THEORETICAL & APPLIED MECHANICS LETTERS **1**, 024001 (2011)

Unsteadiness in non-transferred dc arc plasma generators

Chengkang Wu[a] and Wenxia Pan

Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

(Received 20 February 2011; accepted 26 February 2011; published online 10 March 2011)

Abstract Non-transferred dc arc plasma generators are widely used in materials processing. They are generally considered steadily-operating devises. However, unsteady phenomena do exist in them, and may cause non-ideal effects in processes which require high controllability and reproducibility. These unsteady phenomena can cause parameter fluctuations in the arc and the plasma jet, some of which have been studied in recent years. Several types and mechanisms of these phenomena have been identified. This paper reviews the research progress in this specific area, hoping to present a more complete picture of this subject. [doi:10.1063/2.1102401]

Keywords unsteadiness, fluctuation, arc, plasma jet, plasma generator

I. INTRODUCTION

Over several decades, the non-transferred dc arc plasma jet has demonstrated many hard-to-replace practical achievements in the wide technical areas related to gas and materials heating, owing to its high temperature (2 000 K–30 000 K), almost arbitrary gaseous composition, and relatively simple method of production and inexpensive equipments.[1–11] Along with the rapid advancements in science and technology, increasingly higher requirements are brought up in the more exact and finer control of its working parameters resulting in better steadiness and reproducibility of the processes. In this respect, the unsteadiness or fluctuation characteristics of the dc arc plasma has become an important factor affecting its further application in the field of high-precision materials processing.[6,8,12–15]

Research till now has shown that, there are three main types of factors causing fluctuations in the electric power of the arc: one is the fluctuations in the arc voltage resulting from the complex dynamic interaction between the aerodynamic force due to the supplied gas heated by the arc and the electro-magnetic and breakdown behavior of the arc near the electrodes, often resulting in sporadic motion of the arc root on the electrode surface and variation of the length of the arc,[13–35] a "shunting" type of arc typically can have peak voltage fluctuations almost of the same order as the average arc voltage; another type is voltage fluctuations associated with the Helmholtz (acoustic) resonance, the intensity and frequency of which are determined by the structure of the flow passage, amount and method of gas supply, and the arc current;[29–31,36–43] the third type is the current and voltage fluctuations resulting from the output characteristics of the power supply to the plasma generator.[32–34,38–45] There are two main types of factors causing unsteadiness in the plasma jet issuing from the plasma generator: one is the fluctuations of jet parameters resulting mainly from the varying electric power input to the arc, having the same frequency and magnitude characteristics as the arc fluctuations, usually clearly discernable or can be fully maintained only in the potential core region of the turbulent jet near the generator exit,[14,22,34,35,44,46–48] or to a wider extent in laminar plasma jets,[7,43,49–51] another type is due to the aerodynamic instability in the plasma jet outside the potential core, finally producing a fully turbulent flow, it is generally unrelated to the arc fluctuations, its appearance and intensity depends on the combined effects of rate and form of gas supply, structure of the passage for the arc jet, and the arc power.[38,43,51–54] Briefly summarizing, it can be said that there are two main kinds of unsteadiness, those of the arc and those of the jet. Some of these two types have a cause and effect relationship, and some do not.

The significance of studying the unsteadiness in arc plasma generators can be twofold: one is for the refined control of plasma materials processing, where fluctuations in plasma jet parameters need to be understood or minimized; another is for applications in basic research such as plasma flow and heat transfer studies, non-equilibrium effects, standard heat source, etc., where steady and reproducible plasma parameters are necessary. This paper will review progress in research on fluctuations of the arc and jet in non-transferred dc arc plasma generators.

II. CHARACTERISTICS AND INFLUENCING FACTORS OF FLUCTUATIONS IN THE ARC

A. Jumping of the arc root and variation in the arc length

Fluctuation characteristics of the arc are often studied by measuring the arc voltage and its fluctuation, also, to a much lesser extent, by simultaneously measuring the arc voltage and current. Some studies were made by observing the sporadic motion of the arc root, or measuring the thickness of gas layer between the arc column and wall of the generator passage. Usually, in

---

[a] Corresponding author. Email: ckw@imech.ac.cn.

