Control of Cathode Arc Root Behavior in a Reverse Polarity Hollow Electrode Plasma Torch Using an Exit Nozzle

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ABSTRACT

In this study, a hollow electrode plasma torch with a cylindrical exit nozzle was proposed and tested to control the behavior of cathode arc roots in the reverse polarity electrical connection for the non-transferred mode operation. The test results revealed that in the absence of an exit nozzle, cathode arc roots cause arcing on the electrically floated torch housing, producing an unstable plasma jet. However, in the presence of an exit nozzle, when injecting the secondary gas with a swirl through a gap between the exit nozzle and front electrode, it was confirmed that cathode arc roots can be controlled to form only on the surface of the front electrode, producing a stable plasma jet without arcing on the torch housing. Additionally, the presence of an exit nozzle was observed to have little influence on the voltage–current characteristics of a reverse polarity hollow electrode plasma torch. Instead, heat loss to the coolant was reduced compared to that in the absence of an exit nozzle, thereby improving thermal efficiency.

Keywords: Hollow electrode plasma torch, Reverse polarity, Exit nozzle, Non-transferred, Cathode arc root

1. Introduction

As a typical DC vortex plasma torch, a hollow electrode plasma torch primarily consists of the rear electrode with one side blocked and the cylindrical front electrode with both sides open, and an arc column is formed between these two electrodes facing each other [1–5]. To form an arc column, accordingly, each electrode needs to be electrically connected to the negative or positive leads of the power supply. For example, in an electrical connection with normal polarity, the rear and front electrodes are connected to the negative and positive leads of the power supply, respectively, to use the rear electrode as a cathode. In this case, owing to the structural feature of the rear electrode with one side blocked, the attachment position of the cathode arc roots can be controlled inside the rear electrode, generating a stable plasma flame in the non-transferred mode [6–8].

On the other hand, in an electrical connection with reverse polarity, the cylindrical front electrode is electrically connected to be set as a cathode [9]. When the torch is operated in this type of an electrical connection with reverse polarity, due to the absence of the blocked side, cathode arc roots can move axially along with the plasma gas flow and attach at the exit of the front electrode [10–13]. This behavior of the cathode arc roots in reverse polarity can bring unique features to the hollow electrode plasma torches. For example, the length of the arc column and arc voltages can be increased compared with those in normal polarity [10, 11]. At a given power level, it is well known that the increase of arc voltages increases the service life of the electrodes [14–16]. In addition, with the elongation of the arc column, the injected gases can be heated until they leave the front electrode, producing a high enthalpy plasma flame. Thanks to these features, hollow electrode plasma torches with reverse polarity have been employed as

a specialty heat source for scientific and industrial facilities requiring a hot flame with high specific enthalpy, e.g., waste treatment [10, 11] and plasma atomization [12, 13].

However, in the non-transferred mode of operation of the torch with reverse polarity, the axially moving cathode arc roots can often come out of the front electrode, causing an arcing outside the front electrode, such as torch housing or furnace wall in melting applications [11, 17]. As the plasma gas flow rate and the plasma power level are increased, the frequency and intensity of such arcing can also be increased, thereby causing damage to the torch. Therefore, for practical applications in a non-transferred mode, this unstable behavior of cathode arc roots needs to be controlled.

For this purpose, in this study, we propose a hollow electrode plasma torch equipped with a cylindrical exit nozzle. In this type of plasma torch, when injecting a cold gas with a swirl through the gap between the exit nozzle and the front electrode, cathode arc roots are expected to rotate continuously on the surface of the front electrode without jumping to the nozzle, enabling a stable arc column to be formed in reverse polarity. To verify this control method of cathode arc root behavior, we carried out basic performance tests of the proposed plasma torch in reverse polarity and compared the test results with those in the absence of a cylindrical exit nozzle.

2. Experimental details

Figure 1 illustrates a cross-sectional view of the plasma torch used in this study for performance test in an electrical connection with reverse polarity. As shown in this figure, the designed plasma torch primarily consists of an exit nozzle and front and rear electrodes, which are coaxially and sequentially arranged with 2 mm gaps between them.

Figure 1. Cross-sectional view of a hollow electrode plasma torch with a cylindrical exit nozzle designed to control the cathode arc root behavior in a reverse polarity discharge structure.

Figure 2. Schematic of the plasma torch system to test the basic performance of a hollow electrode plasma torch with a cylindrical exit nozzle.

