Effects of working pressure on temperature characteristics in multiphase AC arc

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Received: 7 March 2018; Revised: 24 May 2018; Accepted: 25 June 2018

Abstract
Temperature characteristics of a multiphase AC arc in various working pressures were investigated by an innovative observation system consisting of a high-speed video camera and band-pass filters. Thermal plasmas have been widely applied to many industrial fields because of their unique advantages such as high temperature, high enthalpy, and rapid quenching capability. In particular, the multiphase AC arc is advantageous in terms of large plasma volume and high energy efficiency. Therefore, this heat source has been applied to innovative material processing such as in-flight glass melting, and functional nanoparticles fabrication. However, the temperature field and its fluctuation characteristics in the multiphase AC arc have not been understood because of the difficulties of temperature measurement due to their rapid fluctuation in millisecond timescale as well as the axisymmetric spatial characteristics. To understand and control the fluctuation phenomena is important to realize this method as industrial technology. Temperature measurement system using a high-speed camera was constructed to visualize the temperature fields of the multiphase AC arc. The fluctuations in the two-dimensional intensity distributions of particular line emissions from atomic argon were successfully observed. By analyzing these images using the Boltzmann plot method, the temperature distribution was estimated. The experimental results indicated that the arc temperature fluctuated in the range from 6,000 to 12,000 K. Higher temperature, smaller arc existence area, and decrease in the diameter of the arc were observed with an increase of working pressure. The arc temperature in the multiphase AC arc is sufficiently high to treat the refractory metals and ceramics powders at high processing rate.

Keywords: Thermal plasmas, High-speed observation, Temperature distribution measurements, Arc discharges

1. Introduction
Thermal plasmas have been widely applied to many fields. Features such as high temperature, high enthalpy to enhance reaction kinetics, rapid quenching capability to synthesize chemically non-equilibrium materials, and selectivity of reaction atmosphere in accordance with required chemical reactions have enabled innovative industrial applications. There are several methods for generating thermal plasmas. DC arc has been widely used as a technique of welding, cutting and plasma spraying with simple equipment and high controllability. Inductively coupled plasma using radio frequency has been used for synthesizing functional nanoparticles utilizing features of stable plasma and less contamination. Many studies on applied techniques using these thermal plasmas have been addressed. Studies on nanoparticle synthesis (Shiogeta and Murphy, 2011; Kodama et al., 2014), surface modification (Maruyama et al., 2016), and waste treatment (Heberlein and Murphy, 2008; Li et al., 2013) were reported.

DC arc discharge is an effective method to generate thermal plasma, although the high temperature volume is limited. Expansion of the high temperature region is required to realize inexpensive material processing at high productivity. Therefore, a multiphase AC arc was proposed to solve this issue. The multiphase AC arc is expected to be a promising
heat source for mass production of functional materials because it possesses many advantages such as high energy efficiency, large plasma volume, easy to scale-up, and low equipment cost.

Research results with conventional 3-phase arc by high-speed camera were reported for arc behavior (Rehmet et al., 2013). Three-dimensional modeling of heat and mass transfer on 3-phase arc torch were reported (Takali et al., 2016). However, the researches about characteristics in 12-phase AC arc are limited to the in-flight particle behavior for glass melting (Yao et al., 2008; Tanaka et al., 2011a; Liu et al., 2012).

The multiphase AC arc has some issues to be solved such as arc instability and arc fluctuations in spite of a number of experimental efforts. Fundamental phenomena in the multiphase AC arc such as electrode erosion, arc behavior, and temperature fluctuation must be investigated to realize this method as industrial technology. Recent studies using a high-speed video camera revealed the arc behavior (Tanaka et al., 2011b) and the electrode phenomena (Tanaka et al., 2013a; Tanaka et al., 2013b; Watanabe et al., 2014) of the multiphase AC arc have been revealed. Two-dimensional temperature measurement method using a high-speed video camera and band-pass filters has been developed (Tanaka et al., 2017). Understanding the temperature characteristics is significantly important in the nanoparticle process and the material synthesis. To clarify the influence of various process parameters on the temperature characteristics is strongly required to achieve the practical use of the multiphase AC arc in industry. In particular, the working pressure of the multiphase AC arc is one of the most important parameters to control the fluctuation characteristics although its effect has not been understood yet.

The purpose of this study is to clarify the effects of working pressure on temperature characteristics in the multiphase AC arc. The observation system consisting of the high-speed video camera and band-pass filters are utilized to investigate temperature characteristics.

