Energy Fluctuations in a Direct Current Plasma Torch with Inter-Electrode Inserts Operated at Reduced Pressure

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Abstract Direct current (dc) plasma torch with inter-electrode inserts has the merits of fixed arc length, relative high enthalpy and may show advantages in future plasma processes where stability and controllability are must-have. Energy fluctuations in the plasma may result from power supply ripple, arc length variation, and/or acoustic oscillation. Using an improved power supply with a flat waveform, the characteristics of an argon plasma energy instabilities under reduced pressure were studied by means of simultaneously monitoring the arc voltage and arc current spectrum. Dependence of the arc fluctuation behavior on the plasma generating parameters, such as the current intensity, the plasma gas flow rates and the vacuum chamber pressure were investigated and discussed. Results show that the plasma torch has a typical U-shaped voltage-ampere characteristic (VAC). The correlation between the VAC and the probability of energy distributions was studied. Through pressure measurements at the cathode cavity and the vacuum chamber, the existence of sonic flow in the inter-electrode insert channel was confirmed.

Keywords dc plasma · Inter-electrode insert · Fluctuation · Stability

Introduction

Because of its high energy density, thermal plasma is widely accepted as a processing medium which facilitates high fluxes of radical species, high processing rates, a wide choice of reactants, and high quench rates [1]. A broad range of industrial processing methods have been developed based on thermal plasma technology, and have been intensively applied in the areas of novel material processing, advanced machining, high enthalpy flow ground simulation (e.g. plasma wind tunnels), etc. [2–4]. Although various types of thermal plasma sources have been developed in the last several decades, direct current (dc) plasma, with the merits of structural simplicity, high thermal efficiency, being easy to realize automation, is still the most competitive thermal plasma source in industrial applications [5]. However, the

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intrinsic non-steady features of the dc plasma limited its new applications in advanced processing, where reliability, reproducibility and precise controllability are of great importance. For example, when particles are used as feedstock in plasma spraying, their characteristic residence time is in the order of milliseconds, which is close to the typical fluctuation period of a dc plasma. This may lead to different thermal histories for different particles and make the fine controlling of coating microstructure almost impossible. For nano-particle injection, the momentum change of the particle could be much faster [6], thus, not only fluctuations in hundred Hz but also those in 10–100 kHz may affect the thermal history of nano-particles. These challenges call for better understanding of the arc behavior in dc plasma torches with different configurations over a wide range of generating parameters, which may facilitate the improvement of the stability and controllability of the dc plasma through optimizations of the torch geometry and operating parameters. Continuous efforts have been dedicated to this purpose both theoretically and experimentally. In the 1960s–1970s, researchers in the United States and former Soviet Union began to study the pulsation characteristics of dc plasma arcs [7–9], and the observed arc voltage fluctuation are mainly regarded to be the result of large scale arc root movements and the corresponding change of arc length [10–12]. In recent years, Delair et al. [13] first suggested that Helmholtz oscillation in the arc chamber may be the reason for high frequency fluctuations of the arc voltage. Coudert et al. [14, 15] further studied this phenomena and has confirmed the coupling of pressure and arc voltage oscillations. These studies were mainly conducted with a self-setting arc length torch, namely, the arc length at any instant is mainly determined by the interaction between aerodynamic and electro-magnetic forces.

