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ORIGINAL PAPER

Contributions to Plasma Physics

Production of long, laminar plasma jets at atmospheric pressure with multiple cathodes

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Plasma jets from conventional non-transferred arc plasma devices are usually operated in turbulent flows at atmospheric pressure. In this paper, a novel non-transferred arc plasma device with multiple cathodes is introduced to produce long, laminar plasma jets at atmospheric pressure. A pure helium atmosphere is used to produce a laminar plasma jet with a maximum length of >60 cm. The influence of gas components, arc currents, anode nozzle diameter, and gas flow rate on the jet characteristics is experimentally studied. The results reveal that the length of the plasma jet increases with increasing helium content and arc current but decreases with increasing nozzle diameter. As the gas flow rate increases, the length of the plasma jet initially increases and then decreases. Accordingly, the plasma jet is transformed from a laminar state to a transitional state and finally to a turbulent state. Furthermore, the anode arc root behaviours corresponding to different plasma jet flows are studied. In conclusion, the multiple stationary arc roots that exist on the anode just inside the nozzle entrance are favourable for the generation of a laminar plasma jet in this device.

KEYWORDS
anode arc root, arc plasma, jet length, laminar plasma jet, multiple cathodes

1. | INTRODUCTION

An atmospheric DC arc jet is widely used in plasma spraying and in powder material processing because of its high temperature, high energy intensity, and high activity.[1–3] In conventional non-transferred arc plasma devices, the plasma jet is usually operated under turbulent flow. The turbulent plasma flow is extremely unstable, showing a short plasma jet, a high temperature gradient in the axial direction, and high-intensity noise emission.[1,4,5] The fluctuating characteristic of a turbulent jet leads to asymmetrical heating and the acceleration of particles in the jet's cross section, causing difficulty in process control and also limiting its application in material preparation requiring high precision and high reproducibility. One of the methods for tackling such issues is the production of a long, quasi-laminar plasma jet. A laminar plasma jet has such properties as a long and stable plasma jet, reduced entrainment of the atmosphere, reduced temperature gradient in the axial direction, and negligible noise emission.[1,6–8] Several experiments have established that a laminar plasma jet has better performance in plasma spraying,[9,10] remelting/cladding processing,[11] hardening of a cast iron surface,[12] and thermal barrier/hydroxyapatite coatings preparation[9,13] compared with a short, turbulent plasma jet.

Previous research has shown that the movement of the arc root is one of the key factors affecting the stability and length of plasma jets.[4,5] Long, laminar plasma jets at atmospheric pressure may be produced when the fluctuation of the anode arc root is restrained. For example, Pan et al.[5,14–16] designed a non-transferred arc plasma device with inter-electrode inserts. This structure could confine the arc root to a certain circular range on the anode wall, thus producing long and stable laminar plasma jets within a relatively wide range of control parameters. In addition, improving the gas flow conditions, such as adding a spiral gas flow, is also an effective way to restrain the movement of the anode arc root, thus leading to the production of laminar plasma jets.[6,17,18] Many attempts have been made recently in generating laminar plasma jets at atmospheric pressure.

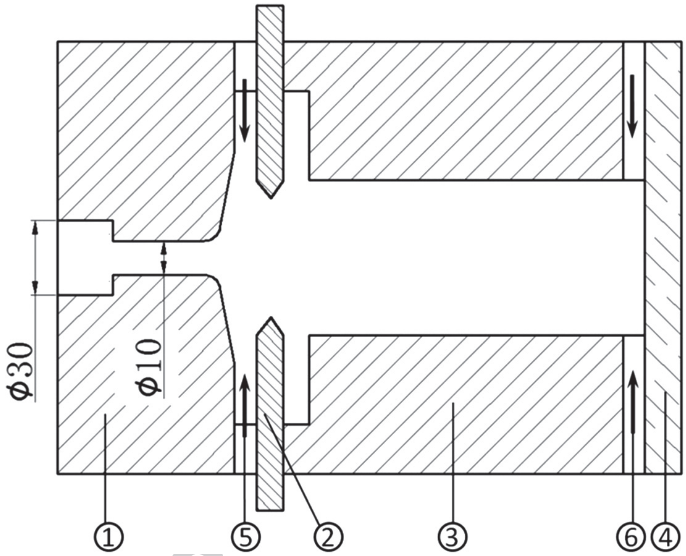


FIGURE 1 Schematic drawing of the new device. ① anode; ② cathode; ③ chamber; ④ glass window; ⑤ plasma-forming gas; ⑥ window protection gas.