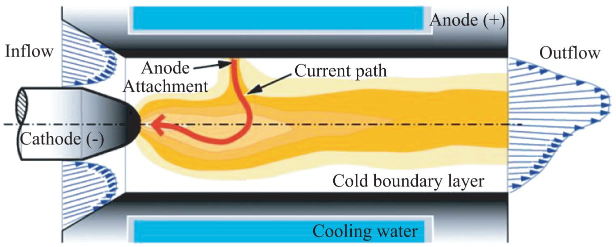


Fig. 1. Schematic representation of the flow inside a dc plasma torch.[25]

the non-transferred dc arc plasma generator, the supplied working gas flows through a cylindrical passage between the cathode and the anode, where a column of electric arc current exists under the potential difference between the electrodes. The near region of arc attachment to the electrode surface is called the arc root. The gas temperature in the central region of the arc usually exceeds 10 000 K, thus the gas density in this region is very much lower than that of the gas layer near the wall of the plasma generator, due to the effect of thermal expansion. In these cases, the arc column can be considered to behave like a body separated from the cold gas with relatively little inter-diffusion between them, and will move due to the aerodynamic force acting on it by the flow of the cold gas. With the usual configuration of the arc in the passage, as shown in Fig. 1,[25] the arc column is curved near the point of attachment of the arc root, the gas flow causes the arc to move downstream, lengthening the arc column and causing a higher arc voltage. At the same time, according to the Steenbeck Minimum Principle, the electric arc always tends to stabilize at a point where the energy dissipation is a minimum, which results in a shortening of the arc. These factors create a dynamic balance between the various tendencies of the arc column behavior.

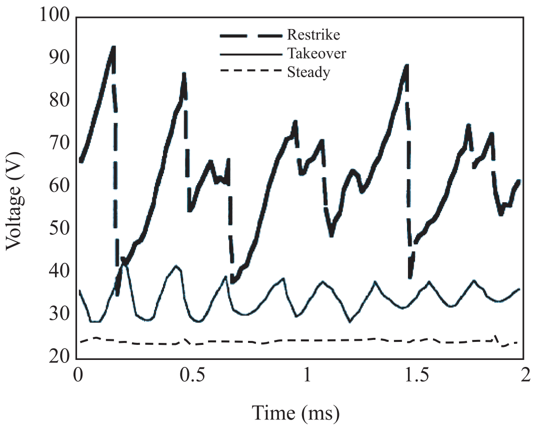


Fig. 2. Basic arc operating modes. Restrike mode: 100 A, 12/40 slm of Ar/He; takeover mode: 500 A, 40/20 slm of Ar/He; and steady mode: 900 A, 60 slm Ar.[13]

In a "shunting" (re-strike) mode of arc voltage behavior as shown in Fig. 2,[13] when the arc column has lengthened to such a point that the potential difference between a certain point along the arc column and the wall of the generator passage becomes high enough to cause an electric breakdown of the gas layer at that point, the arc is suddenly much shortened and the voltage suddenly drops to a much lower value. Such large-scale fluctuations of the arc is dependent on the type, flow rate, supply method of the working gas, structure of the arc passage of the plasma generator, and magnitude of the arc current,[13,16,17,20,21] and are fluctuating inputs hard to control to the heating of the arc and the unsteadiness in the plasma jet. However, it is also the sporadic jumping around of the arc root in such mode of operation that avoids the catastrophic rapid burning out at local spots on the electrode, and could result in longer electrode life of the generator under large currents. The steady mode of operation shown in Fig. 2 was produced under the conditions of large arc current and no swirling in gas supply, where the arc root is attached at a fixed point on the anode surface. The arc voltage shows no noticeable variation with time. With such low arc voltage in this mode of operation, the thermal efficiency of the plasma generator would be quite low, and electrode erosion is likely to occur in a short period. Also, it can easily change into other modes of operation.[13,21]

For the simple plasma generators without inter-electrode inserts, which are often used in industry, the operation is generally in the re-strike mode. A large number of studies have been made on this mode and its effect on the plasma spray processes for materials treatment.[13–35] In actual applications, there often exists transforming between or coexisting of the different modes, including a mixture of several modes involving arc root jumping, or other modes without jumping of the arc root.[13,21,29–34]

It is worthwhile to point out that in most studies so far, fluctuations in the arc current have not been dealt with. Usually it is assumed that the arc current is fixed at a given value controlled by the setting of the electrical power supply. Actually, there are also fluctuations of the arc current around this mean value set by the control knob, the nature of which is dependent not only on the V-A characteristic of the arc, but also on the type and output characteristics, both time-averaged and transient, of the power supply. The instantaneous electric power supplied to the arc is the product of the arc voltage and arc current, thus the energy fluctuation of the arc is not manifested by the variation in arc voltage alone (e.g. see Ref. 54).