2. Experiments
2.1 Experimental apparatus

A schematic diagram of the multiphase AC arc is shown in Fig. 1. It consists of arc chamber, 12 electrodes installed from side wall, and 12 AC power supplies. Since the arc chamber can be evacuated, experiments under various gas atmospheres are possible. The electrodes are divided into 2 layers consisting of upper and lower 6 electrodes. The upper electrodes are positioned on the horizontal direction, while lower electrodes are at an angle of 30 deg with regard to the horizontal plane. The 12 electrodes are symmetrically arranged by the angle of 30 deg to enlarge the plasma area. The distance between the facing electrodes is about 100 mm. Each AC power supply is connected to each electrode. The phase of the AC power supply is set to shift by 30 deg between adjacent electrodes. For example, with respect to the phase of electrode No. 1, No. 7 is delayed by 30 deg and No. 2 is delayed by 60 deg. Therefore, the phase difference between the facing electrodes is 180 deg, and the maximum voltage is supplied. All of the electrodes have a mechanism to move in the front and rear direction in order to start the discharge and adjust the distance between the electrodes. Gas supply piping and circulating water piping for cooling are connected to the respective electrodes.

![Fig. 1 Overall view of multiphase AC arc generator (a) and top view of placement of electrodes (b).]
The procedure of the discharge ignition is explained. First of all, the chamber was evacuated to about several Pascals. Argon gas was injected around electrodes at 3 L/min of gas flow rate. The working pressure of arc chamber was set at 40, 80 and 120 kPa by the pressure control valve. Electric power was supplied to ignite arc discharge when the pressure adjustment was completed. The driving frequency of AC was 60Hz. Arc current for each electrode was fixed at 100 A.

The observation system consisting of the high-speed video camera and band-pass filters is placed on top of the chamber. All electrodes and arc can be observed through quartz window. The observation timing was controlled to be synchronized with the trigger signal from the oscilloscope connected to the AC power supply.

2.2 Measurement system and principle

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 is difficult because many radiations based on different emission mechanisms exist around thermal plasma region. These emissions include the line emissions due to bound-bound transition of atomic and/or ionic species in the plasma, continuum emissions due to free-bound and free-free transition based on the recombination of the free electron and ions, and continuum emissions due to thermal radiation from solid and liquid surface such as electrodes or reactor walls in the case with optically thin condition. 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. The emissions from the arc are split into two light paths by the splitter. Two-dimensional emission intensity distributions at each wavelength can be observed on the CCD by using the band-pass filters which transmit different wavelengths. The band-pass filters of 675 ± 5 nm and 794 ± 5 nm which include line emissions from atomic argon at 675.2834 nm and 794.8176 nm respectively are used (Tanaka et al., 2017). The continuum emission on this measurement was considered as negligible. Typical frame rate and shutter speed were 1.0×10^4 fps and 14.5 μs, respectively.

![Fig. 2 Schematic diagram of observation system with high-speed camera and band-pass filters.](image)

The temperature measurement was conducted on the basis of Boltzmann plot method because the Boltzmann distribution is assumed to be satisfied in the most region of arc discharge. The obtained emission intensity can be expressed as:

\[
I_{pq} = \frac{A_{pq}g_p}{\lambda} \cdot \frac{hc\bar{n}(T)}{4\pi Z(T)} \cdot \exp\left(-\frac{E_p}{k_BT}\right)
\]

where \(\lambda\) is a selected wavelength through band-pass filter, \(I_{pq}\) is an emission intensity, \(n\) is a number density, and \(T\) is an excitation temperature.

From Eq. (1), the ratio of emission intensities at different wavelengths can be expressed as:
The intensity ratio can be expressed as a function of temperature $T$ as:

$$\ln \left( \frac{I_{pq}}{I_{p'q'}} \right) \cdot \frac{A_{pq}g_p\lambda_{pq}}{A_{p'q'}g_{p'}\lambda_{p'q'}} = -\frac{1}{T} \cdot \frac{E_{p'}}{k_B} \cdot \frac{E_p}{k_B}.$$  \hspace{1cm} (3)

The temperature can be calculated from the slope of the graph by plotting the term of energy and the term of intensity ratio. The basic principle of the method, corresponding to equation (1) is shown in Fig. 3 (a).

Two-dimensional temperature distribution was obtained by calculating the temperature for each pixel of CCD as shown in Fig. 3 (b). Fluctuations in the temperature distribution in the AC cycle were clarified by arranging these temperature distribution images in order.

