ISSN 1674-1056
http://cpb.iphy.ac.cn
http://iopscience.iop.org/cpb
中国物理 B
Chinese Physics
中国物理 Chinese Physics B

Fluctuation of arc plasma in arc plasma torch with multiple cathodes

Zelong Zhang(张泽龙), Cheng Wang(王城), Qiang Sun(孙强), Weidong Xia(夏维东)
Citation: Chin. Phys. B . 2019, 28(9): 095201 . **doi:** 10.1088/1674-1056/28/9/095201
Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Experimental investigation on electrical characteristics and ignition performance of multichannel plasma igniter

Sheng-Fang Huang(黄胜方), Hui-Min Song(宋慧敏), Yun Wu(吴云), Min Jia(贾敏), Di Jin(金迪), Zhi-Bo Zhang(张志波), Bing-Xuan Lin(林冰轩)
Chin. Phys. B . 2018, 27(3): 035203 . **doi:** 10.1088/1674-1056/27/3/035203

Characteristics of helium DC plasma jets at atmospheric pressure with multiple cathodes

Cheng Wang(王城), Zelong Zhang(张泽龙), Haichao Cui(崔海超), Weiluo Xia(夏维珞), Weidong Xia(夏维东)
Chin. Phys. B . 2017, 26(8): 085207 . **doi:** 10.1088/1674-1056/26/8/085207

Production of a large area diffuse arc plasma with multiple cathode

Cheng Wang(王城), Hai-Chao Cui(崔海超), Wan-Wan Li(李皖皖), Meng-Ran Liao(廖梦然), Wei-Luo Xia(夏维珞), Wei-Dong Xia(夏维东)
Chin. Phys. B . 2017, 26(2): 025202 . **doi:** 10.1088/1674-1056/26/2/025202

Evolution of magnetically rotating arc into large area arc plasma

Wang Cheng, Li Wan-Wan, Zhang Xiao-Ning, Zha Jun, Xia Wei-Dong
Chin. Phys. B . 2015, 24(6): 065206 . **doi:** 10.1088/1674-1056/24/6/065206

Growth of small diameter multi-walled carbon nanotubes by arc discharge process

K. T. Chaudhary, J. Ali, P. P. Yupapin
Chin. Phys. B . 2014, 23(3): 035203 . **doi:** 10.1088/1674-1056/23/3/035203

Fluctuation of arc plasma in arc plasma torch with multiple cathodes*

Zelong Zhang(张泽龙), Cheng Wang(王城)†, Qiang Sun(孙强), and Weidong Xia(夏维东)‡

Department of Thermal Science and Energy Engineering, University of Science and Technology, Hefei 230027, *China*

(Received 13 June 2019; revised manuscript received 9 July 2019; published online 7 August 2019)

Fluctuation phenomena commonly exist in arc plasmas, limiting the application of this technology. In this paper, we report an investigation of fluctuations of arc plasmas in an arc plasma torch with multiple cathodes. Time-resolved images of the plasma column and anode arc roots are captured. Variations of the arc voltage, plasma column diameter, and pressure are also revealed. The results indicate that two well-separated fluctuations exist in the arc plasma torch. One is the high-frequency fluctuation (of several thousand Hz), which arises from transferring of the anode arc root. The other is the low-frequency fluctuation (of several hundred Hz), which may come from the pressure variation in the arc plasma torch. Initial analysis reveals that as the gas flow rate changes, the low-frequency fluctuation shows a similar variation trend with the Helmholtz oscillation. This oscillation leads to the shrinking and expanding of the plasma column. As a result, the arc voltage shows a sinusoidal fluctuation.

Keywords: arc fluctuation, arc plasma, Helmholtz oscillation, anode arc root, multiple cathodes

PACS: 52.25.Gj, 52.80.Mg, 52.70.Kz **DOI:** 10.1088/1674-1056/ab344b

1. Introduction

Arc plasmas, characterized by high temperatures and high enthalpies, are used widely in industrial applications such as cutting and welding,[1,2] plasma spraying,[3–5] and synthesis of nanomaterials.[6] However, the instability that is common in arc plasmas limits their applications to some extent. For example, in plasma spraying, the fluctuation of the arc plasma can lead to non-uniform distributions of velocity and temperature of the particles, which directly affect the quality of the final coating.[7–9]