B. Helmholtz resonance

When gas flows through a cavity passage, Helmholtz resonance can arise, depending on the structure of the passage and the flow conditions. These oscillations in

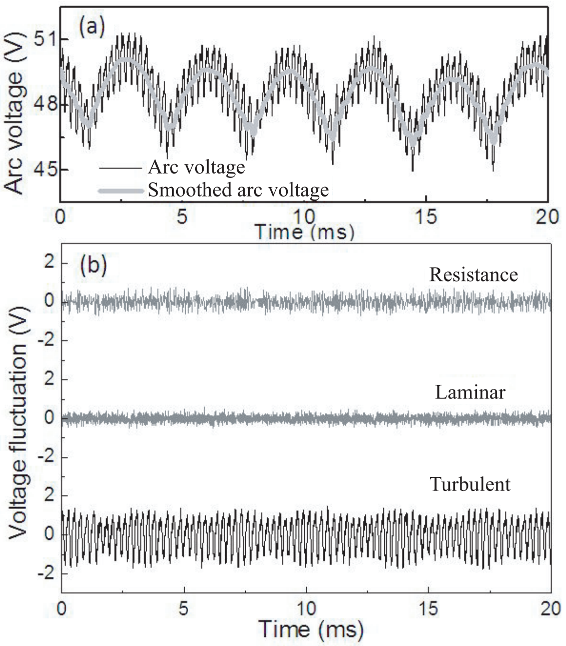


Fig. 3. Time resolved arc voltage in turbulent plasma jet generation (gas flow rate: 4.0×10^{-4}kg/s) and its smoothed counterpart (a) , voltage fluctuation on resistance and arcs in laminar (gas flow rate: 1.9×10^{-4}kg/s) and turbulent (4.0×10^{-4}kg/s) plasma generation (b), at arc current of 180 A.[38]

pressure and flow are acoustic in nature, and can have an effect on the parameters of the arc through the interaction between the gas flow and the electric discharge. These waves are detected most conveniently by the fluctuations in the arc voltage.

Neglecting effects of viscosity, the frequency of oscillation is given by

$$f = a/2\pi\sqrt{A/VL} \tag{1}$$

which is deduced from the vibration of small mass of gas in the neck with sectional area A and length L of a cavity with volume V.

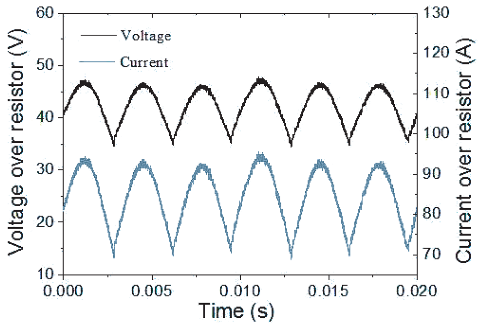
When a plasma is generated in the cavity, Eq. (1) is also applicable to the estimation of the Helmholtz oscillation frequency. However, the speed of sound in the cathode cavity and the inter-electrode channel are not easily measured. It is essential to estimate the plasma density through the measurement of specific enthalpy of the plasma in the inter-electrode channel. Thus Eq. (1) can be revised to $f = K\sqrt{\gamma_c(\gamma - 1/\gamma)(P_c/P)h}$.[18] Here, $K = 1/2\pi\sqrt{A/VL}$, subscript c refers to the quantity in the cathode cavity, P and h stand for the pressure and specific enthalpy in the inter-electrode channel, respectively.

Figure 3(a) shows the voltage fluctuations due to Helmholtz resonance superposed on the 300 Hz variation due to ripples in the power supply.[38] The lower curve in Fig. 3(b) shows the arc voltage variation due to Helmholtz resonance only. The arc voltage in the same generator but with a much lower gas flow rate is shown in the middle curve, exhibiting no fluctuations due to Helmholtz resonance. In this generator, there is a rather long inter-electrode insert with a floating potential, so the arc was stretched to a relatively great length. Although there still existed erratic motion of the arc root,[52,53] the variation of arc length caused by such motion and thus the voltage variations are quite negligible.[38,40,43]

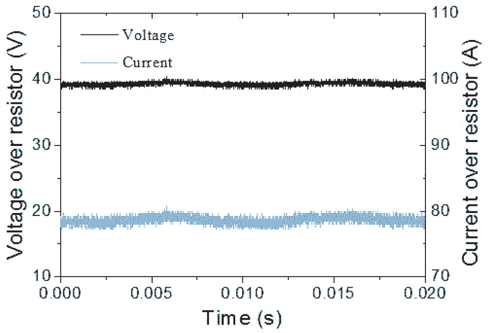
The frequency of Helmholtz fluctuation in generators is usually several kilo-Hertz, often superposed on the voltage fluctuations due to arc shunting or ripples in power supply.[29–31,38–43] In a recent study, pure Helmholtz fluctuations in arc voltage are detected in a generator using a power supply without ripples and having multiple inter-electrode inserts, under the condition of fixed gas flow and arc current.[54]