3. Results and discussion

Figure 4 shows representative snapshots of high-speed video camera (a) and excitation temperature distribution calculated by Boltzmann plot method (b) of the 12-phase AC arc at the working pressure of 40 kPa. Counter-clockwise arc motion is clearly observed in the snapshots of high-speed camera.

Arc swing motion is observed by focusing on the discharge at an arbitrary electrode. Arc discharge starts in the direction of the arc from the adjacent electrode advanced in AC phase, and gradually swings toward the opposite electrode. This swing is affected by the Lorentz force from the nearby arc.
The temperature has a range of approximately 6,000 to 9,000 K during the anodic period and 6,000 to 12,000 K during the cathodic period from the temperature distribution images. Arc in the cathodic period is more constricted than that in the anodic period. The higher current density leads to higher temperature in the cathodic period.

Fig. 4  Representative snapshots (a) and temperature distribution (b) of the 12-phase AC arc at 40 kPa. Electrodes during anodic period and cathodic period are shown with the solid (yellow) and dashed (red).

Fig. 5  Representative snapshots (a) and temperature distribution (b) of the 12-phase AC arc at 80 kPa.
near the electrode is particularly high, approximately 13,000 K. The arc behavior and the temperature fluctuation in one AC cycle were observed.

The observed excitation temperature can be considered as the gas 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. This is assumed to be satisfied at observed excitation temperature range of 6,000 to 12,000 K. The local thermal equilibrium is almost established at the working pressure above 40 kPa (Gravellet et al., 1989). Therefore, the 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 (Tanaka et al., 2013b).

Representative snapshots (a) and temperature distribution (b) of the 12-phase AC arc at 80 kPa and 120 kPa are shown as Fig. 5 and Fig. 6 respectively. The influence of working pressure on the behavior of the arc and temperature is revealed from Figs. 4-6. Decrease in the diameter of the arc is observed from the snapshots of the high-speed camera as the pressure increases. Higher temperature is also observed from the images of temperature distribution.

Arc area was investigated to clarify the influence of the working pressure in the arc discharge. The arc area was defined as the proportion of the pixels where the arc is present from the snapshot of the high-speed camera. Figure 7 shows time variations of arc area in different pressures. Arc area decreases with an increase of pressure. Figure 8 shows contour maps of the arc existence probability. The existence probability was defined as the ratio of the time during which the arc existed to total time period of AC cycle. Therefore, "1" means that the arc always exists and "0" does not exist at all. These images were constructed by superimposing the distribution of arc existing for one AC period. Uniform existence probability is obtained at lower pressure. In contrast, region where the arc exists at high probability in the central part is found at 120 kPa.

In order to clarify the reason for the different existence probabilities of the arc and the temperature in different pressures, the arc near the electrode was focused. The difference of arc diameter at different pressures is clearly observed as shown in Fig. 9 (a), where the representative arc images in the cathodic period is shown. The Pressure dependence on the arc diameter is shown in Fig. 9 (b). Arc diameter was measured at 4 mm above the electrode tip. The arc diameter is larger at low pressure, and arc constriction is observed with increasing pressure. Therefore, larger arc diameter at lower pressure leads to larger arc area. The arc is constricted and the current density is higher at higher pressures. Consequently,
the higher temperature and smaller arc area is observed. This can be explained by the difference in number densities of plasma species and mean free path. The current density of the arc decreases due to the decrease of the number density with decreasing pressure. The arc diameter increases to maintain a constant current. The spread of the arc is also affected by the increase in mean free path.

Fig. 7 Time variation of arc area in different pressures.

![Fig. 7 Time variation of arc area in different pressures.](image)

Fig. 8 Arc existence probability of the 12-phase AC arc.

![Fig. 8 Arc existence probability of the 12-phase AC arc.](image)

Fig. 9 Snapshot of arc near the electrode (a) and Pressure dependence of arc diameter (b).

![Fig. 9 Snapshot of arc near the electrode (a) and Pressure dependence of arc diameter (b).](image)
4. Conclusion

Effects of working pressure on temperature characteristics in the multiphase AC arc are investigated by the observation system consisting of the high-speed video camera and band-pass filters. Effect of working pressure on temperature distribution, arc area, and arc existence probability of the 12-phase AC arc in different pressures was clarified. Lower pressure is suitable for processes requiring uniform and large temperature fields, such as processing of materials with relatively low evaporation temperature. Higher pressure is suitable when evaporation of high melting point material or evaporation in a short time is required. Understanding these characteristics makes it possible to apply multiphase AC arc to the industry, and it will contribute to the production of functional materials at low cost.

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