From a macro perspective, arc-plasma instability shows itself mainly as a fluctuation of plasma power. The power fluctuation is usually revealed by the arc voltage fluctuation when the gas flow rate and arc current are fixed. Two main sources of arc voltage fluctuation have been suggested. One is the movement of the anode arc roots. In the anode nozzle, due to the coupling effect of gas drag force and electromagnetic force, a reciprocating motion of the anode arc root occurs along the anode nozzle wall.[10] The movement of the arc root causes the change of the arc length, resulting in arc voltage fluctuations.[11–18] This kind of fluctuation is related to the arc current, gas flow rate, nozzle diameter, etc. The other source is Helmholtz oscillation, which is caused by the special geometry and gas flow conditions. Coudert *et al.*[19,20] developed the theory of Helmholtz oscillation in an arc plasma torch. Their theory does a good job of predicting the frequency of the Helmholtz oscillation. However, the two sources of fluctuations, anode arc root movement and Helmholtz oscillation, are always tightly coupled together, so it is difficult to distinguish specific causes of fluctuation experimentally. In order to study the different fluctuation modes, special arc torches and numerical filtering techniques have been proposed. For instance, Huang *et al.*[21] designed an arc plasma torch with the insert of a floating electric potential between the cathode and the anode to study the arc fluctuation. The anode arc root was then considered to be fixed, so the fluctuation from the Helmholtz oscillation might be investigated independently. Other research on Helmholtz oscillation has been mainly centered on the analyses of arc voltage waveforms for the identification and extraction of fluctuation modes.[19,20,22] Nevertheless, previous research has not established a sufficient connection between the arc configuration (e.g., plasma column and anode arc root) and arc fluctuation, because mechanical obstructions in the plasma torch make it difficult to observe the arc configuration. This limits further understanding of arc fluctuation, especially the Helmholtz oscillation.

Recently, we developed a novel arc plasma torch with multiple cathodes.[23,24] Its special structure can provide a new way to observe the arc column and anode arc root. In this paper, we report on investigations of the fluctuation phenomenon of arc plasma in an arc plasma torch with multiple cathodes. By analyzing variations of the arc voltage, plasma column diameter, and pressure using high-speed photography, the evolution processes of the plasma column/anode arc root are revealed. The fluctuations from the anode arc root and Helmholtz oscillation are well distinguished.

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11875256, 11675177, and 11705202) and Anhui Provincial Natural Science Foundation, China (Grant No. 1808085MA12).

†Corresponding author. E-mail: awcheng@mail.ustc.edu.cn

‡Corresponding author. E-mail: xiawd@ustc.edu.cn

© 2019 Chinese Physical Society and IOP Publishing Ltd

2. Experimental apparatus

Figure 1 shows the schematic diagram of the experimental setup, which is primarily composed of a plasma generator, a gas supply unit, a DC power source unit, and a measurement system. The plasma generator consists mainly of six multiple tungsten cathodes and a common tungsten anode nozzle. Each cathode has a diameter of 6 mm and a top cone angle of 60°. The cathode tips are distributed at vertices of a regular hexagon, and the diagonal distance between opposite cathode tips is 35 mm. The diameter of the anode nozzle is 10 mm, and its length is 40 mm. The vertical distance from the cathode tips to the anode is about 15 mm. Plasma-forming gas is introduced into the chamber through the gaps around the cathodes (gas inlet 1) and the glass window (gas inlet 2), respectively. Their flow ratio is 1 : 1. A detailed description of the plasma generator can be found in our recent reports.[18,23,24] Six individual modulated DC power supplies (IGBT source,140 V/250 A; Jin Yi Power Co., Ltd, Anhui, China) are connected to the cathodes and anode. The conversion efficiency of the power supply is higher than 90%, and the current fluctuation is less than 10%. The measurement system includes a data acquisition card (100-kHz wideband, RBH8223; Rui Bohua Co., Ltd, Beijing, China), a high-speed charge-coupled device (CCD) camera (FASTCAM SA5 1000 K-M3; Photron, Tokyo, Japan), and a pressure sensor (AIR SENSOR AE-S, 200 kHz bandwidth, Nanjing, China). The data acquisition card is used to record the arc voltage signals. The CCD camera is placed exactly opposite to the glass window, so as to best observe the arc discharge. The recording frame rate is 1000–100000 frames/s and the exposure time is 0.5–100 μs. The pressure sensor is installed near the glass window to detect the pressure in the arc plasma torch. In experiments for this paper, the arc current of each cathode is 50 A, and the total arc current is 300 A. The plasma-forming gas is helium with 99.999% purity. The experiment is operated at atmospheric pressure.

Typical window-viewed images of the cathodes and arc discharges are shown in Fig. 2. Six cathodes, an aluminous plasma column, and two anode arc roots are clearly observed in the CCD image. Although six individual DC power supplies are used in the plasma generator, there do not exist six discrete discharge channels or six discrete anode arc roots in our experiment. Between the cathode tips and anode nozzle, the arc plasma presents a relatively uniform and low-density state. The optical emission spectrum diagnosing has been done in a previous work and the electron density is of the order of 10^{15} cm^3, which is lower than that in a constricted helium arc of the order of 10^{16} cm^3.[23,24] The special discharge phenomenon is closely related to the plasma forming gas type, self-induced magnetic field of adjacent arcs, arc currents, etc. The radiation from the diffuse arc is so weak that the plasma column and anode arc roots are visible.

