Investigation of temperature characteristics of multiphase AC arc by high-speed visualization

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Abstract

The objective of the present study is to understand fluctuation phenomena in a multiphase AC arc as a heat source for material processing based on the high-speed visualization technique of the temperature field. The multiphase AC arc is one of the most attractive thermal plasmas which possess extremely high temperature, high chemical reactivity, rapid quenching capability, and selectivity of the reaction atmosphere in accordance with required chemical reaction. In particular, the multiphase AC arc has a strong advantage on higher energy efficiency compared with other thermal plasmas. Therefore, this heat source has been applied to innovative material processing such as in-flight glass melting. However, the temporal and spatial characteristics of the multiphase AC arc have not been clarified although these are essential to control the characteristics of the products such as particle size distribution, yields of the desired materials. The high-speed visualization of the temperature field of the multiphase AC arc was conducted at 1×10^4 fps as typical framerate to observe the dynamic behavior of the multiphase AC arc in millisecond time scale. An optical system including the band-pass filters was combined with the high-speed camera to observe particular line emissions from atomic argon with negligible emissions from thermal plasma. The obtained experimental results indicated that the temperature of the multiphase AC arc was around 1.0×10^4 K. The arc temperature fluctuated in the range from 0.6×10^4 to 1.3×10^4 K. Consequently, the arc temperature in the multiphase AC arc is sufficiently high to treat the refractory metals and/or ceramics powders. Furthermore, the obtained temperature was well-validated by the conventional spectroscopic method with high accuracy.

Keywords : Thermal plasma, High-speed imaging, Temperature measurement, Arc fluctuation

1. Introduction

Thermal plasmas have been widely applied to many fields because of their 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 reactions. These advantages have brought advances in plasma chemistry and plasma processing (Heberlein and Murphy, 2008; Shigeta and Murphy, 2011).

Among various thermal plasmas reactors, arc plasma as an energy source with high energy efficiency has been utilized in arc welding, plasma arc cutting, plasma spraying, and nanoparticle fabrications. In particular, an innovative multiphase AC arc is one of the most attractive thermal plasmas due to its advantages such as high energy efficiency (Tanaka et al., 2011), large plasma volume, low gas velocity, and low cost compared with other thermal plasmas. Therefore, the multiphase AC arc has been applied to an innovative material processing such as in-flight glass melting technology (Watanabe et al., 2010) and nanomaterial fabrication processes. However, temperature field and its fluctuation characteristics in the multiphase AC arc have not been understood because of the difficulties of temperature measurement in the multiphase AC arc. These difficulties originate from the fluctuation characteristics of the multiphase AC arc in millisecond time scale. In addition, the asymmetric spatial properties of the multiphase AC arc also cause the difficulty of measurement, although the understanding the temporal and spatial characteristics of temperature field in the multiphase AC arc is essential to apply this heat source to material processing.

Temperature measurements of thermal plasmas have been intensively developed. Conventionally, optical spectroscopic techniques were widely used to measure the temperature distribution of thermal plasmas. From the spectroscopic data, the plasma temperature can be determined by several different methods, such as the atomic or ionic line intensities or intensity ratios of two spectral lines, and the ratios of line-to-continuum intensity. Among these methods, the Fowler-Milne method and its modified method have been widely used due to their precision (Fowler and Milne, 1923; Murphy, 1994; Ma et al., 2008) while the Boltzmann plot method has also been used due to its convenience (Hiraoka et al., 1997; Shah et al., 2015).

Spatially resolved profiles of emission intensities from atomic or ionic species should be captured to obtain the spatial distributions of temperature in thermal plasmas. The point-to-point scanning technique (Fowler and Milne, 1923; Murphy, 1994; Ma et al., 2008; Hiraoka et al., 1997; Shah et al., 2015) was one of the most common-used techniques to obtain the spatially resolved information of plasma temperatures. However, the only steady state temperature fields of thermal plasmas can be measured by this technique because of the requirement of long acquisition time to complete the scanning of the whole plasma region. Then, the conventional spectroscopic measurement had been extended to obtain one-dimensional temperature profiles simultaneously by means of two-dimensional CCD. One dimension of CCD was utilized to resolve the spectral information, while another dimension corresponded to the spatial information. Temperature distributions in radial or axial direction were reported (Semenov et al., 2001), although these obtained information was not sufficient to understand the temperature fluctuation of thermal plasmas. In recent, the imaging technique based on high-speed camera observation with imaging monochromators or appropriate band-pass filters has been developed. Temperature distribution of free-burning arc during tungsten-inert gas arc welding process was successfully visualized (Nakanishi et al., 2013; Bachmann et al., 2013).

The purpose of the present work is to understand the fluctuation characteristics of the multiphase AC arc. Above mentioned imaging technique with high-speed camera was adopted to visualize fluctuated and complicated temperature field of the multiphase AC arc. The effect of ambient pressure on the temperature characteristics was discussed because the pressure is one of the most important parameter to control the plasma temperature field.