In this design, the exit nozzle can be separated for the plasma torch to become a conventional hollow electrode plasma torch, enabling comparison of the effect of an exit nozzle on the torch performance with one torch system. In addition, the plasma forming gas (Gas 1) and the secondary gas (Gas 2) are injected through the gaps between the front and rear electrodes and between the front and exit nozzle, respectively. In the absence of an exit nozzle, the torch housing and the front electrode are designed to be electrically insulated from each other with an annular space between them, thus making the torch housing electrically floating. In this case, Gas 2 is just sprayed through the silica fabric filled in the annular space. Table I lists the diameters (D) and lengths (L) of the exit nozzle, front electrode, and rear electrode. As presented in this table, the L/D ratio for an exit nozzle was designed to be 2, in order to minimize the heat loss in the nozzle.

Figure 2 shows a schematic of the plasma torch system used in this work. As described in this figure, the plasma system primarily consists of a hollow electrode plasma torch with an exit nozzle, a 180 kW class DC power supply (250 A $\times$ 720 V), a gas supply system to form

Table I. Design values of the exit nozzle, front electrode, and rear electrode for the hollow electrode plasma torch used in this work.

Items	Parameters	Values
Exit nozzle	Length, L_1 [mm]	36
	Diameter, D_1 [mm]	18
Front electrode	Length, L_2 [mm]	178
	Diameter, D_2 [mm]	16
Rear electrode	Length, L_3 [mm]	152
	Diameter, D_3 [mm]	16

Figure 3. Photographs of the plasma flames generated by a reverse polarity hollow electrode plasma torch in the absence of an exit nozzle showing cathode arc roots (a) formed on the front surface of the cathode, and (b) arcing on the torch housing.

the plasma jet, and a chiller with cooling capacity of 180 kW to supply cooling water to the power supply and the torch. In Fig. 2, for reverse polarity operation of the torch, the front and rear electrodes can be connected to the negative and positive leads of the DC power supply, respectively. In other words, the front and rear electrodes are set as a cathode and an anode, respectively. Furthermore, in each gas line for Gas 1 and Gas 2, we used two mass flow controllers for Ar and N_2 gases, respectively, to control the flow rate and composition of the injected gases. Moreover, the flow rate and temperature change of the cooling water were measured using a turbine flow meter (Kometer Co., KTM-100) with an uncertainty of ± 3 lpm and T-type thermocouples (uncertainty of ± 0.5 $^{\circ}C$), respectively, installed at the inlet and outlet of the coolant line, as shown in Fig. 2. Table II lists the experimental conditions for the torch performance tests. For the experimental condition given in Table II, arc voltages were measured 20 times in 1 min considering the arc voltage fluctuation caused by the movement of arc roots. Then, they were averaged to calculate the plasma power, P_0 , which is calculated as arc voltage (V) $\times$ arc current (I). From the plasma power measurement results, flow rate and temperature rise of the cooling water thermal efficiencies of the torch, defined using Eq. (1), were calculated for the two cases with and without an exit nozzle, and the calculation results were compared with each other.

$$\eta = 1 - \frac{\rho_{water} Q_{water} C_{p,water} \Delta T_{water}}{P_0} \quad (1)$$

In Eq. (1), ρ_{water} , Q_{water} , $C_{p,water}$, and ΔT_{water} represent the density, flow rate, specific heat, and temperature rise, respectively, of the cooling water. The uncertainties of the measured parameters, such as thermal efficiency and heat loss to the cooling water, were estimated according to the following equations for propagating random and systematic uncertainties.

$$P = \pm \sqrt{\left(\frac{\partial y}{\partial x_1} P_1\right)^2 + \left(\frac{\partial y}{\partial x_2} P_2\right)^2 + \dots + \left(\frac{\partial y}{\partial x_K} P_K\right)^2} \quad (2)$$

$$B = \pm \sqrt{\left(\frac{\partial y}{\partial x_1} B_1\right)^2 + \left(\frac{\partial y}{\partial x_2} B_2\right)^2 + \dots + \left(\frac{\partial y}{\partial x_K} B_K\right)^2} \quad (3)$$

$$U = \pm \sqrt{B^2 + (1.96P)^2} \quad (95\%), \quad (4)$$

Table II. Experimental conditions of a reverse-polarity hollow electrode plasma torch for basic performance tests.