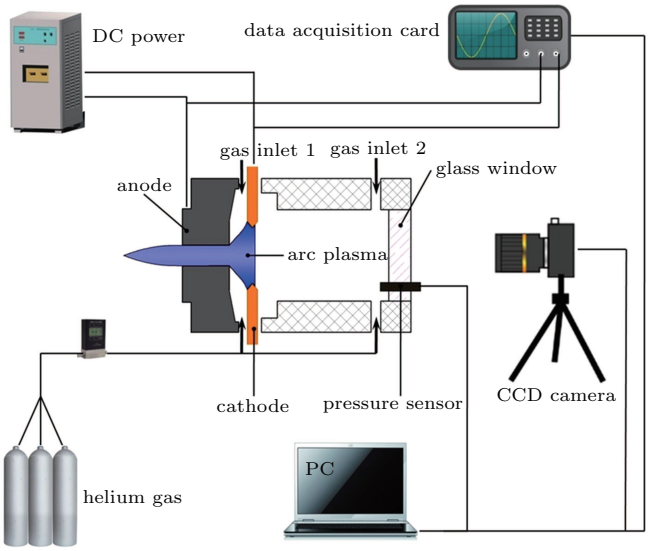


Fig. 1. Schematic diagram of the experimental setup.

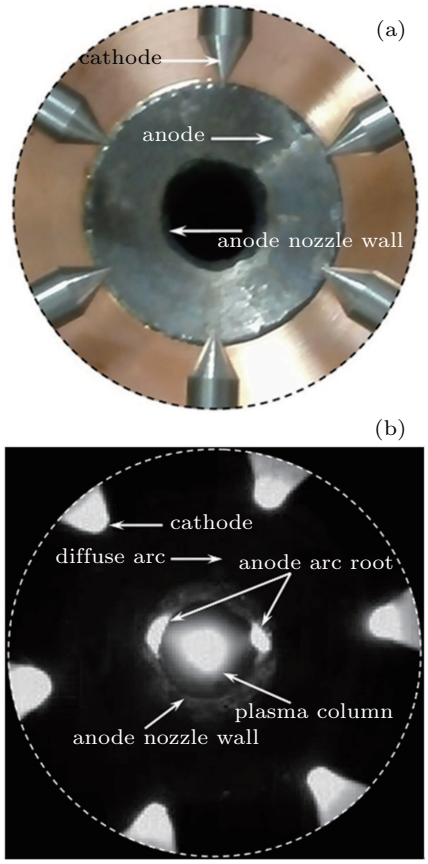


Fig. 2. Typical window-viewed images of (a) the cathodes and (b) arc discharges. Gas flow rate: 75 slm. Exposure time: 1.5 μs.

3. Results and discussion

3.1. Successive CCD images of arc

Figure 3 exhibits the evolution of the anode arc root over about 0.7 ms at the gas flow rates of 67.5–82.5 slm. Markers are used to indicate the location of the anode arc root in these images. When 82.5 slm inlet gas is imposed, two luminous

spots appear on the anode just at the nozzle entrance. However, most of the time only a single anode arc root (arc attachment) is observed. As shown in Fig. 3(a), the plasma column moves on the luminous spots periodically. When the arc column moves to an aluminous spot, a clearly defined anode arc root forms; when the plasma column leaves the luminous spot, the previous anode arc root disappears and a new one appears. The cycle time of the anode arc root transferring to each luminous spot is in the range of 0.3–0.4 ms.