Krowka[19,20] achieved a self-sustained pulsed laminar arc jet by using a phase-locking Helmholtz oscillation, which could suppress the re-arcing events in the nozzle. However, the control method is not straightforward, and the pulsed mode of operation may limit the jet's application in some cases. Ghorui[21] reported a long, self-propelled plasma jet, which was thought to be the result of the presence of axial and transverse currents in the external jet. However, the stability of the plasma jet in the device faces a serious challenge because the fluctuation of anode arc root's location is usually very strong. Cao et al.[22] proposed a new laminar plasma torch with a segmented anode. This torch had three characteristics, namely high specific enthalpy, a long laminar plasma jet, and low arc current. Essentially, the generation of a laminar jet in this device was possibly due to the restraint of the arc root's fluctuation. Recently, we reported an arc plasma device with multiple cathodes.[23,24] Multiple stationary anode arc roots on the anode just inside the nozzle entrance were observed within a certain range of the parameters. Therefore, this structure might provide proper conditions to produce laminar plasma jets. Moreover, a structure with multiple cathodes offers ample space for axially fed feedstock particles, and the multiple roots may reduce anode erosion effectively. Thus, the performance of plasma jets in such a device requires necessary investigation.

In this paper, we report a long, laminar plasma jet obtained in a non-transferred arc plasma device with multiple cathodes. The effects of the gas components, arc current, anode nozzle diameter, and gas flow rate on the appearance of plasma jets are experimentally investigated. Moreover, the anode arc root's behaviours corresponding to different plasma jet flows are observed and discussed.

2. | EXPERIMENTAL APPARATUS

Figure 1 shows a longitudinal sectional view of the novel DC arc plasma device. The device is built mainly with a tungsten anode, six tungsten cathodes, a chamber, and a glass window. It consists of a 10/13/16 mm diameter nozzle (40 mm length) and a 30 mm diameter backward-facing step (30 mm length) at the anode's centre. Six tungsten cathodes (2% wt lanthana) are radially inserted into the chamber. The diameter of each cathode is 5 mm and the cone angle of its top is 60°. The cathode tips are distributed at the vertices of a polygon, and the diagonal distance between the cathode tips is 30 mm. The vertical distance from the cathode tips to the anode is ∼15 mm. The plasma-forming gas is introduced via a gap on the chamber wall where the cathodes are inserted. The window protection gas is introduced through the inlets near the glass window. The volume flow ratio of plasma-forming gas and window protection gas is 1:1. Six 0–200 V and 0–180 A DC power supplies with a common anode are connected to the device, and each cathode is connected to a power supply independently. A digital camera (Canon 5D Mark III) is employed to capture the appearance of the plasma jet. The arc discharge is observed by a high-speed charge-coupled device (CCD) camera (Photron, FASTCAM SA5 1000K-M3), which is placed exactly opposite the glass window. A voltage divider and a 100-kHz wideband data acquisition card are used to record the arc voltage. The plasma-forming gas is a mixture argon and helium (99.999%), and the window protection gas is always consistent with the plasma-forming gas. The arc currents mentioned in this paper refer to the total currents. More detailed information about the device structure and the measuring methods can be found elsewhere.[24]

Figure 2 shows typical window-viewed images of the arc discharge. It is necessary to state that six independent DC power supplies are used, but no six discrete discharge channels or six discrete anode arc roots exist below 200–300 A arc current. The

