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Fluctuation characteristics of arc voltage and jet flow in a non-transferred dc plasma generated at reduced pressure

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Abstract
A torch with a set of inter-electrode inserts between the cathode and the anode/nozzle with a wide nozzle exit was designed to generate plasma jets at chamber pressures of 500–10 000 Pa. The variation of the arc voltage was examined with the change in working parameters such as gas flow rate and chamber pressure. The fluctuation in the arc voltage was recorded with an oscilloscope, and the plasma jet fluctuation near the torch exit was observed with a high-speed video camera and detected with a double-electrostatic probe. Results show that the 300 Hz wave originated from the tri-phase rectified power supply was always detected under all generating conditions. Helmholtz oscillations over 3000 Hz was detected superposed on the 300 Hz wave at gas flow rates higher than 8.8 slm with a peak to valley amplitude lower than 5% of the average voltage value. No appreciable voltage fluctuation caused by the irregular arc root movement is detected, and mechanisms for the arc voltage and jet flow fluctuations are discussed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Non-transferred direct current (dc) plasmas are widely used as a heating source for various purposes such as materials processing, high temperature wind tunnel and special waste treatment. Fluctuation characteristics of the jet flow seem to affect the uniform heating of precursors or particles injected into it continuously in a film deposition or spray coating process [1, 2], causing an increase in the structural defects in the film or coating and making it difficult to control their properties. Reports show that the fluctuation characteristics in the jet flow near the torch exit are generally similar to that of an arc voltage [3–5], according to the simultaneous detection of light emission intensity from the jet flow and the measurement of arc voltage. That is, the change in the arc voltage modifies the input energy to plasma generation, which causes different gas heating effects and brings about the fluctuation of the parameters in the jet flow.

Generally, the possible mechanisms causing the arc voltage fluctuation can be mainly divided into three different types [4–8]. The most common type could be that caused by the length change of the arc column between the cathode tip and the anode, due to the arc root movement on the anode surface owing to the interaction between the drag force of gas flow and the electro-magnetic force around the arc column. Many factors could affect the attachment pattern and the form of movement of the arc root on the anode surface, such as the working gas component, feeding method, flow rate, arc current and boundary layer between the anode surface and the arc column [6, 7, 9]. The amplitude and frequency of the fluctuation change in a wide range and can be over 100% of its average voltage and several kilohertz [7, 8, 10]. Another type of arc voltage fluctuation is considered originating from the power supply. The fluctuation amplitude of the arc voltage is generally lower than 15% of its average value with a characteristic frequency around 100–300 Hz [4, 5, 11], which reflects the output characteristics of the rectified power supply. For a chosen power supply, the fluctuation characteristic frequency is fixed at a certain value, and the voltage always fluctuated at the frequency with a limited amplitude change with the change in gas flow rate or arc current. This kind

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of fluctuation can be removed only by changing the power supply with minimized ripple characteristics. The third type of fluctuation seems to arise from Helmholtz oscillations affected mainly by the torch geometry and also the gas flow condition and input power level [4, 8]. In this case, the torch gas flow channel appears as a Helmholtz resonator, which allows a resonance to occur at a certain frequency determined by the channel structure and operating conditions. This kind of resonance is generally superposed on the other two types of fluctuations with its own characteristic frequency and amplitude.

Regarding the first type of arc voltage fluctuation, a fixed arc length may be preferred to ensure stable arcing which can be achieved by an abruptly expanded channel of the torch design [12]. Besides, between the cathode and the anode of the non-transferred dc plasma torch, an insert of floating electric potential with a relative long, narrow tunnel through which the arc column passes was added to generate the plasma under an almost fixed arc length condition [13–15]. That is, with the special torch structure, the arcing can only find its suitable attachment position on the anode surface within an almost fixed and narrow region at a given gas feeding condition and arc current. In this kind of torch, the change in arc column length caused by the movement of the arc root on the anode surface could generally be neglected compared with its long column passing through the inter-electrode insert. Thus, the fluctuation component of the arc voltage originating from the length change of arc column can be kept generally at a negligible level [4]. Experimental results indicate that this kind of torch can generate a plasma jet of laminar or turbulent flow state at atmospheric pressure by regulating the gas flow rate and arc current [14]. When a laminar plasma jet was generated, only the voltage fluctuation originated from the feature of the power supply was observed [4]. This kind of laminar plasma jet can be used for the surface treatment of metals, such as re-melting hardening, cladding and spray coating [16, 17], with greatly improved process controllability compared with that by using the turbulent plasma jet.

In this work, a torch with a set of inter-electrode inserts between the cathode and the anode of a wide nozzle exit was designed to generate dc thermal plasma of larger volume and moderate parameter gradient at reduced pressures. The voltage characteristics of the torch and the fluctuation in arc voltage and plasma jet flow were examined with the change in working parameters such as gas flow rate and chamber pressure.

