Plasma jet characteristics in long DC arc with ring-shaped anode

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Abstract
Fluctuation characteristics of plasma jet flow in an innovative long DC arc system with ring-shaped anode were successfully clarified on the basis of the high-speed camera visualization. The long DC arc with long electrode gap distance more than 350 mm has been applied to gas decomposition due to its advantages such as large plasma volume and long residence time of treated gas. However, large heat loss at a conventional hemispherical-shaped anode was critical issue in the long DC arc system. Therefore, a ring-shaped anode was utilized to convert large energy loss at the anode into the plasma jet flow. Two kinds of the experiments were conducted. One was the estimation of energy balance in the long DC arc system. Calorimetric measurements were carried out. Another was the high-speed camera observation of the arc fluctuation and the plasma jet fluctuation. Results indicated that the 60% of heat loss at the conventional hemispherical-shaped anode was converted into the plasma jet flow when the ring-shaped anode was utilized. High-speed camera observation revealed that the plasma jet fluctuation with sharp FFT peak in the range of 25-500Hz was attributed to the arc fluctuation, which originated from the restrike phenomena of the anode spot. In contrast, results also suggested that the plasma jet fluctuation with broad FFT peaks in the range of 100-300Hz was attributed to the eddy formation due to the entrainment of ambient cold gas. To understand and control the fluctuation phenomena in the plasma jet enables to establish the innovative waste treatment by thermal plasmas.

Keywords: Thermal plasmas, Plasma jet flow, Fluctuation phenomena, High-speed camera, Restrike phenomena

1. Introduction
Thermal plasmas have been received a great attention in the application to waste treatment accompanying the increasing number of environmental issues and tightening regulations in past decades. The distinct advantages of thermal plasmas in the waste decomposition are high temperature and abundant radicals, which promote the decomposition and conversion of waste into environmentally benign materials in a compact system. Since the temperature of typical thermal plasma is over 10,000 K, thermal plasma can destroy any kind of non-degradable material preventing the generation of undesired chemical compounds such as furan, dioxin, sulfur oxides, nitrogen oxides in waste treatment processes (Heberlein and Murphy, 2008; Narengerile et al., 2010).

A long DC arc is one of the most attractive thermal plasma sources due to its advantages such as large plasma volume and long residence time of treated gas. The long DC arc system with a hemispherical-shaped anode has been developed and utilized in industrial fields for harmful material decomposition such as perfluorocarbons. Numerical (Choi et al., 2013) and experimental (Li et al., 2012) efforts have been reported. Decomposition mechanism of organics in the long DC arc has reported (Li et al., 2013) and feasibility of the long DC arc for organic waste decomposition has been revealed. However, further improvements in terms of energy efficiency and processing rate are essential to expand the applications of the long DC arc system in industrial fields. In the long DC arc system with the hemispherical-anode, the only arc channel between cathode and anode was utilized to decompose the treated material. More than 50% of energy was lost at the anode. In the present work, a ring-shaped anode is introduced to convert the large energy loss at the anode into the
Plasma jet characteristics in the conventional DC plasma torch have been intensively studied by many researchers. Pfender et al. (1991) experimentally investigated the turbulence structures of plasma jet flow in conventional DC plasma jet using Schlieren photography. They revealed that the turbulence transition occurs due to eddy formation, resulting from entrainment of ambient cold air into a plasma jet. Shigeta (2016) succeeded in numerical reproduction of the turbulence transition due to the eddy formation at the fringe of the plasma jet.

Measurements of plasma jet have also been carried out to reveal the plasma jet characteristics in terms of temperature and flow fields. Temperature field of the thermal plasma jet was investigated by enthalpy probe system (Caetti and Pfender, 1989). Velocity measurement of the plasma jet flow was also conducted by an optical method (Coudert, et al., 1994). Dynamic behaviors of the plasma jet core and its temperature fluctuation have been investigated by Hlína et al. (2005 and 2010) using optical measurements. In contrast to the conventional DC plasma torch, the plasma jet characteristics in the long DC arc system has not been reported yet in spite of the importance of understanding of the plasma jet characteristics for utilization of the thermal plasma jet.