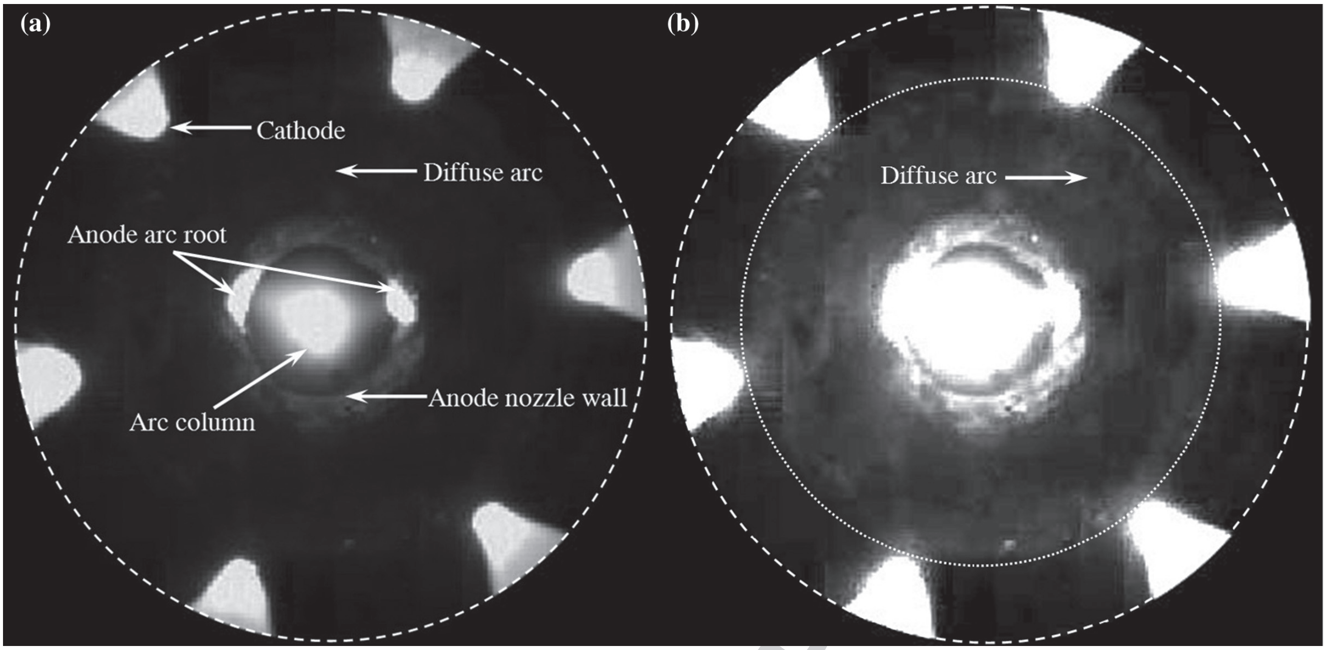


FIGURE 2 Images of the arc discharge viewed through the window (10 mm anode nozzle diameter, 250 A, helium gas, 25 slm, 5,000 frames/s). (a) 1 μs shutter, (b) 3 μs shutter.

special discharge phenomenon mainly depends on the self-induced magnetic field of the adjacent arcs, the arc currents, and the plasma-forming gas. The relevant results have been communicated elsewhere.[24] In the range of the experimental parameters, the radiation of the "diffuse arc" that exists between the cathodes and the anode nozzle wall is rather weak; thus the influence of the "diffuse arc" on the arc root observation can be ignored. Remarkably, the stationary anode arc roots can be located on the anode just inside the nozzle entrance within a certain range of parameters, as shown in Figure 2.

3. | RESULTS AND DISCUSSION

3.1 | Effects of gas components

Figure 3 shows the plasma jets generated at 250 A arc current but with different gas components. The plasma-forming gases are argon and helium. The total gas flow rate is 22.5 slm. It can be seen that the length of the plasma jet increases with decrease in the argon flow rate. When the argon flow rate ratio is 20%, the plasma jet is very short and is accompanied by a high noise emission,

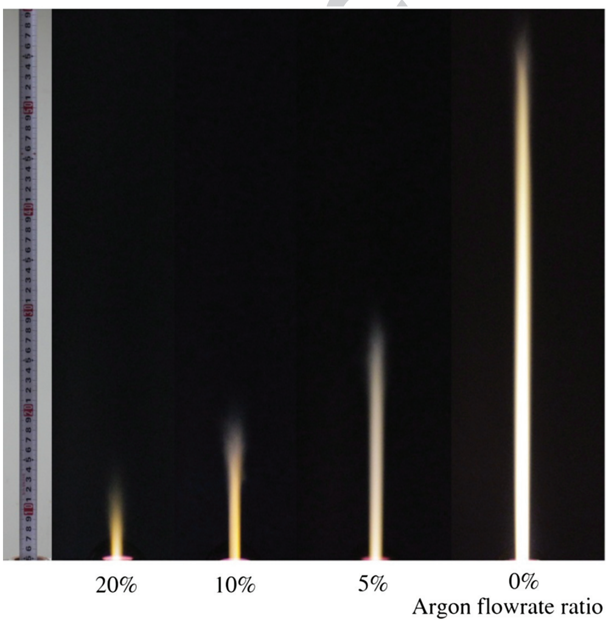
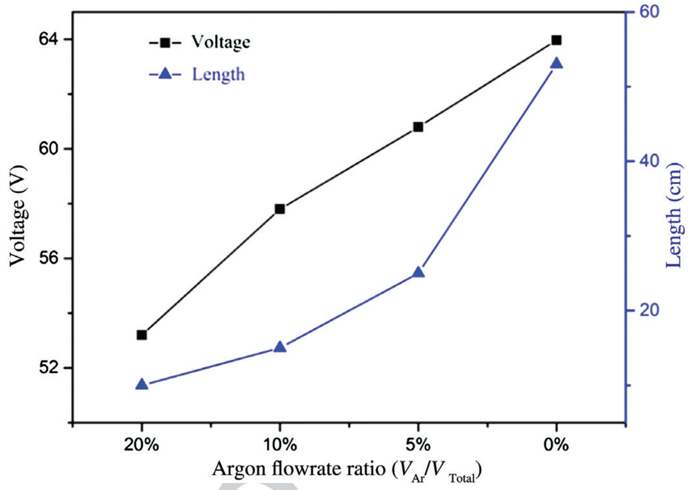