On the other hand, compared to self-setting arc length dc plasma torches, the torch with sectional inter-electrode inserts (IEI) [16–19] may generate plasma with a fixed arc length. This is achieved by using a relatively long and narrow IEI channel with floating potential and an abruptly expanded anode. The length of the arc should be at least larger than the length of the IEI channel to maintain the discharge, which is generally longer than it could be under free-setting conditions. Therefore, on one hand, the aerodynamic force cannot push the arc downward any further. While on the other hand, the insulated IEI channel also prohibits the shortening of the arc. These two restrictions keep the arc length variation limited. Accordingly, it is possible to modulate the arc voltage by varying the size of IEI channel. With a long IEI channel, the arc length may be extended much longer than that in self-setting arc length torches, which leads to higher arc voltage for a given input power. Our previous research shows that in a non-transferred dc plasma torch with IEI, the arc voltage of argon plasma can reach about 50 V at atmospheric pressure [20], while in a reduced pressure chamber, the arc voltage can reach 75 V [21]. When a certain power level is needed for an arc, such a combination of higher voltage with lower current intensities is preferred in some applications because with lower current, there might be less heat loss and electrode erosion [10]. Although wall-stabilized arc with IEI has been developed for more than half a century, its fluctuation behavior has not yet been fully understood, especially those originated from sources other than the arc root movements. In addition, the originations and transportations of the fluctuations from the arc to the plume, the complex coupling effect of aerodynamic forces and magneto-hydro-dynamic forces, the effect of compressible flows etc. are still not well clarified. Our previous research shows that with the addition of IEI, the fluctuation behavior of the arc is different from that of the self-setting arc. The dependence of arc voltage pulsation on the arc root movement seems to be much less both in atmospheric and reduced pressure conditions [21–23]. This is explained as such: although the arc root movements are not fully restricted by the IEI and the larger diameter anode, especially in the circumferential direction, the arc length change caused by

arc root movements is relatively small and the percentage of arc voltage fluctuations in voltage spectra caused by arc root movements can be negligible when the IEI channel is long enough. Besides, without changing the torch structure, laminar or turbulent plasma flow can be generated freely according to specific application requirements through adjustments of plasma generating parameters, such as plasma gas flow rates or arc current, etc. And it is interesting to note that the flow state of the plasma plume is determined by its aerodynamic conditions and is not affected apparently by the arc voltage fluctuations.

To describe the instability behavior of the arc, arc voltage spectrum is accepted as the most informative method, because in most dc plasma generations, a constant-current power source is used and the arc voltage is directly related to the power inputted into the arc and its fluctuation may affect the stability of the plasma jet. However, some power supplies such as those utilize saturation resistor or silicon controlled rectifier may have intrinsic low frequency fluctuations. For example, in Ref. [24], a 150 Hz arc voltage and current fluctuation inherited from the power supply have been identified. In our previous work, a similar 300 Hz fluctuation also exists [20–23]. In these cases, the amplitude of energy fluctuations in plasma might be larger than the arc voltage fluctuations. Therefore, it is necessary to characterize the energy fluctuation instead of only arc voltage fluctuation to describe the instability of dc plasma arc better.

In this research, an LC filter consisting of two levels of inductors and capacitors to eliminate the 300 Hz power supply fluctuation was added and the energy fluctuation in the non-transferred dc plasma torch with IEI was estimated.

Experimental Details

Figure 1 shows the schematic diagram of the experimental system. Arc goes from the tip of the cathode, through a 70 mm long channel of the IEI and reaches the upper surface of an

Fig. 1 Schematic illustration of the dc plasma torch with a water-cooled IEI

Fig. 2 Illustration of the main LC filter circuit components

abruptly expanded anode. In the present research, the inner diameter of the IEI channel is 8 mm while that of the anode is 60 mm. All the electrodes are water-cooled. And the IEI has a floating potential. Through this torch design, an almost fixed arc length can be achieved. Argon was fed into the plasma torch through inlets G_1 and G_2 with a volume ratio of 2:1. At each position, the gas was injected through 8 circumferentially even-distributed small holes. The directions of gas flow through inlets G_1 and G_2 are tangential and radial respectively. Using Elenbaas-Heller equation, the electric field inside the IEI channel is estimated to be about 5.2 V/cm, when the arc current is 80 A and the argon gas flow rate is 6 slm. Therefore, the 70 mm long IEI channel is divided into 3 sections insulated with each other to keep the voltage gradient in each section being less than the break down voltage between the arc column and the IEI channel surface. With this configuration, double arcing was not observed experimentally. A pressure tap was set at the end of the cathode cavity and the pressure p_{ca} was measured for both cold and thermal cases by a pressure transducer. The vacuum chamber pressure p_{vc} was also measured on the vacuum chamber wall, which is far downstream from the plasma torch exit. Time dependent arc voltage, arc current and the pressure signals were monitored simultaneously through different channels of an oscilloscope. The sampling rate was set to be 1 MHz to monitor high frequency fluctuations in arc current and voltage. Plasma gas flow rates varied from 4.2 to 16.8 slm in this research. p_{vc} was controlled to between 0.5 and 10 kPa and the arc current between 70 and 100 A. Compared to previous system [23], a two-levels LC filter was designed and installed to stabilize the power supply. The main components of the circuit are shown in Fig. 2. The inductors of L_1 and L_2 equal to 2 mH, and the capacitors of C_1 and C_2 equal to 1,500 μ F, with a designed filtering effect of the 300 Hz fluctuation amplitude of greater than 99.5% and the resistance to direct current less than 3%. The positions of sensors for arc voltage and current measurements are also shown in Fig. 2.