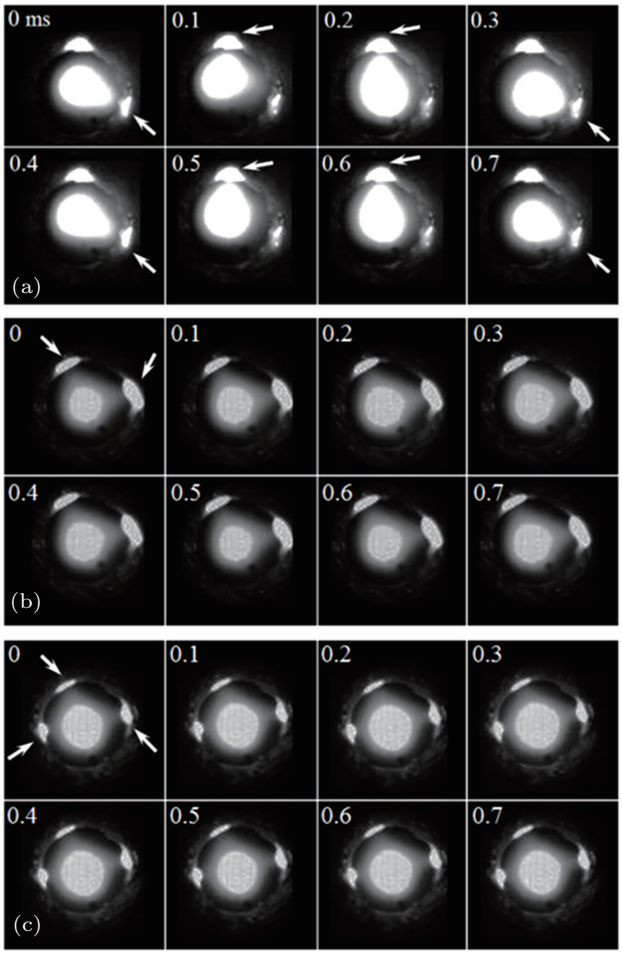


Fig. 3. Successive CCD images of the anode arc root at different gas flow rates: (a) 82.5 slm, (b) 75 slm, (c) 67.5 slm. Exposure time: 0.5 μs, 10.000 frames/s.

With a decrease of the gas injection rate from 82.5 slm to 75 slm, a significant transferring of anode arc root is no longer observed, as shown in Fig. 3(b). The plasma column is relatively stable and seems to connect to both of the luminous spots, which indicates that there may coexist two stationary anode arc roots. It is noticeable, however, that the diameter of the plasma column under goes minor changes over time. When the gas flow rate is further reduced to 67.5 slm, the diameter of the plasma column clearly increases and three luminous spots emerge on the anode nozzle. The plasma column connects to all spots all the time, which means three anode arc roots coexist in this case. Similar to what Fig. 3(b) shows, a minor change of the plasma column diameter is also found in Fig. 3(c).

3.2. Arc voltage waveform

The arc voltage signals under different gas flow rates are shown in Fig. 4. Fast Fourier transformation (FFT) spectra of the arc voltages in Fig. 4 are displayed in Fig. 5. Figure 4 indicates that all arc voltage waveforms have a typical sinusoidal pattern. For 82.5 slm, the average voltage is 59.5 V, and the fluctuation amplitude is larger than 20%. By analyzing the arc voltage waveform in Fig. 4(a), it is found that there are two sources of fluctuations of the arc voltage. One is the sinusoidal fluctuation; the other is a sharp voltage signal that is superimposed on the sinusoidal pattern. Such a sharp voltage signal has a typical feature of slow increase and rapid decrease, which is similar to the physical process of arc shunting/re-strike.[11,18] Possibly, the sharp voltage fluctuation reflects the transferring of the anode arc root between two luminous spots because the formation of a new anode arc root is the result of arc shunting/re-strike. This phenomenon is also confirmed by the FFT spectra of the arc voltage in Fig. 5(a),

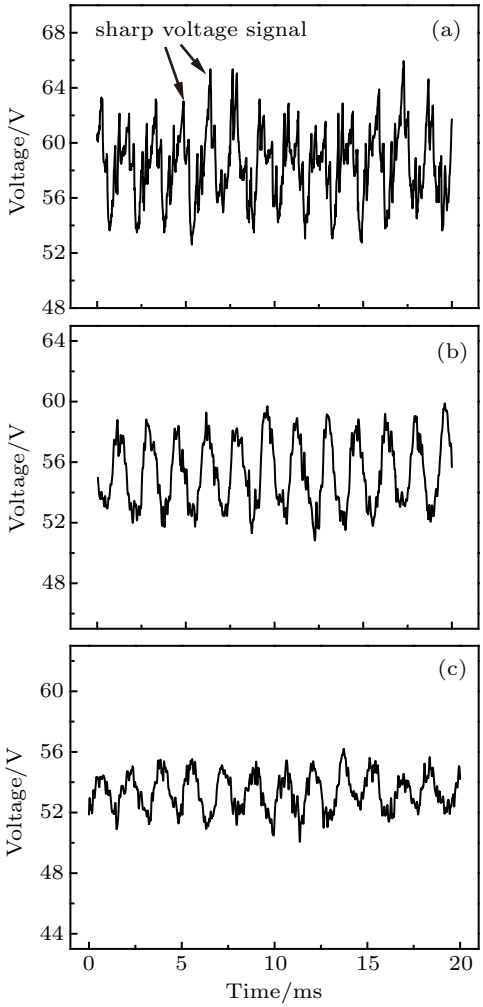


Fig. 4. Time-resolved arc voltage waveforms under different gas flow rates: (a) 82.5 slm, (b) 75 slm, (c) 67.5 slm.