FIGURE 3 Variation of the plasma jets with different flow rate ratios (10 mm anode nozzle diameter, 250 A, total 22.5 slm).



AQ3 **FIGURE 4** Arc voltage and length of plasma jet corresponding to Figure 3.

which indicates that the plasma jet is under typical turbulent flow. As the argon flow rate ratio decreases, the length of the plasma jet increases and the noise gradually decreases. When the argon gas flow rate is decreased to zero, the length of the plasma jet increases to 53 cm and the jet achieves satisfactory stability. Therefore, it can be concluded that the plasma jet has already been transformed from a turbulent state to a laminar state. Figure 4 shows the arc voltage increase with decreasing argon flow rate ratio. The increase in the arc voltage may be due to the higher enthalpy and lower electrical conductivity of helium than argon.

The reasons for the plasma jet's variation within different gas components may be summed up as follows: on one hand, an increase of helium improves the arc power, which increases the plasma jet's power; on the other, as our previous research has confirmed, the "diffuse arc" presents better uniformity and stability with an increase in the helium content.[24] The stable arc is beneficial to restrain the fluctuation of the anode arc root, and thus helium is more favourable for the production of a long, laminar plasma jet. In the experiments described in the following sections, helium is used as the plasma-forming gas.

3.2 | Effects of arc current

Figure 5 shows the appearance of the jet produced at a fixed helium gas flow rate of 22.5 slm but at different arc currents from 200 to 300 A. The results indicate that the length of the plasma jet increases with increasing arc current in the experimental range. At 200 A, the length of the plasma jet is ~30 cm, and the ratio of the jet length to the nozzle diameter is ~30. Since the plasma jet is very stable and is accompanied by very low noise, the plasma jet can be considered to be reasonably operating in laminar flow. As the arc current increases, the length of the plasma jet increases gradually. The maximum length is >60 cm at 300 A arc current and 22.5 slm gas flow rate. The corresponding arc voltage and plasma jet length are plotted in Figure 6. The

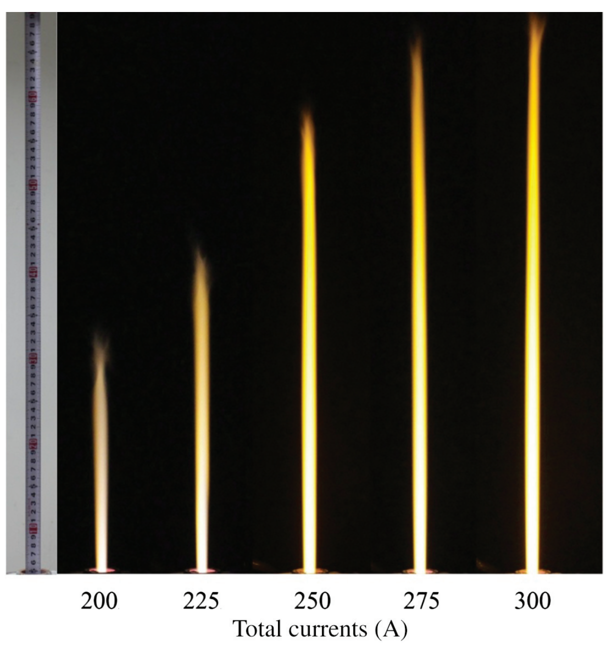


FIGURE 5 Variation of the plasma jet with different arc currents (10 mm anode nozzle diameter, helium gas, 22.5 slm).