2. Plasma generation

Plasma jets were generated with the torch shown schematically in figure 1 by using pure argon as the working gas at a fixed arc current of 80 A. A tri-phase rectified dc power supply capable of 20 kW output was used. Gas is injected tangentially near the cathode tip and also at the entrance to the anode cavity. The inter-electrode insert in figure 1 comprises three copper inserts and two insulator inserts in between. The inserts have a floating electric potential and an inside diameter of 8 mm to form an arc channel through which the arc column just passes but cannot find its attachment spot on the channel surface. The

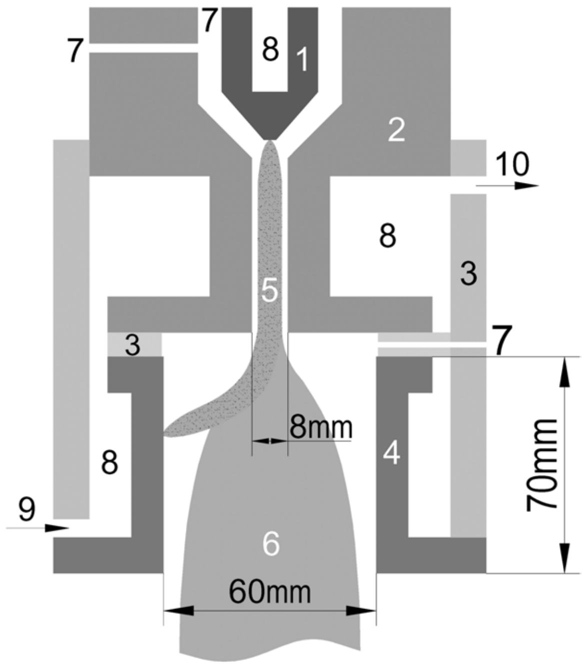
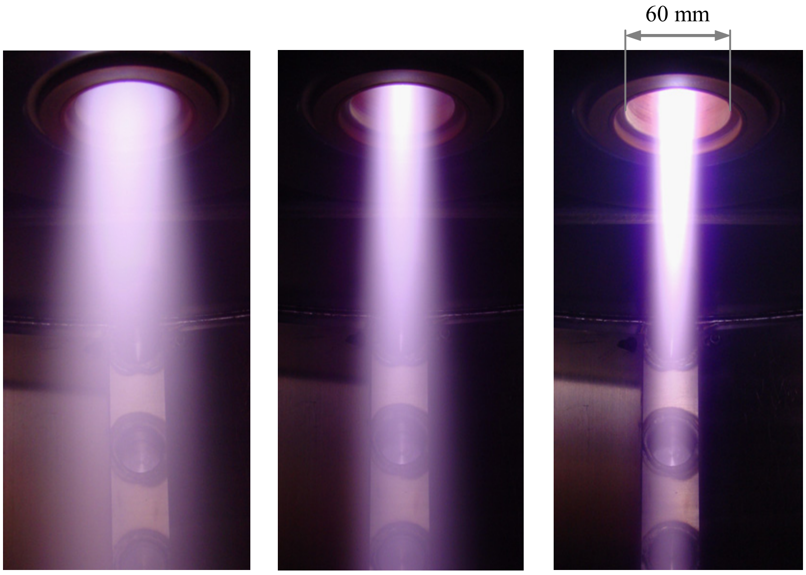


Figure 1. Schematic diagram of the plasma torch. 1, cathode; 2, inter-electrode insert; 3, insulator; 4, anode; 5, arc column; 6, plasma jet; 7, gas inlet; 8, cooling water; 9, water inlet; 10, water outlet.

anode nozzle has an inside diameter of 60 mm which is much wider than the inter-electrode channel. It is predicted that the drag force of the flow in the wide nozzle region is too weak for driving the arc root movement intensively and producing arc voltage fluctuation of the restrike mode, under the present working conditions of gas flow rate and chamber pressure.

The appearances of the plasma jet flow taken by an ordinary camera are shown in figure 2. The shutter time for each photo is 1/200 s. The luminous region of the jet flow expanded with decreasing chamber pressure and the light intensity at the centre of torch exit increased with increasing chamber pressure. These suggest that the plasma volume increased and the temperature gradient decreased with decreasing chamber pressure. Such kinds of plasmas operated at a reduced pressure may have advantages for certain kinds of materials processing where large area and uniform treatment are preferred.

The arc voltage increases with increasing gas flow rate or, more gently, with increasing chamber pressure, as indicated in figure 3. This dependence of the arc voltage change on the gas flow rate was also observed when a similar torch with only one piece of inter-electrode insert and relatively narrower nozzle diameter was operated at atmospheric pressure [4]. The arc voltage is generally related to the column length and the intensity of the electric field $E = j/\sigma$. Here j is the arc current density and σ is the electric conductivity, and usually arc constriction leads to a higher E. In the case of the present torch, the length change of the arc column can almost be neglected. Accordingly, the characteristic of the arc voltage in figure 3 indicates that E varies with chamber pressure and gas flow rate. Previous pressure measurements show that when the gas flow rate increases from 6.8 to 17.6 slm, the pressure in the upstream cathode cavity increases from 12 000 to 27 000 Pa.



(a) (b) (c)

Figure 2. Photographs showing the appearance of the pure argon plasma jets at a gas flow rate of 4.4 slm and chamber pressures of (*a*) 170 Pa, (*b*) 500 Pa and (*c*) 2000 Pa. The shutter time of the camera is 1/200 s.