C. Fluctuations from power supply characteristics

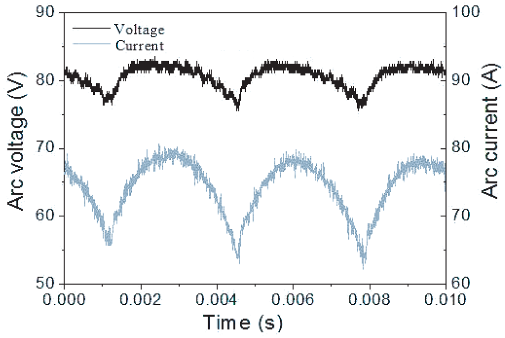
Many non-transferred dc arc plasma generators, especially those of higher power rating, employ rectified power supplies. For 50 Hz lines, these power supplies have ripples of 300 Hz or 150 Hz in their output voltage wave shape, depending on the rectifying circuit used.[32,33,42–44] Also, depending on the circuitry used, the instantaneous output current is not necessarily constant at the control setting, but may have fluctuations related to the transient behavior of the power supply. These will cause fluctuations in the arc voltage and current with the same frequency, sometimes resulting in large fluctuations in arc power input. The electric arc, being resistive in nature but with varying resistance, the resistivity of which depending on the arc current and configuration of discharge, might have either rising or falling V-A characteristics. So the magnitude of fluctuations in arc input power will also depend on the characteristics of the arc. These voltage fluctuations resulting from the power supply are often superposed with those caused by the sporadic arc root motion and the Helmholtz resonance.[32–34,38–43] Figure 3(a) shows a typical superposition of the voltage fluctuations from Helmholtz resonance and those from the power supply.[38] Figure 4(c) shows mainly fluctuations caused by the power supply, with weak fluctuations from Helmholtz resonance superposed on them.[54] The ripples in the power supply output can be reduced or largely eliminated by various means, but most simply in smaller power supplies by placing L-C filters between the power source and the plasma generator. Figure 4(d) shows an arc voltage record in such an arrangement, using long inter-electrode inserts and a correct combination of gas flow and arc current, producing a basically fluctuation-free, steady arc. The plasma jet produced in this case is a steady, laminar one. With varying values of gas flow rate and arc current, fluctuations purely due to Helmholtz resonance may appear.[54] While using ripple-free power supply and the commonly



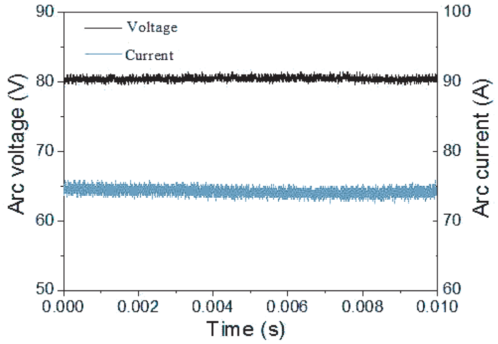
(a) Without LC filter



(b) With LC filter



(c) Without LC filter



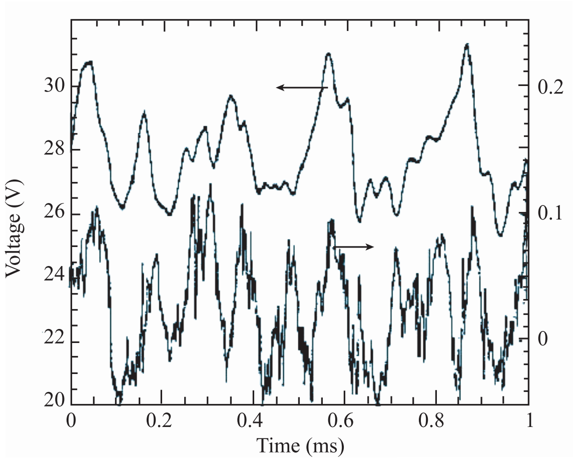
(d) With LC filter

Fig. 4. 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.[54]