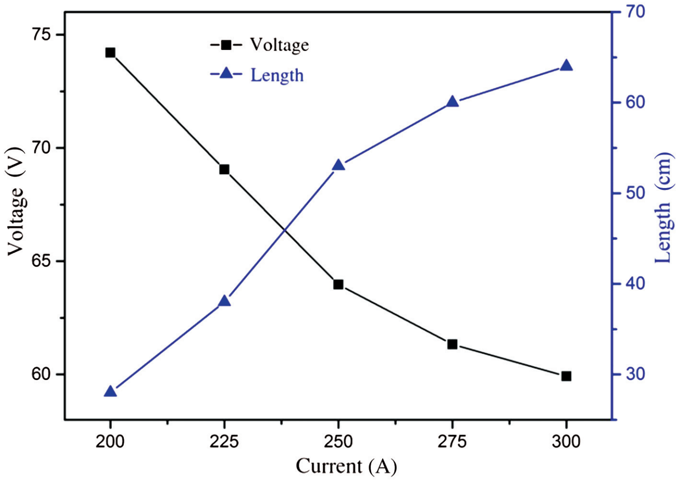


FIGURE 6 Arc voltage and length of plasma jet corresponding to Figure 5.

arc voltage decreases significantly with the increase of the arc current. However, the arc power increases monotonically from 12.9 kW at 175 A to 18.3 kW at 300 A with the increase in arc current. Generally, the increase of arc power would also increase the gas temperature in the anode nozzle when the gas flow rate remains constant, and then the length of the plasma jet increases accordingly.

3.3 | Effects of anode nozzle diameter

Figure 7 shows the plasma jet appearance with different anode nozzle diameters. Experimental results show that, as the nozzle diameter increases, the diameter of the plasma jet increases but the jet length reduces. Although all plasma jets may have quasi-laminar states (higher length, relative stability, and quiet flow), the outer end of the plasma jet has significant air entrainment phenomenon for the larger diameter nozzles, which indicates that the jet's stability decreases under these conditions. The corresponding arc voltage in Figure 8 indicates that the voltage only slightly decreases with the increase of nozzle diameter. The decrease of voltage may be ascribed to the weaker cooling effect in the larger diameter nozzles. However, the minor variation of arc power is not enough to explain the obvious change of the jet's appearance. We propose that the plasma jet's variation is mainly caused by two factors. On one hand, the smaller diameter nozzle is effective in restricting the arc column's diameter, thus improving the gas temperature and velocity in the anode nozzle. On the other hand, with the increase of the nozzle diameter, the thickness of the cold gas boundary layer between the nozzle wall and the arc column increases, which would exacerbate the instability of the anode arc root.[25] Thus, the larger diameter anode nozzle is unfavourable for the generation of a laminar plasma jet.

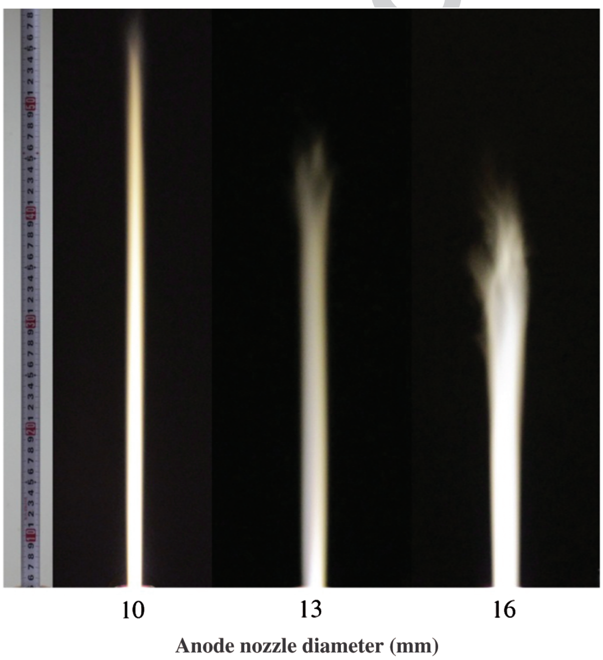


FIGURE 7 Variation of the plasma jets with different anode nozzle diameters (helium gas, 250 A, 22.5 slm).