which shows three strong frequency peaks (f_1, f_2, and f_3). The lower peak is from the sinusoidal fluctuation of the arc voltage, and the higher peaks are exactly consistent with the frequency of the anode arc root transferring on the two luminous spots in Fig. 3(a). In other words, the higher peaks represent the fluctuation of the anode arc root. As the gas flow rate decreases to 75 slm and then to 67.5 slm, both the average voltage and its fluctuation amplitude decrease. The FFT spectra of the arc voltage in Figs. 5(b) and 5(c) show only a low-frequency peak. This is because the anode arc roots at the gas flow rates of 75 slm and 67.5 slm are stationary. As described in Subsection 3.1, a minor change of the arc column diameter is noticed, so the low-frequency peak may be ascribed to the variation of the plasma column, but further work is necessary to confirm this.

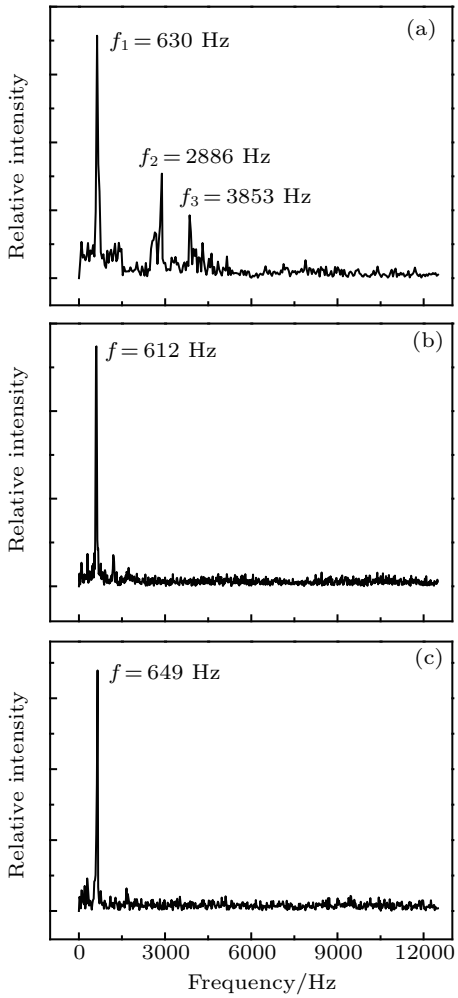


Fig. 5. FFT spectra of the arc voltages shown in Fig. 4.

3.3. Plasma column diameter and pressure fluctuation

Figures 3 and 5 show that the plasma column may have a characteristic low-frequency fluctuation. In order to help understand this phenomenon, the plasma column diameter variation at 75 slm gas flow rate is exhibited in Fig. 6. The radiation emitted from the plasma column and the radiation gradient are so strong that it is difficult to get an accurate measurement of the plasma column diameter. In this paper, the arc images are processed by MATLAB software to obtain the light intensity distributions. We define the edge of the plasma column as being the saturated contour of the CCD image, as shown in Fig. 6(a). The detailed processing method has been introduced in a previous work.[18] Note that the saturated contours differ markedly for different exposure time, and that the exposure time is fixed at 0.5 μs when measuring the plasma column diameter. The plasma column diameter is an approximate qualitative result; the measurement does not represent the actual physical diameter. Obviously, the arc column diameter variation also has a typical sinusoidal pattern, which is similar to the arc voltage waveform in Fig. 4(b). Corresponding FFT spectra in Fig. 6(b) show a strong frequency peak of 612 Hz, which is exactly the same as the frequency peak of the arc voltage in Fig. 5(b). Thus, it is inferred that the low-frequency/ sinusoidal fluctuation of the arc voltage comes from the variation of the plasma column.

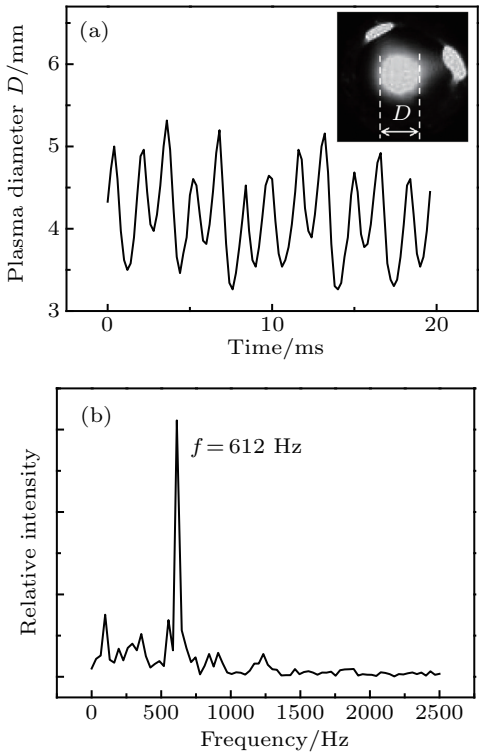


Fig. 6. (a) Plasma column diameter variation over time. (b) The corresponding FFT spectra of the arc column diameter. Gas flow rate: 75 slm.