2. Experiments

2.1 Experimental setup

A schematic illustration of the multiphase AC arc is shown in Fig. 1. It consisted of multi electrodes, an arc chamber, vacuum pump, and AC power supply at 60Hz. The arc chamber was filled with argon at different pressures. The multiphase AC arc was stably generated among multi-electrodes. These electrodes with a diameter of 6 mm were made of tungsten (98wt%) and transition metal oxide (2wt%). Thorium oxide was doped into tungsten to reduce the effective work function to generate a stable thermionic emission. Tap-water was used to cool the electrodes at a water flow rate for each electrode. The electrodes were symmetrically arranged at angles of 60 deg. More details about the equipment of the multiphase AC arc including power supply are available in our previous reports (Watanabe et al., 2010). Typical operating conditions are as follows; arc current: 80 A, the diameter among the electrode region: 100 mm, the number of the phases: 6 phase, gas flow rate around the electrode region: 3 L/min for each electrode. Ambient pressure in arc chamber was changed from 40 to 120 kPa because the pressure is one of the most important parameters which have strong influences on the temperature field in thermal plasma.

Fig. 1 Cross-sectional side view of multiphase AC arc reactor (a) and top view of electrode region (b).

2.2 Measurement system

Visualization of temperature field in the multiphase AC arc was carried out. A high-speed camera (FASTCAM SA-5, Photron Ltd., Japan) was used to observe the fluctuated temperature field in milliseconds time scale. Conventionally, to observe the particular emission from thermal plasmas was difficult because many radiations based on different emission mechanisms exist around thermal plasma region. These emissions under optically thin condition include the followings. First one is the line emission due to bound-bound transition of atomic and/or ionic species in the plasma. Second, the continuum emissions exist due to free-bound and free-free transition based on the recombination of the free electron and ions. In addition, other continuum emissions also exist due to thermal radiation from solid and liquid surface such as electrodes or reactor walls. To separate the particular emission from others, an optical system (MSI-2, Photron Ltd., Japan) including the band-pass filters was combined with the high-speed camera as shown in Fig. 2. Two synchronized images of the particular species at two different wavelengths were visualized to measure the temperature field. Typical frame rate and shutter speed were 1.0×10^4 fps and $14.5 \mu\text{s}$, respectively.

Sensitivity calibration though the optical system for different wavelengths is required to obtain accurate intensity ratio in the case of camera measurements. The free-burning arc was used as standard line emission source because the temperature distribution is already well-known. 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 the line emissions from atomic argon was used for the sensitivity calibration of the whole optical system. Finally, excitation temperature of atomic argon in the multiphase AC arc was determined by Boltzmann plot method.

One of the most important parts of visualization of the accurate temperature distribution is to select appropriate emissions from plasma gases. Spectroscopic measurements (iHR 550, Horiba Jobin Yvon, Japan) were conducted to select the appropriate transmission wavelengths of the band-pass filters for the emissions from atomic argon.

Fig. 2 Conceptual illustration of measurement system of high-speed video camera with appropriate band-pass filters.

3. Results and Discussion

3.1 Selection of appropriate band-pass filters

To utilize appropriate band-pass filters is most important to measure accurate temperature of thermal plasmas, therefore, the spectroscopic measurements of the multiphase AC arc were conducted to select the appropriate transmission wavelengths of filters. Figure 3 shows representative emission spectrum of the multiphase AC arc. Line emissions from atomic argon were observed.

Criteria to select the wavelengths for the separation of the particular emissions from others is as follows. First, the isolated emission from other line emissions should be selected. Because the wavelengths resolution of the band-pass filter is wider than the conventional spectroscopic method, to select the separated wavelengths is important. Second, the energy difference between upper energy states corresponding to the two different emissions should be carefully considered. Only two different wavelengths can be selected to measure the temperature in this work. The energy difference should be larger otherwise the determined temperature includes large error. In addition, the emissions with negligible self-absorption should be selected. Some emissions which have high self-absorption efficiency should be avoided otherwise the accurate intensity ratio cannot be obtained. In the present work, two appropriate wavelengths of line emissions from atomic argon at 675 ± 5.0 and 794 ± 5.0 nm were finally determined on the basis of the above mentioned criteria and the obtained emission spectrum.

Fig. 3 Representative emission spectrum of the multiphase AC arc under atmospheric pressure.

3.2 Visualized temperature distribution in multiphase AC arc

Representative excitation temperature distributions of the 6 phase AC arc at 80 kPa for AC half-cycle and the corresponding high-speed snapshots filtered at 794 nm are shown in Fig. 4. The numbers indicated in the high-speed snapshots correspond to the electrode number as shown in Fig. 4(a). Electrodes No. 1 and 2 are in anodic period at 0.0 ms, while the electrode No. 4 and 5 are in the cathodic period at the same time. The obtained excitation temperature distributions indicated that the excitation temperature of atomic argon in the multiphase AC arc fluctuated in the range from 6000 K to 13000 K as shown in Fig. 4(b). The excitation temperature near the electrode was more than 10000 K, while the excitation temperature at the center region was about 6000-7000 K.