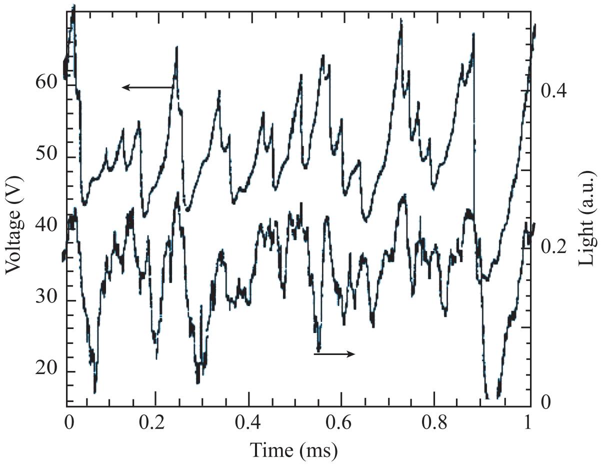
employed plasma generators without inter-electrode inserts, several modes of fluctuations (Fig. 2) and mixed modes[29–34,38–43] may appear, according to the operating conditions.

III. FLUCTUATIONS IN THE PLASMA JET

There are several methods to detect fluctuations in the plasma jet, for instance: light emission spectrum measurements in the jet near the generator exit can detect the light intensity and its variation;[22,34,35] direct observation of the jet appearance and its variation;[43,46–50] electrostatic probe measurements in the jet for detecting the value of ion saturation current and its variation,[43] etc. Figure 5 is a comparison[22] between the record of variation of arc voltage and the record of light intensity variation of the jet, showing



(a) 50 slm Ar



(b) 4/50 slm H_2/Ar

Fig. 5. Typical time dependence of the torch voltage and light emission collected on jet axis at 1 mm from the nozzle exit for two gas mixtures: (a) 50 slm Ar and (b) 4/50 slm H_2/Ar (500 A, straight flow gas injector, sampling time 0.2 μs).[22]

generally a direct correlation between the two quantities. These observations were made at a point near the exit of the generator, and the position of the arc root was quite near the exit. At this point, the gas temperature was very high, so the density was low and viscosity high, and the flow was nearly laminar in this core region of about 10 mm in length. Downstream of this region and in the jet boundary, the flow quickly developed into the turbulent state.

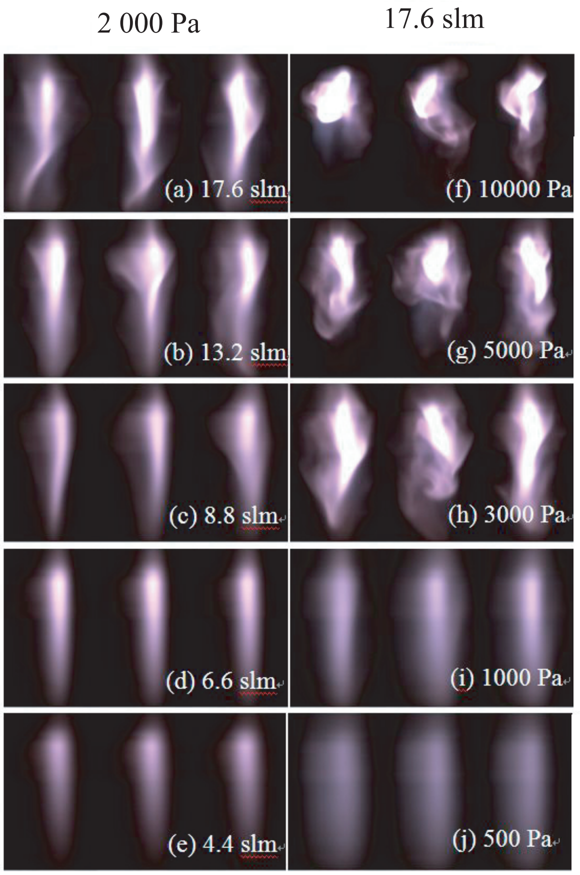


Fig. 6. High-speed video camera images of the plasma jet generated under different working conditions. (a)–(e) at chamber pressure of 2 000 Pa, (a) at gas flow rate of 17.6 slm, (b) 13.2 slm, (c) 8.8 slm, (d) 6.6 slm and (e) 4.4 slm; (f–j) at gas flow rate of 17.6 slm, (f) at chamber pressure of 10 000 Pa, (g) 5 000 Pa, (h) 3 000 Pa, (i) 1 000 Pa and (j) 500 Pa. The recording rate of the camera was 2 500 fps and the exposure time was 10 μs for each image, three images under the same working condition are taken in the successive sequence.[43]