Parameters			Values
Arc Current [A]			153 ~ 204
Plasma Gases [slpm]	Gas 1	Nitrogen	90
		Argon	0
	Gas 2	Nitrogen	65
		Argon	35

Figure 4. Photographs of (a) the front surface of the cathode and (b) the edge of the torch housing showing oxidation and discolored area, respectively, in terms of the arcing evidence.

Figure 5. Photographs of plasma flames generated by a reverse polarity hollow electrode plasma torch in the presence of an exit nozzle [(a) Gas 1 = 90 slpm, Gas 2 = 100 slpm; (b) Gas 1 = 99 slpm, Gas 2 = 110 slpm. Here, nitrogen was used as Gas 1, but a mixture of gases with 35% Ar and 65% N₂ was used as Gas 2].

where, y is the measured parameter as the function of the independent variable x_k . In addition, P and B denote the random and systematic uncertainty, respectively, and U is the total uncertainty evaluated with a 95% confidence level.

3. Results and discussion

Figures 3(a) and 3(b) show the photographs of plasma flames generated in the non-transferred mode operation of the hollow electrode plasma torch with reverse polarity in the absence of an exit nozzle. Figure 3(a) displays that the cathodic arc roots came out of the cylindrical front electrode and attached themselves to the front surface of the electrode in reverse polarity. In addition, Fig. 3(b) shows that the cathode arc roots can have an arcing with the torch housing even though the torch housing was electrically insulated from the front electrode, as explained in Fig. 1. These behaviors of the cathode arc roots in reverse polarity can be confirmed again in the photographs of the front surface of the cathode and edge of the torch housing, as presented in Figs. 4(a) and 4(b), respectively. For example, Fig. 4(a) reveals that the cathodic arc roots left the oxidation area in the front surface of the electrode. Figure 4(b) shows the discolored traces in terms of the arcing evidence at the edge of the torch housing. In addition, it is noted that the edges of the arc roots had a reddish tint in Figs. 3(a) and 3(b) because a commercial window tint film was installed in front of the digital camcorder lens to reduce the light intensity emitted from the arc roots.

Figures 5(a) and 5(b) display the photographs of the plasma flames generated in the non-transferred mode operation of the hollow electrode plasma torch with reverse polarity in the presence of an exit nozzle. The plasma flame shown in Fig. 5(a) was generated in the same operating conditions as those shown in Figs. 3(a) and 3(b). However, for the flames shown in Fig. 5(b), the gas flow rates were increased by

Figure 6. Photographs of the front surface of the front electrode (cathode) after the plasma generation experiment in the presence of an exit nozzle.

Figure 7. Photographs of the (a) front surface and (b) rear surface of the exit nozzle after the plasma generation experiments for no arcing evidence.

10% in Gas 1 and Gas 2 to check the effect of gas flow rate on the behavior of the cathode arc roots. As presented in Fig. 5(a), no cathode arc roots were observed to come out of the exit nozzle in the presence of the exit nozzle with the injection of the swirling Gas 2. When increasing the gas flow rates in Gas 1 and Gas 2 by 10% at the same arc current as that in Fig. 5(a), it can be seen in Fig. 5(b) that the plasma flame became thicker and larger. Additionally, no arcing was observed on the exit nozzle.

Figure 6 shows the front surface of the cathode photographed after the plasma generation experiment in the presence of an exit nozzle. As observed in this figure, the front surface of the cathode was uniformly eroded by the cathode arc roots. In addition, there was no arcing trace on the front and rear surfaces of the exit nozzle, as presented in Figs. 7(a) and 7(b), respectively, revealing that Gas 2 completely controlled the cathodic arc root jumping to the exit nozzle. From these two figures, it can be concluded that by installing an exit nozzle and injecting Gas 2 with a swirl through the gap between the exit nozzle and front cathode, arc roots can be controlled to be attached and rotated continuously on only the front surface of the cathode.