The observed excitation temperature can be considered as the gas temperature, translational heavy particle temperature when the Local Thermal Equilibrium can be assumed. Basically, two important conditions should be fulfilled. First one is that the collisional excitation is predominant. This can be generally assumed for most of arc region in a high-current arc discharge. Second one is that the energy exchange between the electron and heavy particles should be sufficiently frequent as shown in the following equation (i.e. H. R. Griem, 1964).

$$T_e - T_g / T_e = \left(M_g / 4m_e \right) \left(\lambda_e eE \right)^2 / \left(2/3 k T_e \right)^2 \ll 1 \quad (1)$$

where T_e and T_g are electron temperature and heavy particle temperature. M_e and m_e are the mass of electron and heavy particle. λ_e is the mean free path of electron and E is the electric field strength, k is the Boltzmann constant. Estimated value of left hand term for temperature range from 6000 to 15000 K was on the order from 10^{-4} to 10^{-5} . Therefore, the

Fig. 4 High-speed snapshots of the multiphase AC arc at 80 kPa during half AC cycle (a) and corresponding temperature distributions (b).

measured argon excitation temperature can be treated as the gas temperature in the most region of the multiphase AC arc, except some specific region with steep temperature gradient such as the very close to the electrode. From here, the measured temperature will be written as the “arc temperature”. Above results and this suggestion revealed that the measured arc temperature is sufficiently high to melt and evaporate refractory metals or ceramics in thermal plasma processing for nanoparticles fabrication and in-flight melting treatment, and waste treatment.

Representative temperature distributions and the corresponding high-speed snapshots of the multiphase AC arc at different ambient pressures are shown in Fig. 5. Results show that an increase of the ambient pressure leads to higher arc temperature. The highest temperature at 120 kPa was about 13000 K, while that at 40 kPa was around 11000 K. This can be explained by the different arc current density. As shown in Fig. 5, higher pressure leads to highly constricted arc, resulting in the higher arc current density. Moreover, the result indicates that the arc temperature around the center region at 40 kPa of the pressure is more than 6000 K, therefore, the arc temperature even at the lower pressure is sufficiently high to be utilized in various thermal plasma processing.

3.3 Temperature fluctuation and its validation

Temperature fluctuation at fixed position was analyzed from the obtained temperature distributions. Temperature fluctuation at a distance of 2 mm from the tip of the electrode No.6 under the pressure of 80 kPa is shown in Fig. 6 (a) and the synchronized arc current waveform is shown in Fig. 6 (b). The electrode No. 6 was in anodic period at the first half period, while the second half period corresponds to the cathodic period. Two peaks of the arc temperature were found during one AC cycle of 60Hz. These two peaks originated in the peak values of sinusoidal current waveform, resulting in the peak values of 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. This fact is owing to the basically smaller size of cathode spot than anode spot. Smaller cathode spot leads to stronger Lorentz force acting on near cathode arc due to higher current density, resulting in more constricted arc formation than anodic arc (Heberlein et al., 2010). 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 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 7 shows the comparison of the time-averaged temperature estimated from the present method and the temperature measured by the conventional method. Here, the temperature measured at the anodic period was averaged from 2.0 to 6.0 ms, which range was determined from the exposure time of 4 ms in the conventional method. On the other hand, the temperature at the cathodic period was averaged from 10.0 to 14.0 ms. This comparison shown in Fig. 7 indicated that the time-averaged temperature estimated from the present method showed good agreement with the conventional method.

Fig. 5 High-speed snapshots of the multiphase AC arc at different pressures (a) and corresponding temperature distributions (b).

Fig. 6 Time transient of excitation temperature of argon atom at the electrode region with 2 mm from the electrode tip (a) and corresponding arc current waveform (b).

Fig. 7 Comparison between the measured temperature by the present method and the conventional spectroscopic method. Temperature from present method was averaged for 4 ms. Temperature from conventional method was obtained at exposure time of 4 ms.

4. Conclusion

The high-speed technique with appropriate band-pass filters was successfully applied to visualize the fluctuated and complicated temperature field of the multiphase AC arc. Excitation temperature of atomic argon was measured on the basis of the Boltzmann plot method with two synchronized arc images at two different wavelengths. Measured excitation temperature fluctuated from 6000 to 13000 K while these excitation temperatures can be considered as gas temperature at most of the multiphase AC arc region. The arc temperature at the center region of the multiphase AC arc was more than 6000 K, therefore, the refractory metals or ceramics can be completely treated in the multiphase AC arc. Understanding of the fluctuation phenomena in the multiphase AC arc enables us to utilize this high temperature heat source for various materials processing at high productivity compared with other thermal plasmas.

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