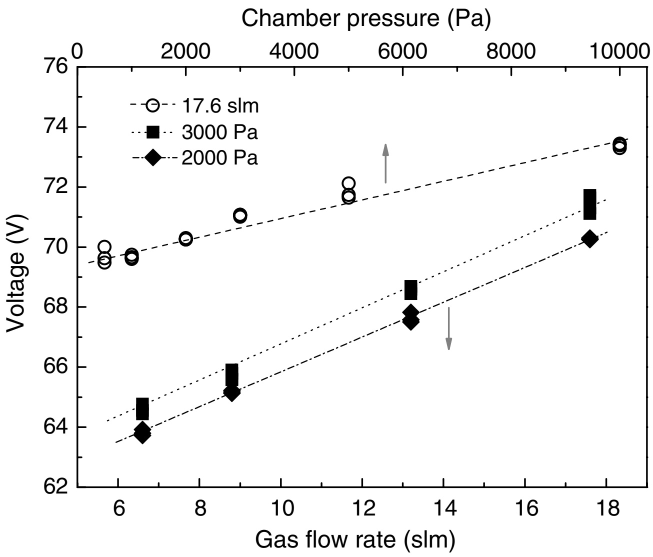


Figure 3. Variations of the mean arc voltage with gas flow rate at fixed chamber pressures of 2000 Pa and 3000 Pa and with chamber pressure at a fixed gas flow rate of 17.6 slm.

However, when the gas flow rate is constant, it is independent of the plenum chamber pressure in this study; e.g. at a gas flow rate of 17.6 slm, the pressure in the cathode cavity remains constant at 27 000 Pa when the plenum chamber pressure is decreased to values below 10 000 Pa. This is the phenomenon known as thermal choking [19]. The velocity of the jet has reached the speed of sound at the exit of the inter-electrode insert, and the downstream pressure does not affect the flow inside the insert channel. Therefore, the measured arc voltage can be divided into two parts: that of the arc inside the inter-electrode channel which varies only with gas flow rate and that of the portion in the anode cavity which changes with both gas flow rate and chamber pressure. Generally, higher gas flow rates lead to more arc column constriction, thus to elevated arc voltage. With the variation of the plenum chamber pressure, although the first part of the arc does not change, the part of the arc column in the anode cavity does become more constricted at higher pressures, also leading to an increase in the arc voltage.

3. Experimental measurement and data analysing methods

The time-resolved arc voltage signals between the torch anode and cathode in generating plasma jets were obtained directly by using an oscilloscope with a sampling rate of 500 kHz. A high-speed video camera capable of 1.2×10^5 frame per second (fps) was used to obtain the instantaneous plasma jet images through the chamber window, with a recording speed of 2500 fps and an exposure time of 10 μs per frame, while the lens aperture was set to 0.95.

A double-electrostatic probe system was set at the jet centre near the torch exit to measure the ion saturation current. The probe system consists mainly of five parts as shown in figure 4. That is, a double-electrostatic probe, one probe holder, a dc bias power supply, a sampling resistance of 500 Ω and an oscilloscope. The double-electrostatic probe comprises two individual tungsten wire electrodes of 0.3 mm diameter with an exposed length of 2 mm in the plasma. The other part of each wire is covered by an alumina tube of 0.5 mm inner diameter, 1 mm outer diameter and 35 mm length. The probe head is fixed in a boron nitride holder with a centre distance of 2 mm between the two wires. The holder can move along the axial and radial directions of the jet. The bias power supply applies a voltage of 18 V between these two tungsten wires, and the ion current is calculated by the voltage collected across the resistance. It was confirmed that the ion current reached its saturation value at the bias voltage of 18 V under the working conditions. An oscilloscope with an isolated channel was used to record the time-resolved voltage signals across the resistance with a sampling rate of 100 kHz.

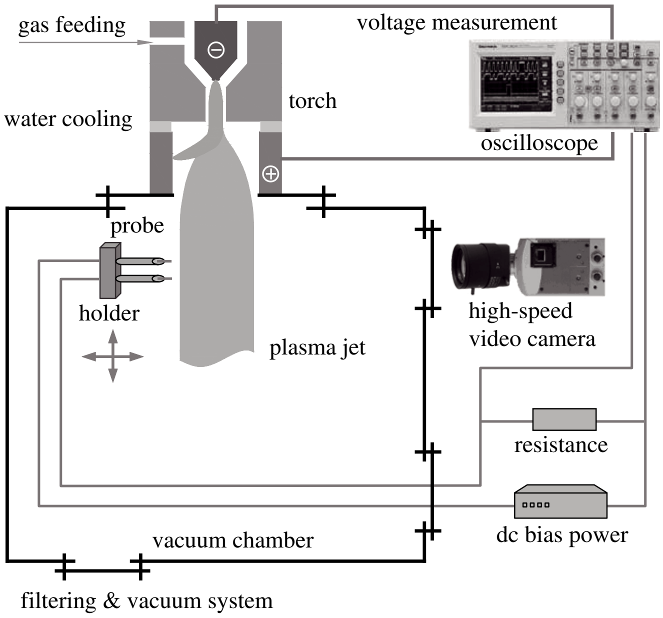


Figure 4. Schematic diagram of the experimental setup.

Fast Fourier transform (FFT) was applied to analyse the detected arc voltage spectra and ion saturation current spectra for discussing the characteristic frequency of the fluctuation in the arc column and jet flow.

4. Results and discussions

The measurement results of fluctuation conditions for arc voltage and plasma jet flow depending on the generating parameters such as gas flow rate and chamber pressure are illustrated and analysed. Correlations between jet flow state and the situation of arc voltage fluctuation are discussed.