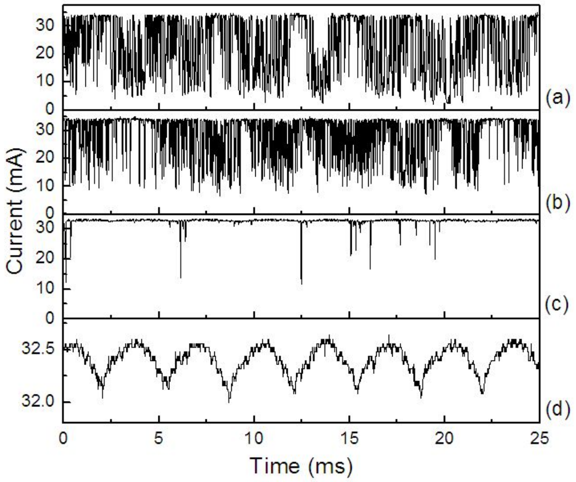


Fig. 7. Time-resolved ion saturation current captured by the electrostatic probe at gas flow rate of 17.6 slm and chamber pressure of (a) 10 000 Pa, (b) 5 000 Pa, (c) 2 000 Pa and (d) 500 Pa.[43]

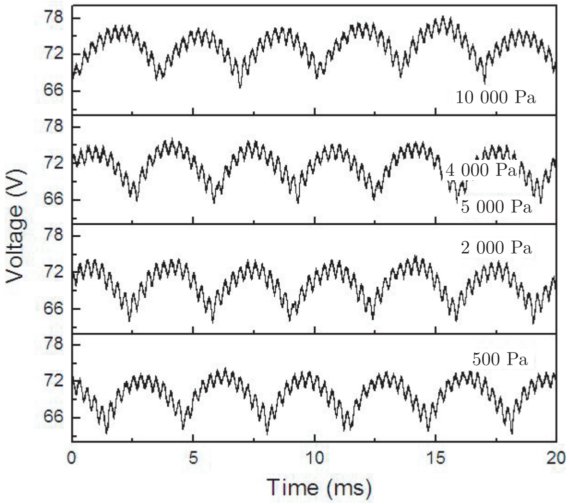


Fig. 8. Time-resolved arc voltages at gas flow rate of 17.6 slm and different chamber pressure of 10000 Pa, 5000 Pa, 2000 Pa and 500 Pa.[43]

The high speed video camera images in Fig. 6 show that[43], with the variations in the flow rate of the working gas and the pressure at the generator exit, the plasma jet appeared in either laminar, transitional or turbulent conditions. At a fixed flow rate of 17.6 slm, laminar flow was observed at an exit pressure of 500 Pa, with a steady picture of the luminous zone; while at exit pressures of 5 000 Pa or 10 000 Pa, the plasma has turned into turbulent jets. Figure 7 shows the variation[43] of ion saturation current on a double electrostatic probe immersed in the plasma jet. It can be seen that, at 500 Pa exit pressure, the signal showed quite regular fluctuation behavior; but at 5 000 Pa and 10 000 Pa, the signal became completely irregular, indicating a turbulent flow. However, the voltage fluctuations corresponding to these conditions, as shown in Fig. 8,[43] have the same characteristics, which is small amplitude Helmholtz oscillations superposed on the 300 Hz fluctuations from the power supply. The regular variations in light emission intensity of the laminar plasma jet as shown in Fig. 9 are entirely in step with the 300 Hz arc voltage variations[40] due to the power supply ripples. Thus, only the laminar plasma jet will completely

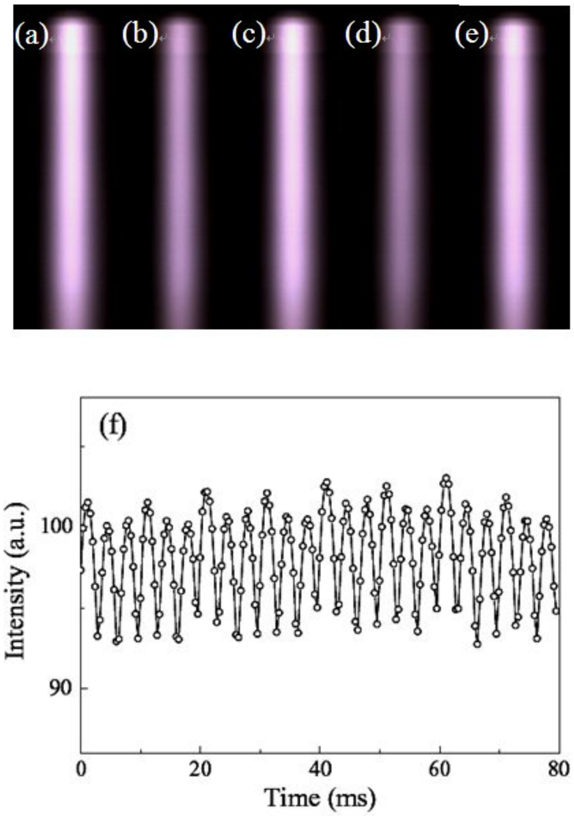


Fig. 9. Time-dependent stability of the plasma jet generated at 80 A, 10 kPa with a total gas flow rate of 16.8 slm. (a)–(e) High-speed video camera photos of the plasma jets with time intervals of 2 ms and exposure time of 1 μs; (f) variation of plasma jet intensities with time.[40]