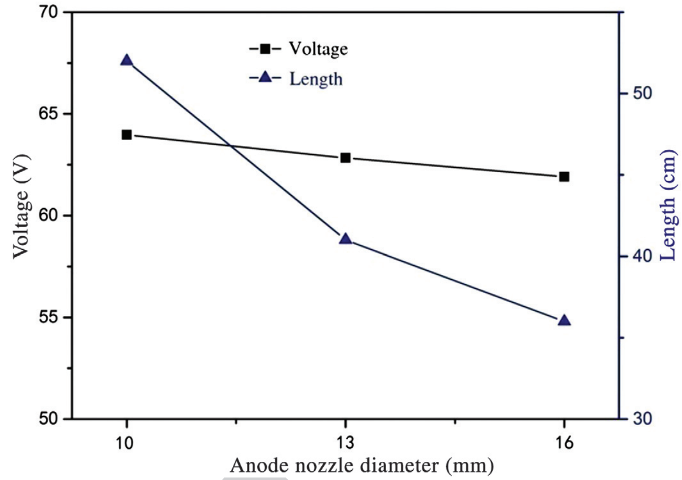


FIGURE 8 Arc voltage and length of plasma jet corresponding to Figure 7.

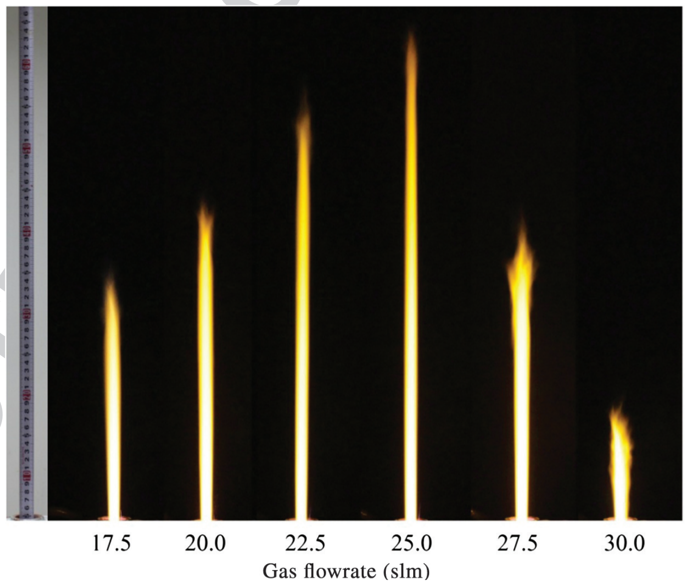


FIGURE 9 Variation of the plasma jets with different gas flow rates (10 mm anode nozzle diameter, helium gas, 250 A).

3.4 | Effects of gas flow rate

Figure 9 shows the variation of the plasma jet with different gas flow rates when the arc current is 250 A. It can be seen that the plasma jet length increases at first, and then decreases with the increase in gas flow rate. Within a certain range of the flow rate (17.5–25 slm), the plasma jet has the appearance of a laminar flow. The plasma jet length increases with the increase of gas flow rate, and reaches its maximum (58 cm) at 25 slm. As the flow rate continues to increase, the plasma jet length sharply reduces, from 58 cm at 25 slm to 38 cm at 27.5 slm. The diameter of the plasma jet obviously increases, and its outer end has a significant air entrainment phenomenon. The variation of its visual appearance shows that the plasma jet is changing from a laminar state to a turbulent state. However, the plasma jet at the transitional state still maintains a considerable length and a relatively stable state. The variation in length of the plasma jet is <3 cm at 27.5 slm. When the gas flow rate exceeds 30 slm, the plasma jet appears stub-shaped and emits high-intensity noise, which indicates that the plasma jet has completely shifted from laminar flow to turbulent flow.

Figure 10 shows the variation of the arc voltage and the plasma jet length at different gas flow rates. It can be seen that the arc voltage increases monotonically with the increase in the gas flow rate, although the jet length shows a dramatic change with the transition of the flow state. Figure 11 shows the typical voltage waves for laminar, transitional, and turbulent plasma jets. For the laminar jet, the arc voltage is relatively low (61 V). The voltage is rather flat, and the voltage fluctuation is about 3% (2 V fluctuation). For the transitional state, the arc voltage increases to 68 V. The voltage shows enhanced fluctuation (less than 9%, 6 V fluctuation). When the plasma jet changes to turbulent flow, the arc voltage reaches its maximum (72 V). The arc voltage wave is a typical saw tooth pattern with a relatively high amplitude, and the voltage fluctuation is more than 15% (11 V fluctuation). Therefore, we can infer that the arc resembles the re-strike mode.[21,25] The voltage fluctuation of the re-strike mode usually has a certain regularity, which mainly depends on the torch structure, control parameters, etc. In this paper, the fluctuation frequency is about 500 Hz, as shown in Figure 11.