4.1. Effects of gas flow rate and chamber pressure on the arc voltage fluctuation

The arc voltage shows low frequency waves in the whole range of gas flow rate as in figure 5 when the chamber pressure is fixed at 3000 Pa. At a low gas flow rate of 4.4 slm, there exists only a low frequency wave in the arc voltage spectra. As the gas flow rate increases, a high-frequency wave appears, superposed on the low frequency one with a smaller amplitude and becomes increasingly clear. FFT results at gas flow rates of 4.4, 8.8 and 17.6 slm corresponding to the data in figure 5 are shown in figure 6. It indicates that the low frequency wave is at 300 Hz, which reflects the characteristics of the power supply and appears in all cases regardless of the generating condition [4]. It will be called 'power fluctuation' in the following discussions. There is a clear peak at frequency near 3160 Hz for the arc voltage generated at a gas flow rate of 17.6 slm, but no high-frequency component could be found at a gas flow rate of 4.4 slm. A weak peak appeared at about 3460 Hz at the flow rate of 8.8 slm, indicating the existence of a high-frequency fluctuation under this working condition.

The effect of chamber pressure is different from that of the gas flow rate. Figure 7 shows that the high-frequency wave

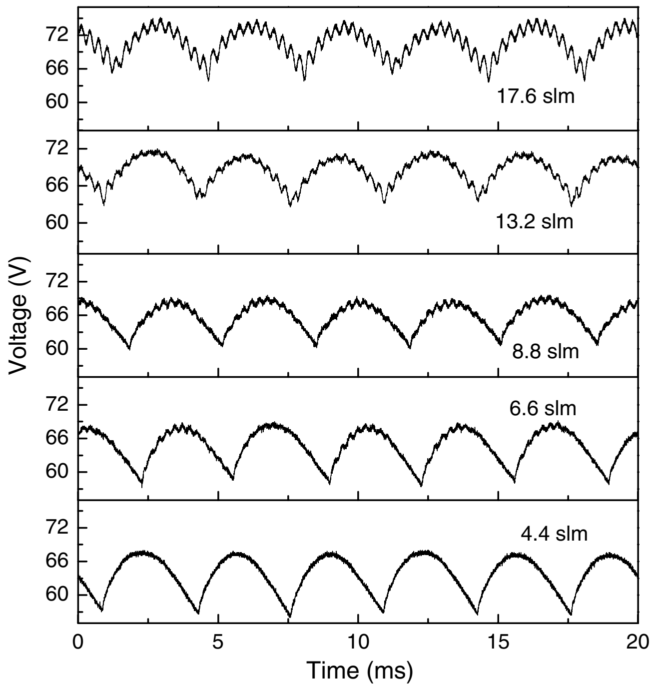


Figure 5. Time-resolved arc voltages at a chamber pressure of 3000 Pa and different gas flow rates of 17.6 slm, 13.2 slm, 8.8 slm, 6.6 slm and 4.4 slm.

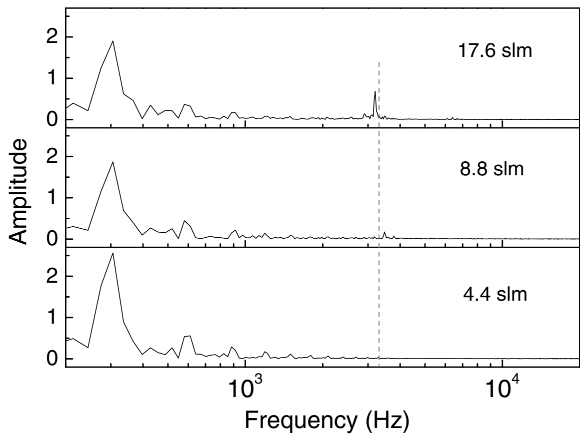


Figure 6. FFT results for arc voltage spectra at a chamber pressure of 3000 Pa and gas flow rates of 17.6 slm, 8.8 slm and 4.4 slm.

exists clearly at all chamber pressures ranging from 500 to 10 000 Pa, when the gas flow rate is fixed at the high level of 17.6 slm. Figure 8 is the FFT results corresponding to the voltage data in figure 7 at chamber pressures of 500 and 10 000 Pa. A sharp and clear peak appears at a frequency of about 3160 Hz under the two working conditions at the very different chamber pressures. That is, unlike the effect of gas flow rate on the high-frequency fluctuation of arc voltage, chamber pressure shows almost no effects on the existence and frequency of the high-frequency fluctuation component in the arc voltage.

Figure 9 summarizes the FFT analysis results for the high-frequency fluctuation in the arc voltage. The horizontal dashed line in the figure is an arithmetic mean of the frequency values, which remains at about 3180 Hz in the whole chamber pressure

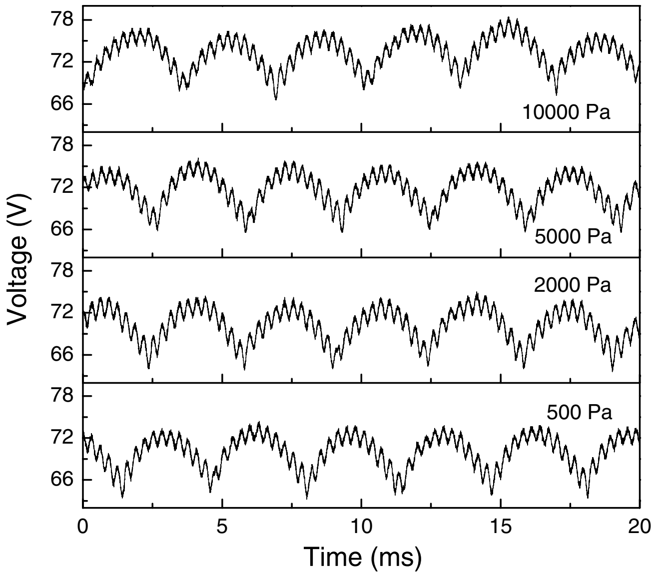


Figure 7. Time-resolved arc voltages at a gas flow rate of 17.6 slm and different chamber pressures of 10 000 Pa, 5000 Pa, 2000 Pa and 500 Pa.