inherit the fluctuations of the electric arc; the fluctuations in the turbulent jet cannot directly represent the fluctuations in the arc inside the generator. Conversely, the fluctuations in the arc cannot solely determine the fluctuations in the turbulent jet.

IV. CONCLUDING REMARKS

From recent studies on unsteadiness in non-transferred dc arc plasma generators, it can be seen that there are fluctuations in the arc caused by motion of the arc root, Helmholtz resonance in the flow passage, and power supply characteristics; and fluctuations in the plasma jet caused by the varying arc input power and the gas-dynamic instability which results in turbulent flow. The latter phenomenon is generally not directly related to fluctuations in arc parameter. Controlling or elimination of these fluctuations may be helpful to materials processing or other applications which require high controllability and reproducibility.

This work was supported by the National Natural Science Fouadation of China (50836007, 10921062).

1. E. Pfender, Plasma Chem. Plasma Process. **19**, 1 (1999).
2. P. Fauchais, J. Phys. D: Appl. Phys. **37**, R86 (2004).
3. M. I. Boulos, P. Fauchais, and E. Pfender, *Thermal Plasmas* (Plenum Press, New York, 1994).
4. P. Fauchais, G. Montavon, M. Vardelle, and J. Cedelle, Surf. Coat. Technol. **201**, 1908 (2006).
5. J. Heberlein, Pure and Applied Chemistry **74**, 327 (2002).
6. W. X. Pan, G. Li, X. Meng, W. Ma, and C. K. Wu, Pure Appl. Chem. **77**, 373 (2005).
7. W. X. Pan, F. X. Lu, W. Z. Tang, G. F. Zhong, Z. Jiang, and C. K. Wu, Diamond Relat. Mater. **9**, 1682 (2000).
8. W. X. Pan, X. Meng, G. Li, Q. X. Fei, and C. K. Wu, Surf. Coat. Technol. **197**, 345 (2005).
9. B. Bottin, M. Carbonaro, O. Chazot, G. Degrez, D. V. Abeele, P. Barbante, S. Paris, V. Van Der Haegen, T. Magin, and M. Playez, Contributions to Plasma Physics **44**, 472 (2004)
10. W. X. Pan, T. Li, and C. K. Wu, Chin. Phys. Lett. **26**, 125201 (2009)
11. J. Heberlein, and A. B. Murphy, J. Phys. D: Appl. Phys. **41**, 1 (2008).
12. J. F. Bisson, B. Gauthier, and C. Moreau, J. Thermal Spray Technol. **12**, 38 (2003).
13. Z. Duan, and J. Heberlein, J. Thermal Spray Technol. **11**, 44 (2002).
14. C. Moreau, J. F.Bisson, R. S. Lima, and B. R. Marple, Pure Appl. Chem. **77,** 443 (2005).
15. R. Etchart-Salas, V. Rat, J. F. Coudert, P. Fauchais, N. Caron, K. Wittman, and S. Alexandre, J. Thermal Spray Technol. **16**, 857 (2007).
16. E. Nogues, M. Vardelle, P. Fauchais, and P. Granger, Surf. Coat. Technol. **202**, 4387 (2008).
17. E. Nogues, P. Fauchais, M. Vardelle, and P. Granger, J. Thermal Spray Technol. **16**, 919 (2007).
18. J. F. Coudert, V. Rat, and D. Digot, J. Phys. D: Appl. Phys. **40**, 7357 (2007).
19. S. Ghorui, M. Vysohlid, J. Heberlein, and E. Pfender, Physical Review E **76,** 016404 (2007).
20. M. Vysohlid, and J. Heberlein, Thermal Spray 2004/Advances in Technology and Application, May 10–12, Osaka, 998 (2004).
21. Z. Duan, *Investigations of plasma instabilities in a spray torch*, Ph. D thesis, University of Minnesota, 2000.
22. J. L. Dorier, C. Hollenstein, A. Salito, M. Loch, and G. Barbezat, 14th Int. Symp. on Plasma Chemistry, Aug. 2–6, Prague, **1**, 331 (1999).
23. R. Etchart-Salas, V. Rat, and J. F. Coudert, High Temperature Material Processes **10**, 407 (2006).
24. J. F. Coudert, and P. Fauchais, Annals of the New Your Academy of Sciences **891**, 382 (1999).
25. J. P. Trelles, E. Pfender, and J. Heberlein, J. Phys. D: Appl. Phys. **40**, 5635 (2007).
26. A. Kaminska, and W. Zmudzinski, 15th Int. Symp. on Plasma Chemistry, July 9-13, Orleans, **3**, 1123 (2001).
27. S. Janisson, A. Vardelle, J. F. Coudert, P. Fauchais, and E. Meillot, Annals of the New Your Academy of Sciences **891**, 407 (1999).
28. E. Nogues, M. Vardelle, P. Fauchais, and P. Granger, High Temperature Material Processes **11**, 161 (2007).
29. J. F. Coudert, and V. Rat, Surf. Coat. Technol. **205**, 949 (2010).
30. V. Rat, and J. F. Coudert, J.Applied Physics **108**, 043304 (2010).
31. V. Rat, and J. F. Coudert, Applied Physics Letters **96**, 101503 (2010).
32. J. F. Brilhac, B. Pateyron, G. Delluc, J. F. Coudert, and P. Fauchais, Plasma Chem. Plasma Process. **15**, 231 (1995).
33. P. Mohanty, Jovan Stanisic, Jelena Stanisic, A. George, and Y. Wang, J. Thermal Spray Technol. **19**, 465 (2010).
34. W. H. Zhao, K. Tian, D. Liu, and G. Z. Zhang, Chin. Phys. Lett. **18**, 1092 (2001).