Results and Discussion

Using a water-cooled resistor with a resistance of 0.5 Ω and an argon plasma as the loads respectively, voltage and current spectra with and without the LC filter were compared in Fig. 3. For the argon plasma generation, the vacuum chamber pressure was 0.5 kPa, the arc current intensity was 65 A and the argon gas flow rate was 16.8 slm. Without the filter (Fig. 3a, c), appreciable fluctuations both in voltage and current are seen. The waves are in half sinusoidal forms, which are typical for the rectified power supply when the 3-phases are not well balanced. Under the experimental condition, the arc voltage and arc current

Fig. 3 Effect of LC filter on the voltage and current fluctuations when using water-cooled resistor (a), (b) and an Ar plasma (c), (d) as the load

fluctuations are in the same phase, which means that the generated arc is also a kind of resistive load and the energy fluctuation which equals to the product of arc voltage and arc current is even larger. The equivalent resistance of the argon arc in these conditions is about 1.1Ω . It clearly shows that the two-levels LC filter can effectively eliminate the 300 Hz current fluctuation originated from the rectified power supply, as shown in Fig. 3b, d. FFT analysis shows that with the LC filter, the amplitude of fluctuation at 300 Hz has been reduced to near zero for all the cases.

With an increment of 0.2 kW, the frequency count of the energy dissipated (equals to the product of arc current and arc voltage) in the water-cooled resistor or argon arc are calculated. Divided by the total count of the measurement points for each spectrum in Fig. 3, the probability distributions of energy dissipated are plotted in Fig. 4. Without the LC filter, the distribution is asymmetric and the peak is close to the right side, which is in correspondence with the spectrum in Fig. 3 where half sinusoidal pulse dominates. Although the probability distributions are not in normal forms, the coefficient of variation

$CV = \frac{\sigma}{|\mu|}$ can also be used to qualitatively estimate the degree of dispersion. Here $\sigma = \sqrt{\frac{\sum_{i=1}^n (E_i - \bar{E})^2}{n}}$ is the standard deviation, E_i is the energy calculated for each time point, $\bar{E}$ is the mean value of all the measured points, n is the total count of measurements which equals to 10,000 in this research and $\mu = \bar{E}$.

Fig. 4 Probability distributions of the energy dissipated in the two kinds of loads with or without the LC filter

Using CV_I – CV_4 to represent the coefficient of variation for the four energy distributions as marked in Fig. 4, the calculated values of $CV_I \sim CV_4$ are 15.9, 1.3, 6.9 and 0.7%, respectively. Because of the difference in the resistance, at similar current levels, the energy dissipated in the argon plasma is about twice of that in the water-cooled resistor. Compare to its own mean value, the energy distribution is narrower in the case of argon plasma than that in the water-cooled resistor at both conditions with or without the LC filter. For reference, σ_1 – σ_4 are 0.568, 0.040, 0.416, 0.043 kW respectively.