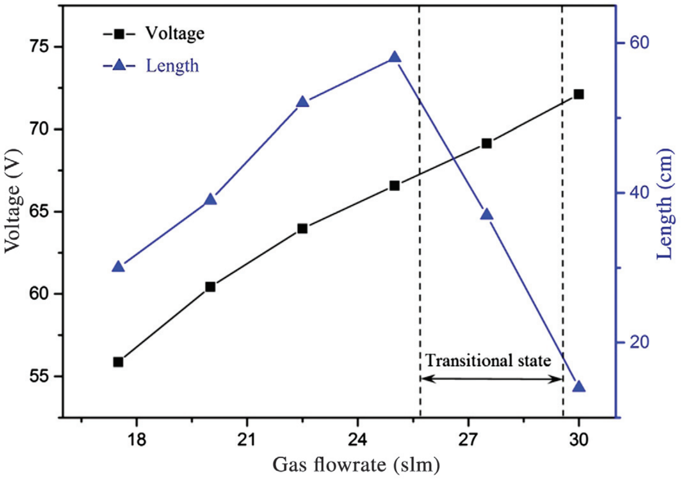


FIGURE 10 Arc voltage and length of plasma jet corresponding to Figure 5.

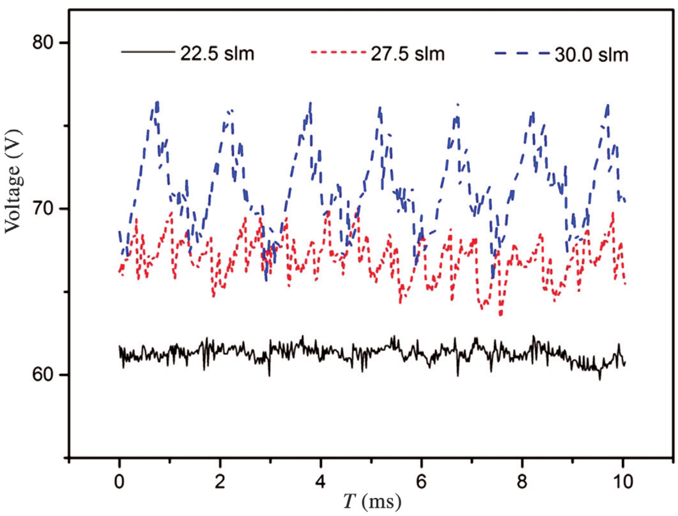


FIGURE 11 Time-resolved arc voltage wave corresponding to Figure 5.

In general, the thermal efficiency of jet generation improves with increase in the gas flow rate.[14] The laminar plasma jet often suffers from lower thermal efficiency because the laminar flow would be destroyed under a higher gas flow rate. Since the plasma jet in the transitional state has the characteristics of high voltage, high gas flow rate, and good stability, the transitional jet may meet the requirements of an actual application more satisfactorily.[6]

3.5 | Anode arc root behaviour

From the foregoing discussion, it is clear that the gas components, arc current, and gas flow rate have a great influence on the length and stability of plasma jets. These factors may directly affect the anode arc root's state, which would have a significant impact on the flow state of the plasma jets. In this section, we show the evolution of the anode arc root within 0.8 ms at different gas flow rates from 22.5 to 30 slm, as shown in Figure 12. At 22.5 slm flow rate, three stationary, luminous anode spots appear on the anode just inside the nozzle entrance. It can be seen that the arc column is always connected to these spots simultaneously, and therefore multiple anode arc roots have formed.[23] The arc roots are quite stable, and hence the arc column can sustain a rather steady shape with minor voltage fluctuation, as shown in Figure 11. The stationary anode arc root behaviour may be used to explain the formation of the laminar plasma jet in this device. As the gas flow rate increases to 25 slm, the diameter of the arc column decreases because the cooling effect of the inlet gas is enhanced, and the number of multiple arc roots decreases from 3 to 2 simultaneously, as shown in Figure 12. According to previous results,[23] this phenomenon is mainly associated with the thickness of the cold gas boundary layer between the anode nozzle wall and the arc column. The arc column still maintains a stable state, and therefore the plasma jet can be operated in the laminar flow in this case. When the gas flow rate increases to 27.5 slm, there are still two stationary luminous spots on the anode. However, the arc column is not always connected with the spots simultaneously but moves on the spots regularly. The shape of the arc column varies constantly during the shift of the arc column, which leads to the transformation of the plasma jet from laminar flow to turbulent flow. In fact, because of the limitation of the spot's locations, arc shunting is often restricted to the circumferential direction. The large-scale shunting of the