One notes also that the pressure variation and its frequency peak in Fig. 7 reveal a behavior similar to that of the arc voltage and plasma column diameter. The pressure presents a sinusoidal fluctuation with a strong frequency peak at 612 Hz. However, a significant phase difference exists between the plasma column diameter waveform and the arc voltage/pressure wave form. That is, when the plasma column shrinks, the arc voltage and pressure reach the maxima; when the plasma column expands, the arc voltage and pressure reach the minima.

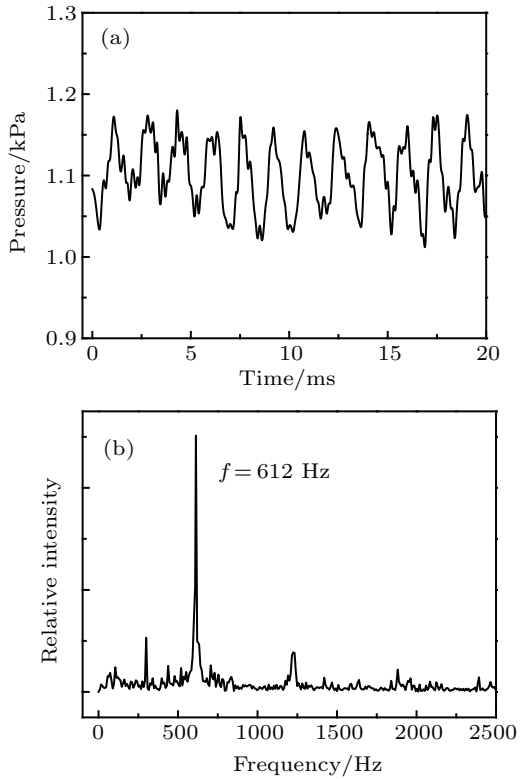


Fig. 7. (a) Pressure variation over time. (b) FFT spectra of the pressure shown in Fig. 6(a). Gas flow rate: 75 slm.

Thus, we suggest that the pressure variation may be the main reason for the low-frequency arc voltage fluctuation. In general, the pressure could affect the diameter of the plasma column. For a higher-pressure condition, the plasma column shrinks, which results in low conductivity, so the arc voltage increases when the arc current is held constant. For a lower pressure condition, the plasma column expands, thereby leading to a lower arc voltage.

3.4. Discussion

In our work, two kinds of fluctuation phenomena are well distinguished. One is the high-frequency fluctuation that is believed to come from transferring of the anode arc root. The plasma column in the anode channel moves on fixed luminous spots, which results in the formation of a new anode arc root and the disappearance of an old one. The high-frequency fluctuation is obvious at high gas flow rates, but almost disappears at a low gas flow rate. This is because the anode arc root can be converted from unsteady mode to stationary mode with a decrease of the gas flow rate. The thickness of the cold-gas boundary layer between the plasma column and the anode nozzle wall is regarded as the main factor of transformation of anode arc root mode.[11,18]

The other fluctuation is the low-frequency fluctuation of several hundred Hz. Experimental analysis indicates that the low-frequency fluctuation is in accordance with the pressure variation. It is postulated that such fluctuation is derived from the Helmholtz oscillation. Here we compare the theoretical analysis of Helmholtz oscillation with experimental results. As suggested by Coudert *et al.*,[19] the Helmholtz oscillation frequency can be estimated by the formula

$$f = C_{\mathrm{R}} \times K_{\mathrm{H}} \times \sqrt{\gamma_{\mathrm{c}} \frac{(\gamma-1)}{\gamma} \frac{P_0}{P} h}, \tag{1}$$