Operated at reduced pressure and with the narrow IEI channel of 8 mm in diameter, flow choking may occur at the exit of IEI channel, in which condition the velocity of the flow reaches the speed of sound and the upstream pressure is independent on the vacuum chamber pressure. Experimental results have confirmed this. Without plasma generation, the pressure of the cold cathode cavity was measured at different argon gas flow rates and chamber pressures. As shown in Fig. 5a, at relative higher chamber pressure, there is a linear relationship between the pressure in the cathode cavity and the chamber pressure. Under these conditions, the flow is sub-sonic and there is no choking of the flow. However, when the chamber pressure decreases to a critical value, the pressure measured does not change with the chamber pressure any more. From the principle of compressible

Fig. 5 Dependence of pressure in the cathode cavity on the chamber pressure for **a** cold state and **b** plasma generated condition

flow in a channel, such behavior suggests that under this condition, flow choking occurs, which means the flow has reached the speed of sound at the IEI channel exit. Mass conservation gives: $\int_0^r \rho a 2\pi r dr = \dot{m}$ at the IEI exit. Here ρ , a , r , $\dot{m}$ are the mass density, sonic velocity, the radial coordinate of the IEI channel and the mass flow rate of the plasma gas respectively. For ideal gas, pressure $p = \rho \frac{RT}{M}$, and the sonic velocity $a = \sqrt{\gamma \frac{RT}{M}}$, thus the former equation can be revised to $\int_0^r p \sqrt{\gamma \frac{M}{RT}} 2\pi r dr = \dot{m}$, where M is the molar mass, γ is the adiabatic index and R is the molar gas constant. The dotted line in Fig. 5a represents theoretical considerations of chamber pressure at which flow choking occurs with different gas flow rates, taking into the speed of sound and the geometry of the channel.

When plasma is generated with arc current of 80 A, the presence of a high-temperature and low-density arc column within the channel heats up the gas and restricts the flow of gas through it, which makes the thermal choking phenomenon more pronounced, as shown in Fig. 5b. In all the plasma generating conditions, the measured pressure in the cathode cavity is independent of the chamber pressure, and sonic flow at the IEI channel exit was confirmed.

Under a constant mass flow rate, the drag force over the arc root is proportional to the square of the gas velocity. When the velocity has reached the speed of sound, the drag force could be much higher than the electromagnetic force and the arc root is almost impossible to anchor inside of the IEI channel. Moreover, as mentioned above, with the sectional structure of the IEI, shortening or double arcing is not likely to occur. This means that the arc length must exceed the length of the IEI channel to produce a plasma jet. Voltage-ampere characteristics (VAC) of the dc plasma torch are shown in Fig. 6. p_{vc} was kept constant at 2 kPa for different argon gas flow rates from 4.2 to 16.8 slm. Compared to dc plasma torch with free-setting arc length, the voltage is much higher here because of the stretching of the arc to a relatively long length. Higher arc voltage at the same arc current level is preferred when high enthalpy plasma flows are needed, especially for some plasma materials processes. Mean arc voltage increases with gas flow rate, and a typical U-shaped VAC for torches with long IEI channel [17] was clearly shown in Fig. 6.

Generally, a wall-stabilized arc has an increasing VAC while a free burning arc has a drooping one. When the electrodes are properly cooled, the electrode voltage drops are almost constant. With the plasma torch illustrated in Fig. 1, the change of arc length can be

Fig. 6 Voltage-ampere characteristic with different plasma gas flow rate at p_{vc} of 2 kPa with arc current of 80 A

neglected when plasma gas flow rate are kept unchanged. In the arc column, the arc voltage is proportional to the electric field $E = j/\sigma$, where j represents the current density and σ represents the electric conductivity. The drooping VAC when the current intensity is low suggests that under this situation, although the diameter of the arc column increases with current, it is still small enough and there is no constriction effect of the IEI channel, therefore, a decrease of j together with an increased σ at higher temperature leads to lower arc voltage. However, when the arc current increases over a critical value, the diameter of the arc column is comparable with the diameter of the IEI channel and a strong constriction effect caused by the water cooled wall and the cold gas around the arc column leads to an increase of j at higher current levels, which consequently lift up the arc voltage. Such U-shaped VAC could also be well predicted by using Elenbaas-Heller equation.

Figure 6 also shows that arc voltage increases at higher gas flow rate because with the increase of gas flow rate, there is a temperature drop leading to a lower σ and further constriction of the arc column leading to a higher j thus an elevated arc voltage. Because of the same reason, the bottom of the U-shaped curve also shifts to smaller current intensities at higher gas flow rates.