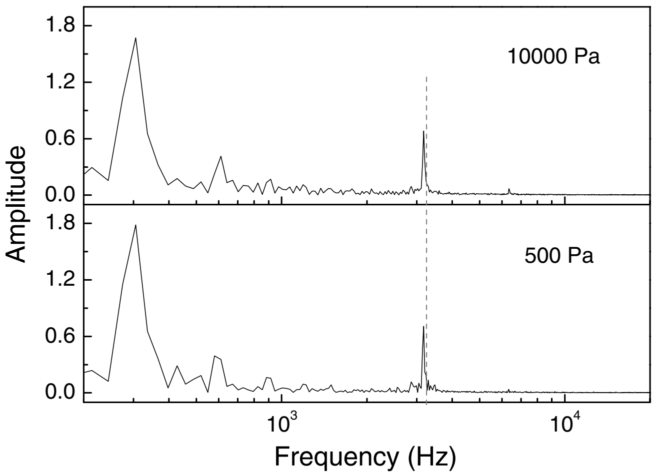


Figure 8. FFT results for arc voltage spectra at a gas flow rate of 17.6 slm and different chamber pressures of 10 000 Pa and 500 Pa.

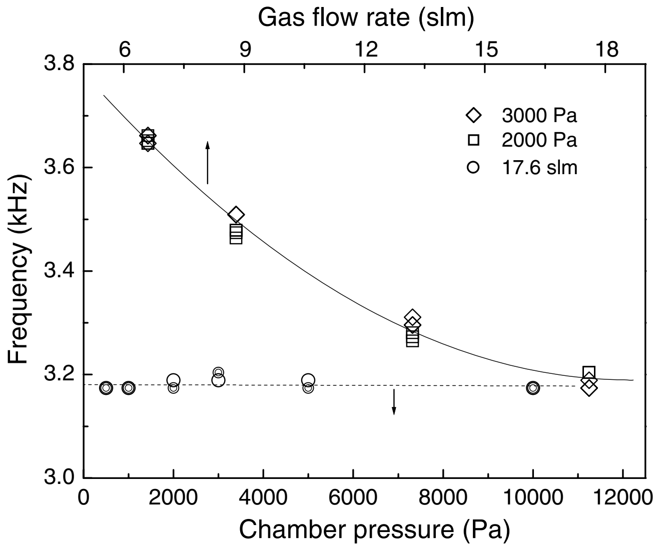


Figure 9. Variations of the characteristic frequency of high-frequency fluctuation in arc voltage with the change in chamber pressure at a fixed gas flow rate of 17.6 slm and with gas flow rate at chamber pressures of 2000 Pa and 3000 Pa.

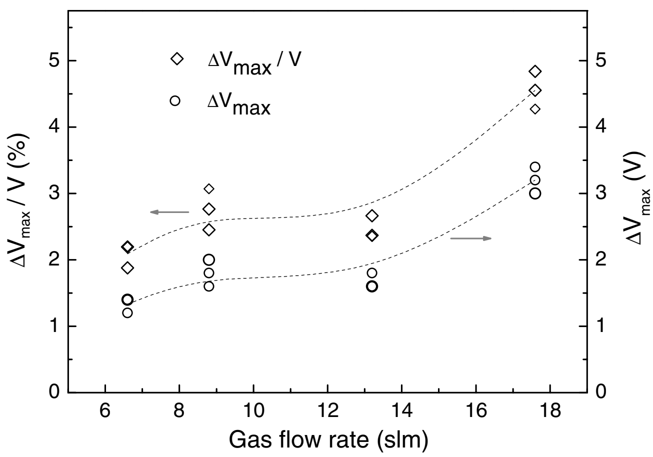


Figure 10. Variations of the maximum amplitude of high-frequency fluctuation in the arc voltage and the ratio of the maximum fluctuation to mean arc voltage with the gas flow rate at a chamber pressure of 2000 Pa.

range from 500 to 10 000 Pa when the gas flow rate is fixed at 17.6 slm. The solid line represents the experimental results at chamber pressures of 2000 and 3000 Pa as the gas flow rate changes from 4.4 to 17.6 slm. The fluctuation frequency decreases with increasing gas flow rate monotonically. This suggests that chamber pressure has no effect on the fluctuation frequency in the entire gas flow rate range in this work.

Setting the maximum value of the peak to valley of the high-frequency fluctuation as ΔV_{max}, and the mean value of the arc voltage as V, figures 10 and 11 show that variations of ΔV_{max} and $\Delta V_{max}/V$ change with the gas flow rate and chamber pressure. In figure 10, ΔV_{max} and $\Delta V_{max}/V$ both increased with increasing gas flow rate when the chamber pressure was fixed at 2000 Pa, and the highest values are about 3.3 V and 4.6%, respectively, at the high gas flow rate of 17.6 slm. However, ΔV_{max} and $\Delta V_{max}/V$ both decreased slightly with increasing chamber pressure when the gas flow rate was fixed at 17.6 slm as shown in figure 11. This could be due to the decrease in the actual flow velocity in the channel with the increase in chamber pressure when the feeding flow rate is kept unchanged.