35. J. F. Coudert, M. P. Planche, and P. Fauchais, Plasma Chem. Plasma Process. **15**, 47 (1995).
36. L.Delair, X. Tu, A. Bultel, and B. G. Cheron, High Temperature Material Processes **9**, 583 (2005).
37. J. F. Coudert, and V. Rat, J. Phys. D: Appl. Phys. **41**, 205208 (2008).
38. W. X. Pan, X. Meng, and C. K. Wu, Plasma Sci. Technol. **8**, 416 (2006).
39. X. Tu, B. G. Cheron, J. H. Yan, L. Yu, and K. F. Cen, Physics of Plasmas **15**, 053504 (2008).
40. H. J. Huang,W. X. Pan, Z. Y. Guo, and C. K. Wu, J. Phys. D: Appl. Phys. **43**, 085202 (2010).
41. X. Tu, B. G. Cheron, J. H. Yan, and K. F. Cen, J. Phys. D: Appl. Phys. **40**, 3972 (2007).
42. X. Tu, B. G. Cheron, J. H. Yan, and K. F. Cen, Plasma Sources Sci.Technol. **16**, 803 (2007).
43. W. X. Pan, Z. Y. Guo, X. Meng, H. J. Huang, and C. K. Wu, Plasma Sources Sci. Technol. **18**, 045032 (2009).
44. J. Hlina, J. Gruber, and J. Sonsky, 2007 IEEE Pulsed Power Conference, **1**–**4**, 622 (2007).
45. W. H. Zhao, K. Tian, H. Z. Tang, D. Liu, and G. Z. Zhang, J. Phys. D: Appl. Phys. **35**, 2815 (2002).
46. J. Hlina, V. Nenicka, and J Sonsky, 16^{th} Int. Symp. on Plasma Chemistry, June 22-27, Taormina, ISPC-514 (2003).
47. O. humak, and M. Hrabovsky, Czechoslovak Journal of Physics **56** Suppl. B, B767 (2006).
48. S. Russ, E. Pfender, and P. J. Strykowski, Plasma Chem. Plasma Process. **14**, 425 (1994).
49. W. X. Pan, X. Meng, T. Li, X. Chen, and C. K. Wu, Plasma Sci. Technol. **9**, 152 (2007).
50. W. X. Pan, W. H. Zhang, W. H. Zhang, and C. K. Wu, Plasma Chem. Plasma Process. **21**, 23 (2001).
51. W. X. Pan, X. Meng, X. Chen, and C. K. Wu, Plasma Chem. Plasma Process. **26**, 335 (2006).
52. H. J. Huang, W. X. Pan, and C. K. Wu, Chin. Phys. Lett. **25**, 4058 (2008).
53. W. X. Pan, T. Li, X. Meng, X. Chen, and C. K. Wu, Chin. Phys. Lett. **22**, 2895 (2005).
54. H. J. Huang, W. X. Pan, and C. K. Wu, Submitted to J. Phys. D: Appl. Phys. (2011).