With the LC filter, as the circuit tends to suppress the variation of arc voltage with time, it is much more difficult to observe high frequency (~ 3 kHz) Helmholtz oscillations, compared to the results shown in Ref. [22]. Only at higher enthalpy levels, for example, in the case of lower gas flow rate with higher power input, there is enough energy to excite the oscillation. Figure 7a shows the arc voltage and current spectra at different current intensities. p_{vc} was kept at 2 kPa with the argon gas flow rate being 8.4 slm. It is shown that when the arc current is at 70 and 80 A, the arc voltage spectrum is smooth, and when the arc current is higher than 90 A, high frequency fluctuations become appreciable. The amplitude of such fluctuation is about 4.2 V, 6% of the mean arc voltage value. The frequency of this fluctuation is 3.3 kHz, which is a little lower than that of 3.6 kHz when LC filter was not applied [22]. The arc voltage and current spectra shown in Fig. 7a further confirmed that these high frequency fluctuations originated from the aerodynamic oscillation instead of the power supply.

Similar to Fig. 4, with an increment of 0.2 kW, the corresponding probability distributions of energy dissipated in the plasmas are plotted in Fig. 7b. Coefficient of variations (CVs) are 1.47, 0.79, 1.67 and 1.65% respectively when the arc current increases from 70 to 100 A. The narrowest distribution is at the arc current intensity of 80 A. The small peaks

Fig. 7 Arc voltage fluctuations at various arc currents at $p_{vc} = 2$ kPa and Ar gas flow rate of 8.4 slm

Fig. 8 Arc voltage and current spectra at different chamber pressures and gas flow rates

in the distribution at higher arc current levels correspond to the fine structures in the voltage spectra in Fig. 7a. Note the middle VAC curve shown in Fig. 6, the bottom of the U-shaped curve is just around arc current of 80 A. And it is where the smallest slop of the arc voltage change over arc current exists, suggesting that the VAC also affects the energy fluctuation behavior of the arc. At the bottom of the U-shaped curve, less correlation between the arc current and arc voltage leads to the narrowest energy distribution in the present research.

Figure 8a, b show the dependence of arc voltage spectra on gas flow rates and chamber pressures. There are no remarkable changes in the arc voltage spectra in the range of plasma generating parameters shown in Fig. 8, except that when gas flow rate increases from 8.4 to 16.8 slm at the same chamber pressure of 2 kPa, the mean arc voltage increases from 65 to 71 V. The arc voltage spectra are smooth and the fluctuations of arc voltage with time are between 1.2 and 1.8%. When the chamber pressure varies from 0.5 to 10 kPa, the fluctuations of arc voltage are between 0.6 and 2.8%. In all the cases, arc current does not change. Compared to previous research [22], at similar plasma generation conditions, high frequency fluctuations originated from Helmholtz oscillation of plasma gas are harder to find after the LC filter was adopted.

Conclusions

Fixation of arc length was achieved through the design of an abruptly expanded anode and a long inter-electrode insert with floating potential. Voltage-ampere characteristic of the plasma torch was in the typical U-shape. The critical arc current level at the bottom of VAC shifted to smaller values at higher gas flow rates. The obtained arc voltage was much higher than those of free-setting arc dc plasma torches. Pressure measurement in the cathode cavity confirmed that there was sonic flow at the IEI channel exit. With the addition of an LC filter, large fluctuation in electric energy input from the power supply was eliminated, and Helmholtz oscillation was also suppressed. At most studied plasma generating conditions, the arc current spectra were smooth and the arc voltage fluctuations were smaller than 0.6%. Only at high arc current level with low gas flow rate, Helmholtz oscillation could be excited. Under these situations, the amplitude of arc voltage fluctuation was also smaller than 6%, and the narrowest probability of energy distribution corresponds to the bottom of the VAC curve. It is expected that such kind of dc plasma torch operated at

reduced pressure may show advantages in future plasma materials processes where high controllability is needed.

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