The purpose of the present study is to establish the long DC arc system with the ring-shaped anode and investigate the plasma jet characteristics. Effect of plasma gas flow rate on the energy balance in the long DC arc system and the plasma jet fluctuation phenomena was addressed.

2. Experiments
2.1 Experimental setup

A representative photograph of the long DC arc system with the ring-shaped anode is shown in Fig. 1. Arc plasma in the DC torch generally consists of two plasma regions. One is arc discharge region, where Joule heating occurs. The arc channel was connected between a cylindrical cathode and the anode. Another is the plasma jet region generated at the anode nozzle structure due to the strong drag gas flow. Plasma jet is generated in the downstream region of the ring-shaped anode in the long DC arc torch. Schematic diagram of the long DC arc system is presented in Fig. 2. The electrode gap distance was fixed at 350 mm. In addition to the ring-shaped anode, the conventional hemispherical-shaped anode made of copper was also utilized for the comparison in terms of the energy balances in the long DC arc system. A nitrogen as plasma forming gas was injected from the upper region in the system. Flow rate of the plasma gas was changed from 30 to 70 L/min. The long DC arc was confined by an inner quartz tube which was cooled by circulating water. The inner diameter of the plasma confinement tube was 60 mm.

An auxiliary metal wire plays a role of a pilot electrode for the ignition of the long DC arc discharge because a breakdown between a pair of the electrodes with the long gap distance of 350 mm at atmospheric pressure is difficult. The auxiliary metal wire was temporally contacted with the anode at the moment of gas breakdown, and then it was pulled back toward the cathode. Finally, the arc was transferred from the auxiliary wire to the cathode when the wire slides by the cathode surface. The arc current was fixed at 10 A. The input power of the long DC arc discharge in nitrogen atmosphere was less than 10 kW since the typical arc voltage was in the range from 500 to 1000 V.

Energy balance in the long DC arc system was estimated on the basis of a calorimetric measurement. Temperature increases and the flow rates of the cooling water at the cathode, the anode, and the inner quartz tube were measured to estimate the heat losses during the arc operation. The energy in the plasma jet was then estimated.
2.2 High-speed visualization

Fluctuation phenomena of anode spot and plasma jet in the long DC arc system were visualized by a high-speed camera (FASTCAM SA5, Photron). Framerate was changed from $10^3$ to $10^4$fps to visualize the fluctuation at several tenth Hz and several hundred Hz of characteristic frequency. Shutter speed for anode spot observation was fixed at 0.34 μs, while that for plasma jet observation was 20 μs because the emission intensity of plasma jet is lower than the anode spot. Arc voltage was measured by an oscilloscope (DL850, Yokogawa) at a sampling rate of 1MHz.

Obtained high-speed images were analyzed to reveal the temporal and spatial characteristics of arc and plasma jet. The captured images of the plasma jet were transformed into binary images in black and white by appropriate threshold value to estimate a luminance area of plasma jet. FFT analysis of the plasma jet luminance area was then performed to clarify the fluctuation frequency of the plasma jet. In addition, FFT analysis of arc voltage was also carried out to verify the arc fluctuation.

3. Results and Discussion

3.1 Energy balance in long DC arc system

Energy balance in the long DC arc system with different flow rates of plasma gas is shown in Fig. 3. Arc power increased with an increase of the gas flow rate. This was because a larger amount of energy for nitrogen decomposition and ionization were required at larger flow rate. Heat losses at the anode and cathode was gradually increased with the increase of the gas flow rate. This was due to the total arc power was increased as mentioned above. In contrast, the heat loss at the inner quartz tube was decreased with the increase of the gas flow rate. This was owing to thermal pinch effect at larger gas flow rate, resulting in a smaller long arc diameter. Consequently, convection heat transfer from the arc to the inner quartz tube was reduced.