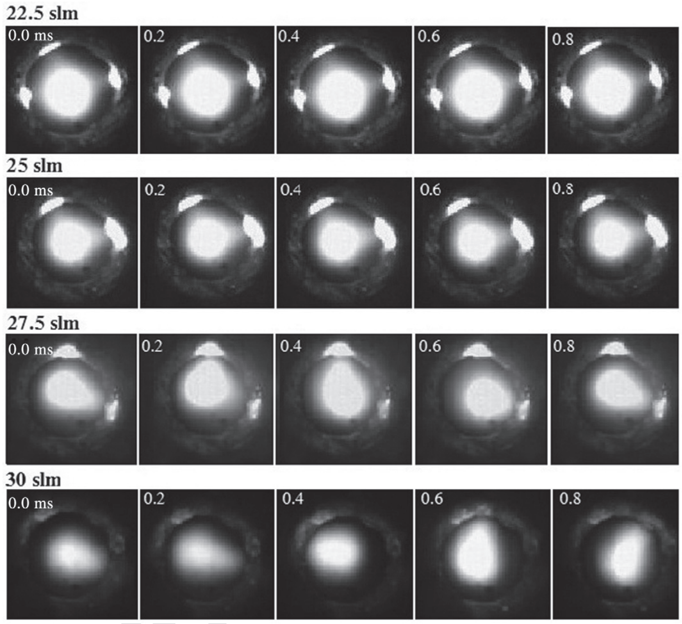


FIGURE 12 Successive images of anode arc root at different gas flow rates (10 mm anode nozzle diameter, 250 A, helium gas, 0.5 μs shutter, 5,000 frames/s).

arc is suppressed, and thus the arc voltage fluctuation is less than 6 V (9% fluctuation) as seen in Figure 11. Consequently, the plasma jet could be operated in the transitional state, which provides good stability and considerable length. As the gas flow rate increases to 30 slm, the anode arc root moves from the nozzle entrance to the nozzle's inner wall. The arc root moves rapidly on the inner wall, and the arc root's location is stochastic. Combining the arc voltage curve in Figure 11, it can be speculated that large-scale shunting of the arc occurs in this process. The shape of the arc column changes dramatically during arc shunting, so the plasma flow is extremely unstable, showing a very short turbulent jet.

4. | CONCLUSION

In this paper, a non-transferred arc plasma device with multiple cathodes was designed to generate long, laminar plasma jets. The maximum length of the laminar plasma jet was >60 cm under pure helium ambient. The correlation between the jet characteristics and experimental parameters such as gas components, arc currents, anode nozzle diameter, and gas flow rate was investigated. Also, the anode arc root's behaviours corresponding to the laminar state, transitional state, and turbulent state were observed and discussed. The main conclusions are as follows:

1. Between an argon and a helium ambient, helium has a beneficial effect on the formation of the laminar plasma jet. The difference primarily comes from the fact that "diffuse arc" displays better stability with increase in the helium content.
2. The plasma jet length increases with increasing arc current but decreases with increasing anode nozzle diameter.
3. The plasma jet length increases at first, and then decreases with increase in the gas flow rate. In the meantime, the plasma jet gradually changes from the laminar state to the transitional state, and finally to the turbulent state. With the transformation of the plasma jet from a laminar to a turbulent flow, both the arc voltage and its fluctuation increase.
4. The variation of the plasma jet states in this device should be mainly attributed to the different anode arc root's behaviours. For the laminar jet, the arc roots are confined to the anode just inside the nozzle entrance, forming multiple stationary arc roots. For the transitional jet, a regular circumferential movement of the arc root is dominant. For the turbulent jet, the arc root moves to the nozzle inner wall and tends to move randomly, which increases the intensity of turbulence in plasma flow.

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