control the nanoparticles characteristics. To correlate between the fluctuation phenomena and the nanoparticles characteristics is currently under investigation.

4. Conclusion

Temperature measurements by the high-speed camera with the appropriate band-pass filters were performed to understand the fluctuation phenomena in the multi-phase AC arc. The results indicated that the excitation temperature of atomic Ar was around 1.0×10^4 K. Thus the arc temperature in the multi-phase AC arc is sufficient high to treat the refractory metals and/or ceramics powders for the nanoparticles fabrication processes. Measured temperature by the present method showed similar trend with the measured temperature by conventional spectroscopic method. The present method will enable to understand the fluctuation phenomena in the multi-phase AC arc and their influence on the nanoparticles fabrication processes.

5. References

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