4.2. *Effects of gas flow rate and chamber pressure on the condition of the jet flow*

The images of the visible plasma jets outside the torch nozzle taken by the high-speed video camera are shown in figure 12. In the case of low gas flow rates of 4.4 and 6.6 slm at the chamber pressure of 2000 Pa, no appreciable swinging can be seen in the luminous region of the jet flow even when the exposure time is as short as 10 μs, which indicates that the plasma jet could be in a stable laminar flow state. As the gas flow rate increases, the high temperature region represented by the high intensity light emission area in the image swung around irregularly. This is in step with the effect of gas flow rate on the fluctuation of

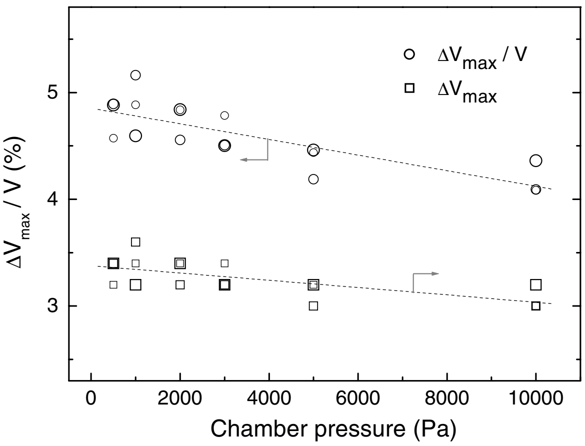


Figure 11. Variations of the maximum amplitude of high-frequency fluctuation in the arc voltage and the ratio of the maximum fluctuation to mean arc voltage with the chamber pressure at a gas flow rate of 17.6 slm.

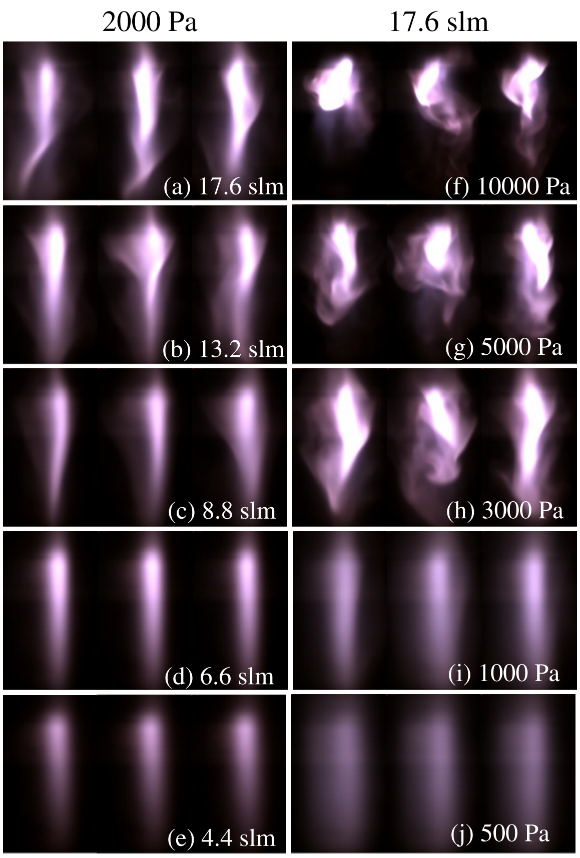


Figure 12. High-speed video camera images of the plasma jet generated under different working conditions. (*a*)–(*e*) at chamber pressure of 2000 Pa, (*a*) at gas flow rate of 17.6 slm, (*b*) 13.2 slm, (*c*) 8.8 slm, (*d*) 6.6 slm and (*e*) 4.4 slm; (*f*)–(*j*) at gas flow rate of 17.6 slm, (*f*) at chamber pressure of 10 000 Pa, (*g*) 5000 Pa, (*h*) 3000 Pa, (*i*) 1000 Pa and (*j*) 500 Pa. The recording rate of the camera was 2500 fps and the exposure time was 10 μs for each image, three images under the same working condition are taken in successive sequence.

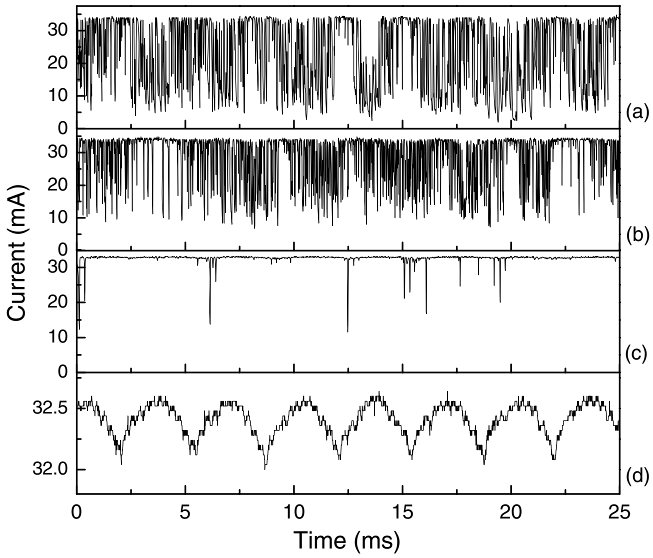


Figure 13. Time-resolved ion saturation current captured by the electrostatic probe at a gas flow rate of 17.6 slm and chamber pressures of (*a*) 10 000 Pa, (*b*) 5000 Pa, (*c*) 2000 Pa and (*d*) 500 Pa.

arc voltage shown in figure 5, in which the high-frequency fluctuation becomes evident as the gas flow rate increased above 6.6 slm. However, luminous images of the jet flow at 500 and 1000 Pa in figures 12(*i*) and (*j*) also show good stability and uniformity at the high gas flow rate of 17.6 slm, while there is a clear high-frequency fluctuation in their arc voltage as in figure 7 and the fluctuation amplitude (ΔV_{max}) is slightly higher than that generated at higher chamber pressures as in figure 11. This suggests that arc voltage fluctuations do not necessarily result in jet flow instability at these low pressures, and the two phenomena are not always directly related as cause and effect.