Anode heat loss at the conventional hemispherical-shaped anode was significantly higher than cathode heat loss and the heat loss at the inner quartz tube. On the other hand, heat loss at the ring-shaped anode was drastically reduced. Consequently, 60% of the conventional anode heat loss was successfully converted into the plasma jet. Anode heat transfer can be divided into thermal contribution and electron contribution. Anode heat transfer due to the electron contribution can be expressed as in Eq. (1),

$$q_{anode} = \frac{J}{e} \left( \frac{5}{2} k_B T_e + e U_a \right) + J \phi,$$

where $J$ is current density, $e$ is elementary charge, $k_B$ is Boltzmann constant, $T_e$ is electron temperature at the boundary layer, $U_a$ is anode fall voltage, $\phi$ is the work function of anode. The estimated heat loss due to the electron contribution was about 0.3 kW, which was less than 20% of the total anode heat loss of 1.5-1.8 kW. This indicated the remained 80% of the total heat loss can be estimated as heat loss due to thermal contribution. Anode heat loss due to electron contribution is essential while that due to thermal contribution can be reduced by changing the anode configuration and/or the plasma gas flow. Consequently, further improvement of anode heat loss is achievable.

![Fig. 3 Energy balance of long DC arc at different gas flow rates.](image-url)
3.2 Fluctuation phenomena in long DC arc system

High-speed snapshots of anode spot fluctuation and corresponding voltage waveform at plasma gas flow rate of 50 L/min is summarized in Fig. 4. Saw-tooth waveforms due to restrike phenomena of the anode spot was clearly observed. Brightest spot at the anode bottom was anode spot as indicated by red circle in Fig. 4 (b). The anode spot was periodically appeared at the bottom side of the anode. FFT spectra of arc voltage at different gas flow rates are presented in Fig. 5. Characteristic frequencies at 25Hz, 237Hz, and 439Hz were found at the gas flow rate of 30 L/min, 40 L/min, and 50 L/min, respectively. Comparison between the FFT spectra and the high-speed snapshots revealed that these characteristic frequencies were attributed to the restrike phenomena in the long DC arc torch.

Effect of gas flow rate on the characteristic frequency is summarized in Fig. 6. An increase of the gas flow rate led to the increase of the characteristic frequency. This was due to the stronger drag force at larger gas flow rate. Arc fluctuations with characteristics frequencies in a few to several hundred kHz were reported in the conventional DC arc torches (Duan and Heberlein, 2002). These fluctuations are basically determined by the thickness of the cold-gas boundary layer and the force balance of the gas drag force and the Lorenz force due to self-induced magnetic field. The characteristic frequencies of 10-500Hz in the long DC arc torch was slower than these conventional cases. This can be explained by different thickness of the cold-gas boundary layer between the arc and the anode nozzle. Larger anode nozzle diameter of 24.5 mm in the long DC arc torch and lower arc current of 10 A than the conventional DC torches led to larger thickness of the cold-gas boundary layer.

Fig. 4 Representative waveform of arc voltage (a) and synchronized high-speed snapshots (b) at gas flow rate of 50 L/min.

Fig. 5 Representative FFT spectra of arc voltage fluctuation at different gas flow rates.
High-speed snapshots of the plasma jet at different gas flow rates are presented in Fig. 7. The counter maps of existence probabilities of the plasma jets at different gas flow rates were shown in Fig. 8. The existence probability of plasma jet was defined as the ratio of the time during which the plasma jet existed to total observation time. Therefore, “1” means that the plasma jet always exists at the observed position and “0” does not exist. Fig. 7 was constructed by superimposing the plasma jet images after binarization at appropriate threshold for 0.5 s of total observation time, which is sufficiently longer than the time period of plasma jet fluctuation mentioned below. Red color in the counter maps of the existence probability indicated that the plasma jet always existed. Plasma jet length was obviously decreased with the increase of the plasma gas flow rate. This was due to an entrainment of the surrounding cold air. Larger gas flow rate led to larger entrainment, resulting in the shorter plasma jet length.

High-speed observation of plasma jet suggested that the plasma jet fluctuations at upstream region near the anode and downstream region of the plasma tail were different. Therefore, the FFT analyses of the luminance areas of the plasma jet at the upstream and downstream regions were carried out to verify the effect of gas flow rate on the plasma jet fluctuation. FFT spectra of the plasma jet at upstream region were presented in Fig. 9. Characteristic frequencies at 27Hz, 247Hz, and 457Hz were found at the gas flow rate of 30 L/min, 40 L/min, and 50 L/min, respectively. These frequencies are quite similar with the frequency of arc fluctuation.