where $C_{\mathrm{R}} = 1/\sqrt{1+\pi d/(4L)}$ is the Rayleigh correction and $K_{\mathrm{H}} = \frac{1}{2\pi}\sqrt{\frac{S}{V_0 L}}$ is the shape factor of the arc plasma torch geometry. L is the anode nozzle length, and d is the diameter of the anode nozzle, which are 0.04 m and 0.01 m according to the geometry of the arc torch, respectively. S is the area of the anode nozzle and V_0 is the volume of the arc plasma torch, which are calculated on the base of L and d. In the multi-cathode arc plasma torch, the calculated values of S, V_0, C_{R}, and K_{H} are 7.85×10^{-5} m^2, 8×10^{-4} m^3, 0.91, and 0.25, respectively. h is the specific enthalpy of the plasma and calculated according to $h = UI\eta/m^0$, where U, I, η, and m^0 are the arc voltage, current, heat efficiency, and gas mass flow, respectively. η is the heat efficiency of the arc plasma torch, which is measured in the experiment. γ_{c} is the isentropic coefficient of the cold gas, 1.66 for helium. γ is the isentropic coefficient of the plasma, which is computed as a function of specific enthalpy h, pressure P, and helium intensity ρ, i.e., $h = \frac{\gamma}{\gamma-1}\frac{P}{\rho}$. P_0 is the pressure in the cold gas chamber and P is the pressure in the anode nozzle. Due to the large cavity volume of the multi-cathode arc plasma torch we studied, P_0/P is about 1. The values of the arc voltage, heat efficiency, specific enthalpy, and isentropic coefficient with the increase of the gas flow rate are displayed in Fig. 8. When the gas flow rate increases, the arc voltage always increases. It is because that as the gas flow rate increases at a fixed arc current, the arc sectional area decreases due to the constriction effect of the working gas on the column, which results in the increase of plasma resistance. With the increase of the gas flow rate, the raised arc voltage results in a relative less heat loss of electrodes. Thus, the thermal efficiency increases with the gas flow rate. Furthermore, the specific enthalpy firstly decreases and then increases with the increase of the gas flow rate. When the gas flow rate is smaller than 75 slm, the plasma is a laminar flow. The input power increases slightly as the gas flow rate increases, resulting in the decrease of the specific enthalpy. However, when the gas flow rate is larger than 75 slm, the plasma is a turbulent flow. The input power increases obviously, leading to the increase of the specific enthalpy.

The theoretical frequency calculated from Eq. (1) and the experimentally measured one are shown in Fig. 9. The calculated frequency is less than 1000 Hz, which is far lower than the frequency of a conventional arc plasma torch (several thousand Hz).[25] This can be attributed to the small shape factor ($K_{\mathrm{H}} \sim 0.25$) of the multi-cathode arc plasma torch, which is only about 1/7 of the conventional arc plasma torch.[19] In ad-

dition, the calculated frequency at first decreases and then increases as the gas flow rate increases. This phenomenon is mainly due to the variation of the specific enthalpy (h) for different gas flow rates. When the gas flow rate is lower than 75 slm, h decreases as the gas flow rate increases; when the gas flow rate is higher than 75 slm, h increases as the gas flow rate increases.

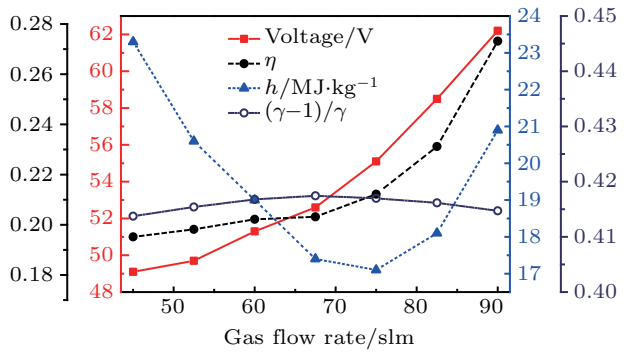


Fig. 8. Variation of plasma parameters with the gas flow rate.

Figure 9 shows that the measured frequency is in good agreement with the theoretical frequency, which have a similar change rule. Thus, the comparison in Fig. 9 can further assist in validating that the Helmholtz oscillation has an effect on the low-frequency fluctuation. However, there is a numerical difference, about 100 Hz between the theoretical and measured values, which may be due to other factors in the multi-cathode arc device, such as energy fluctuations or thermal chocking in the anode nozzle.[26] These factors are coupled with the Helmholtz oscillation, which collectively cause the expanding and contracting of the plasma column. In our further work, these factors will be considered to study the fluctuation in the arc torch with multiple cathodes in more detail.

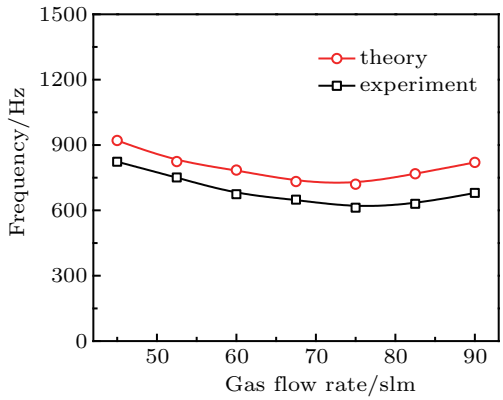


Fig. 9. Comparison between the theoretical analysis of Helmholtz oscillation and the experimental result.