Figure 13 shows the time-resolved ion saturation current passing through the double-probe circuit set in the jet flow generated at different chamber pressures of 500, 2000, 5000 and 10 000 Pa at the fixed gas flow rate of 17.6 slm. The signal fluctuation increased with increasing chamber pressure. At the chamber pressure of 500 Pa, it shows a completely regular wave with about 1.8% amplitude fluctuation, which is similar to that of the arc voltage in figure 7. When the chamber pressure was at 2000 Pa, sudden jumping of the signal occurred occasionally. As the chamber pressure increased to 5000 Pa, the ion saturation current fluctuated violently almost all the time, and sometimes showed a very low value near zero at the chamber pressure of 10 000 Pa. This suggests that the high temperature region with relative high ionization and electron density swung at that instant away from the location at which the probe was set.

Figure 14(*a*) is the FFT analysis results for the ion saturation current shown in figure 13 at low chamber pressures of 500 and 2000 Pa. Similar to the situation for the arc voltage in figure 8, the peaks near 300 Hz owing to the power fluctuation and near 3160 Hz for the high-frequency fluctuation exist clearly at the chamber pressure of 500 Pa. This indicates that the plasma jet flow completely inherited and maintained the fluctuation characteristics of the arc voltage, and no other surge and turbulence factors were introduced to the plasma jet flow under this condition. As the chamber pressure increased to 2000 Pa, noises appear in almost whole frequency range but no evident peak is distinguished at the high-frequency side.

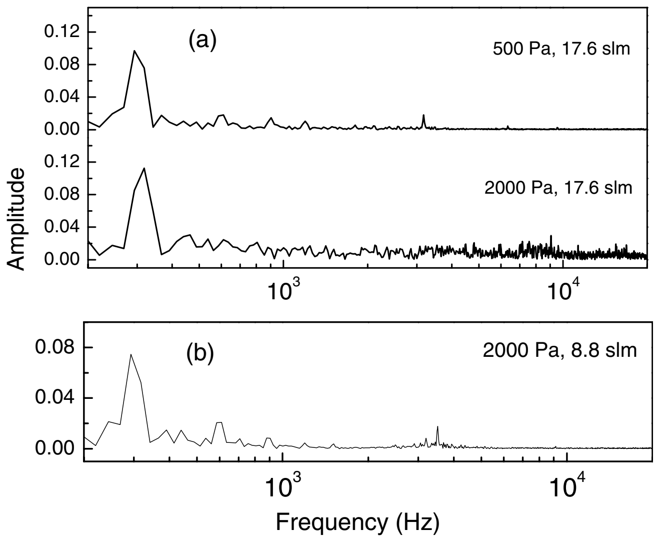


Figure 14. FFT results for ion saturation current captured by the electrostatic probe at (*a*) gas flow rate of 17.6 slm (chamber pressures of 500 Pa and 2000 Pa) and (*b*) at chamber pressure of 2000 Pa and gas flow rate of 8.8 slm.

When the chamber pressure increases to 5000 Pa, the signal shows a completely irregular fluctuation of larger amplitude. At the low gas flow rate of 8.8 slm and chamber pressure of 2000 Pa, peaks at 300 and 3490 Hz can be seen as in figure 14(*b*).

4.3. Discussion

It has been mentioned that the arc voltage fluctuation generally arises from three causes. In this work, the 300 Hz fluctuation is caused by the power fluctuation. It was determined that the high-frequency fluctuation over 3000 Hz did not match the irregular arc root movement observed in the previous work using the same torch and power supply [18], but Helmholtz oscillation seems to be a reasonable cause. According to the analysis of Coudert *et al* [20], the square of the Helmholtz oscillation frequency is proportional to the specific enthalpy h and to the gas pressure ratio of P_0/P. Here P_0 is the pressure in the cold cavity upstream of the arc column and P is the pressure in the nozzle channel. Figure 9 indicates that the change in chamber pressure does not affect the oscillation frequency at a fixed gas flow rate, which means that P_0/P and the arc voltage (hence, input power) were all changed insignificantly and resulted in a negligible effect on the frequency as the chamber pressure is changed. On the other hand, taking the situation at 2000 Pa as the example, figure 3 shows that the arc voltage increases from 63.9 to 70.2 V, a change of 9.9%, at a fixed arc current of 80 A, as the gas flow rate increases from 4.4 to 17.6 slm, an increase of 300%. The specific enthalpy of the flow would decrease quite appreciably and hence the oscillation frequency decreases with increasing gas flow rate clearly as shown in figure 9.

The fluctuations of the light signal at the torch exit generally show similar characteristics as the arc voltage [3, 5]. However, only the stable or laminar flows at the low chamber pressures and/or low gas flow rates show similar fluctuation characteristics between their arc voltage and electrostatic probe signal as shown in figures 7 and 13(*d*) of this work. With the increase in chamber pressure, plasma volume decreases and the high temperature region becomes shortened. And as the gas flow rate increases, the plasma jet flow transits from the stable laminar to a turbulent state. The potential core of the turbulent plasma jet becomes much shortened and locates completely within the long anode nozzle channel and is out of the visible region in the side view. Thus, as the chamber pressure and the gas flow rate increase, the electrostatic probe detects the ion saturation current in the downstream flow after the potential core of the turbulent plasma jet, in which the signal fluctuated irregularly in large scale as shown in figures 13(*a*) and (*b*) at chamber pressures of 10 000 and 5000 Pa.