Fig. 6 Effect of gas flow rate on the characteristic frequency of arc fluctuation.

Fig. 7 Representative snapshots of plasma jet in different gas flow rate of 30 L/min (a), 40 L/min (b), and 50 l/min (c).
FFT spectra of the plasma jet at downstream region were shown in Fig. 10. Characteristic frequencies which correspond the sharp peaks are found as well as the plasma jet fluctuation at the upstream region. In addition, the characteristic frequencies which correspond the broad peaks are also confirmed only at the downstream region. Obtained characteristic frequencies at the upstream and downstream of the plasma jet were summarized in Figs. 11 and 12. Common frequencies were found at the upstream and downstream region of the plasma jet. These frequencies also show similar value with the arc fluctuation frequencies. Consequently, plasma jet fluctuation is attributed to the restrike phenomena in the anode spot.

Characteristic frequencies in the range of 100-300Hz were also found only at the downstream region and discussed here. In the fringe of the plasma jet flow, a number of eddies periodically forms due to the entrainment of the surrounding cold air, which phenomena was firstly reported by Pfender et al. (1991). In recent, such eddy formation due to the surrounding gas entrainment has been reproduced by numerical simulation of plasma jet flow by Shigeta (2016). Numerical simulation suggested that the plasma jet fluctuation with the characteristic frequencies of several hundred Hz possibly occur due to the eddy formation. Furthermore, these fluctuation was observed only at the downstream region of the plasma jet. As a conclusion, the observed plasma jet fluctuation with the characteristic frequencies of 100-300Hz are attributed to the eddy formation due to the entrainment of surrounding cold air.

![Fig. 8 Contour maps of arc existence probabilities in different flow rates of plasma gas.](image)

![Fig. 9 FFT spectra of plasma jet fluctuation at upstream for different flow rates of plasma gas. Analysis region was in the range from 30 mm to 45 mm of the distance from anode bottom.](image)
Conclusion

The long DC arc system with the ring-shaped anode was successfully established. Sixty percent of the energy loss at the anode in the conventional hemispherical-shape was converted into the plasma jet flow when the ring-shaped anode was utilized. Effect of plasma gas flow rate on the arc fluctuation and plasma jet fluctuation was clarified on the basis of the high-speed camera imaging synchronized with the arc voltage measurement. Larger gas flow rate led to rapid arc fluctuation due to the restrike phenomena in the long DC arc torch. Plasma jet fluctuations were attributed to the arc fluctuation and the eddy formation due to the entrainment of surrounding cold air into the plasma jet. Understanding of the fluctuation phenomena enables us to utilize this high temperature heat source consisting of the discharge region and plasma jet region in the long DC arc system for various innovative processing including waste treatment.

Fig. 10 FFT spectra of plasma jet fluctuation at downstream for different flow rates of plasma gas. Analysis region was in the range from 55 mm to 180 mm of the distance from anode bottom.

Fig. 11 Effect of gas flow rate on characteristic frequency of plasma jet fluctuation at upstream region.

Fig. 12 Effect of gas flow rate on characteristic frequency of plasma jet fluctuation at downstream region.

4. Conclusion

The long DC arc system with the ring-shaped anode was successfully established. Sixty percent of the energy loss at the anode in the conventional hemispherical-shape was converted into the plasma jet flow when the ring-shaped anode was utilized. Effect of plasma gas flow rate on the arc fluctuation and plasma jet fluctuation was clarified on the basis of the high-speed camera imaging synchronized with the arc voltage measurement. Larger gas flow rate led to rapid arc fluctuation due to the restrike phenomena in the long DC arc torch. Plasma jet fluctuations were attributed to the arc fluctuation and the eddy formation due to the entrainment of surrounding cold air into the plasma jet. Understanding of the fluctuation phenomena enables us to utilize this high temperature heat source consisting of the discharge region and plasma jet region in the long DC arc system for various innovative processing including waste treatment.
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