4. Conclusion

To investigate arc plasma fluctuations, we construct an arc plasma torch with multiple cathodes. The evolution of the plasma column and the anode arc root under different gas flow rates is captured by a high-speed CCD camera. We exhibit the fluctuation phenomena of arc voltage, arc column diameter, and pressure. The results indicate that two well-separated kinds of fluctuations exist in the arc plasma. One is a high-frequency fluctuation of several thousand Hz. We interpret this fluctuation as coming from the transferring of the anode arc root, and conclude that it occurs only at a high gas flow rate because the anode arc roots are fixed at low gas flow rates. The other kind of fluctuation is a low-frequency fluctuation of several hundred Hz. Analysis shows that the Helmholtz oscillation has an effect on this fluctuation. As the gas flow rate changes, the low-frequency fluctuation shows similar variation trend with the Helmholtz oscillation. It is inferred that, driven by the Helmholtz oscillation, the pressure in the plasma torch changes periodically, which results in a continual shrinking and expanding of the plasma column. Thus, the arc voltage shows a typical sinusoidal fluctuation. Although this study is a preliminary investigation, our direct observations of arc configuration may offer additional insight for understanding arc fluctuation.

References

[1] Mougenot J, Gonzalez J, Freton P and Masquère M 2013 *J. Phys. D: Appl. Phys.* **46** 135206
[2] Nemchinsky V A and Severance W 2006 *J. Phys. D: Appl. Phys.* **39** R423
[3] Bao S C, Guo W K, Ye M Y, Xu P and Zhang X D 2008 *Plasma Sci. Technol.* **10** 701
[4] Xianliang J, Gitzhofer F and Boulos M 2006 *Plasma Sci. Technol.* **8** 164
[5] Pan W, Li G, Meng X, Ma W and Wu C 2005 *Pure Appl. Chem.* **77** 373
[6] Churilov G 2008 *Fuller. Nanotub. Car. N* **16** 395
[7] Coudert J F and Rat V 2010 *Surf. Coat. Technol.* **205** 949
[8] Bisson J and Moreau C 2003 *J. Therm. Spray Technol.* **12** 258
[9] Bisson J, Gauthier B and Moreau C 2003 *J. Therm. Spray Technol.* **12** 38
[10] Eckert E, Pfender E and Wutzke S 1967 *AIAA J.* **5** 707
[11] Duan Z and Heberlein J 2002 *J. Therm. Spray Technol.* **11** 44
[12] Nogues E, Fauchais P, Vardelle M and Granger P 2007 *J. Therm. Spray Technol.* **16** 919
[13] Trelles J, Pfender E and Heberlein J 2007 *J. Phys. D: Appl. Phys.* **40** 5635
[14] Zhao W, Tian K, Tang H, Liu D and Zhang G 2002 *J. Phys. D: Appl. Phys.* **35** 2815
[15] Rat V, Mavier F and Coudert J F 2017 *Plasma Chem. Plasma Process.* **37** 549
[16] Wu C and Pan W 2011 *Theo. Appl. Mec. Lett.* **1** 024001
[17] Goyal V, Ravi G, Bandyopadhyay P, Banerjee S, Yugesh V and Mukherjee S 2017 *Phys. Plasmas* **24** 033506
[18] Wang C, Zhang Z, Xia W, Cui H and Xia W 2017 *Plasma Chem. Plasma Process.* **37** 371
[19] Coudert J F, Rat V and Rigot D 2007 *J. Phys. D: Appl. Phys.* **40** 7357
[20] Coudert J F and Rat V 2008 *J. Phys. D: Appl. Phys.* **41** 205208
[21] Huang H, Pan W, Guo Z and Wu C 2010 *J. Phys. D: Appl. Phys.* **43** 085202
[22] Rat V and Coudert J F 2010 *J. Appl. Phys.* **108** 043304
[23] Wang C, Cui H, Zhang Z, Xia W and Xia W 2017 *Contrib. Plasma Phys.* **57** 58
[24] Wang C, Cui H C, Li W W, Liao M R, Xia W L and Xia W D 2017 *Chin. Phys. B* **26** 025202
[25] Cao J W, Huang H J and Pan W X 2014 *Chin. Phys. Lett.* **31** 115202
[26] Huang H, Pan W and Wu C 2012 *Plasma Chem. Plasma Process* **32** 65