The results indicate that the laminar or turbulent state of the plasma jet flow bears no direct dependence on the power fluctuation and Helmholtz oscillation of its arc voltage. For example, although the laminar flow at 500 Pa and the thoroughly developed turbulent flow at 10 000 Pa show similar fluctuation characteristics of their arc voltage as in figures 7 and 8, their jet appearance and electrostatic signal indicate quite different flow characteristics as in figures 12 and 13. Other factors besides arc voltage fluctuations, such as aerodynamic criteria, might also decidedly affect the state of the jet flow.

With the power supply used in the present setup, the fluctuation originated from the power supply always exists regardless of the torch structure and working parameters, but would be eliminated by selecting or improving the power units. The voltage amplitude of the Helmholtz oscillation is lower than 3.5 V, within 5% of the average voltage value. Accordingly, it could be expected that this kind of oscillation would not become the dominant factor affecting the controllability in materials processing. However, the plasma jet flow state of laminar or turbulent condition could be an important factor affecting the process controllability. One can expect that the general parameter estimation by experimental measurement or numerical simulation for a turbulent jet flow could only give a rough and time-averaged outline according to the results shown in figures 12 and 13, and it is difficult to achieve precise process control under turbulent flow conditions.

5. Conclusions

The results of the study on this type of plasma generator show that the arc voltage increases with increasing gas flow rate and, more gently, with increasing chamber pressure. The Helmholtz oscillations above 3000 Hz are detected superposed on the 300 Hz power fluctuation at high gas flow rates, and the oscillation frequency decreases monotonically with increasing gas flow rate and remains unchanged with the chamber pressure. The voltage amplitude of the oscillation is lower than 3.5 V, within 5% of the average voltage value, which should not have important effects on the controllability in materials processing. It is predicted that the long and narrow inter-electrode inserts mainly decided the length of the arc column, and the drag force of the flow in the wide nozzle region is too weak for driving the arc root movement to produce arc voltage fluctuations of the restrike mode. The laminar or turbulent state of jet flow shows no definite dependence on the power fluctuation of 300 Hz and Helmholtz oscillation in its arc voltage. The laminar jets at low gas feeding rates and/or low chamber pressures show steady flows while the turbulent jet flows at high gas flow rates and high chamber pressures swing around irregularly. Aerodynamic criteria downstream of the arc root attachment in the nozzle channel might decidedly affect the state of the jet flow. It is expected that the turbulent flow state could be a very important factor limiting the controllability for materials processing.

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References

[1] Nogues E, Vardelle M, Fauchais P and Granger P 2008 *Surf. Coat. Technol.* **202** 4387
[2] Kuz'min V, Solonenko O and Zhukov M 1995 *Proc. 8th National Thermal Spray Conference (Houston, TX)* p 83
[3] Dorier J L, Hollenstein Ch, Salito A, Loch M and Barbezat G 1999 *Proc. 14th Int. Symp. on Plasma Chemistry (Prague, Czech Republic)* vol 1 p 331
[4] Pan W X, Meng X and Wu C K 2006 *Plasma Sci. Technol.* **8** 416
[5] Zhao W H, Tian K, Tang H Z, Liu D and Zhang G Z 2002 *J. Phys. D: Appl. Phys.* **35** 2815
[6] Duan Z and Heberlein J 2002 *J. Thermal Spray Technol.* **11** 44
[7] Ghorui S, Vysohlid M, Heberlein J and Pfender E 2007 *Phys. Rev.* E **76** 016404
[8] Coudert J F and Rat V 2008 *J. Phys. D: Appl. Phys.* **41** 205208
[9] Pan W X, Meng X, Li T, Chen X and Wu C K 2007 *Plasma Sci. Technol.* **9** 152
[10] Brilhac J F, Pateyron B, Coudert J F, Fauchais P and Bouvier A 1995 *Plasma Chem. Plasma Process.* **15** 257
[11] Tu X, Cheron B G, Yan J H and Cen K F 2007 *Plasma Sources Sci. Technol.* **16** 803
[12] Zhukov M F and Zasypkin I M 2007 *Thermal Plasma Torches—Design, Characteristics, Applications* (Cambridge, UK: Cambridge International Science Publishing)
[13] Pan W X, Zhang W Hong, Zhang W Hua and Wu C K 2001 *Plasma Chem. Plasma Process.* **21** 23
[14] Pan W X, Meng X, Chen X and Wu C K 2006 *Plasma Chem. Plasma Process.* **26** 335
[15] Pan W X, Lu F X, Tang W Z, Zhong G F, Jiang Z and Wu C K 2000 *Diamond Relat. Mater.* **9** 1682
[16] Pan W X, Meng X, Li G., Fei Q X and Wu C K 2005 *Surf. Coat. Technol.* **197** 345
[17] Pan W X, Ma W and Wu C K 2001 *Proc. Int. Symp. of Young Scholars on Mechanics and Material Engineering for Science and Experiments (Changsha, China)* p 427
[18] Huang H J, Pan W X and Wu C K 2008 *Chin. Phys. Lett.* **25** 4058
[19] Pouring A A 1965 *Phys. Fluids* **8** 1802
[20] Coudert J F, Rat V and Digot D 2007 *J. Phys. D: Appl. Phys.* **40** 7357