Figure 8 shows the current-voltage characteristics for the reverse polarity torch in the absence and presence of an exit nozzle. As can be seen in this figure, arc voltages for both cases were decreasing slightly with the increase of arc current, but globally, they seem to be kept relatively constant in the range of 355 ~ 380 V. Normally, in a plasma torch with normal polarity, arc length decreases with the increase of arc current, causing the decrease of arc voltage [14]. However, in reverse polarity, owing to the aerodynamic drag force pushing out the cathode arc roots to the end of the front electrode, the length of the arc column can be maintained relatively constant, as observed in Fig. 8, even with the increase in arc current. Moreover, in the presence of an exit nozzle, Gas 2 is injected with a swirl to stop further axial movement of the cathode arc roots. However, this has little effect on

Figure 8. Current-voltage (I-V) characteristics of a reverse polarity hollow electrode plasma torch in the absence and presence of an exit nozzle.

Figure 9. Input power and heat loss to the coolant obtained for a reverse polarity hollow electrode plasma torch in the absence and presence of an exit nozzle by varying arc currents from 153 to 204 A.

the attachment of the arc root on the front surface of the cathode (Fig. 6). Accordingly, similar values of arc voltages can be obtained for both cases in the absence and presence of an exit nozzle, as presented in Fig. 8.

Figure 9 shows the input powers calculated from the results of Fig. 8, together with the heat losses to the coolant. First, it can be observed in Fig. 9 that for both cases in the absence and presence of an exit nozzle, the input powers were increasing in proportion to the arc current owing to the relatively constant arc voltage. However, it is interesting that in the presence of an exit nozzle, the heat losses to the coolant were measured to be lower than those in the absence of an exit nozzle. Considering that an exit nozzle also needs water-cooling, the installation of an exit nozzle can increase the heat loss to the coolant. On the other hand, the injection of Gas 2 with a swirl can reduce the heat loss to the coolant in the exit nozzle by building up the cold layer along the inner surfaces of the exit nozzle. In addition, Gas 2 can also participate in cooling the front surface of the cathode during swirling injection into the inside of the torch. In the absence of an exit nozzle, the front surface of the cathode was heated and oxidized continuously by cathode arc roots without external cooling, as shown in Figs. 3(a) and 4(a). Consequently, the results of heat loss shown in Fig. 9 seem to take place as a result of a trade-off between these two opposing effects achieved by installing an exit nozzle and the injection of Gas 2.

Figure 10 presents the thermal efficiencies obtained for the same operating conditions as Figs. 8 and 9 for the reverse polarity torch in the absence and presence of an exit nozzle. In Fig. 10, the thermal efficiencies show relatively high values of 67.8–72.9% and 63.6–67.7%

Figure 10. Thermal efficiencies obtained for a reverse polarity hollow electrode plasma torch in the absence and presence of an exit nozzle by varying the arc currents from 153 to 204 A.

for both cases of with and without an exit nozzle, respectively. Additionally, owing to the reduction in heat loss to the coolant, thermal efficiency was improved in the presence of an exit nozzle.

4. Conclusions

In this study, we investigated the control method of the cathode arc roots behavior in a reverse polarity hollow electrode plasma torch with a cylindrical exit nozzle. Additionally, we tested the basic performance of the torch in the non-transferred mode operation. In the experiment without the exit nozzle, it was observed that the cathode arc roots came out from the cylindrical front electrode and anchored onto the front surface. In addition, the cathode arc roots were also monitored to jump up to the torch housing, which was electrically floated from the rear and front electrode, i.e., anode and cathode, respectively. However, in the presence of an exit nozzle, stable plasma flames without arcing on the torch housing were obtained, and no arcing traces were found on the surface of the exit nozzle. Instead, the front surface of the cylindrical cathode was uniformly eroded by cathode arc roots. From these experimental results, we confirmed that by injecting the secondary gases with a swirl through a gap between the exit nozzle and front electrode, the cathode arc roots can be formed only on the front surface of the cathode, and continuously rotated.

In basic performance tests of the designed plasma torch in reverse polarity, the arc voltages were measured to be slightly decreasing with the increase of arc currents from 153 to 204 A for cases with and without an exit nozzle. In addition, the measured arc voltages showed negligible differences between the two cases, resulting in similar input power level. However, the presence of an exit nozzle allows secondary gas injection with a swirl through a gap between the exit nozzle and front electrode, resulting in lower heat losses to the plasma torch. Consequently, we could observe that in comparison to those in the absence of an exit nozzle, the thermal efficiencies could be improved.

Based on these experimental results obtained by installing an exit nozzle and injecting a secondary gas with a swirl through a gap between the exit nozzle and front electrode, we expect the reverse polarity plasma torches to be practically employed in applications requiring stable and high-enthalpy plasma flame in the non-transferred mode operation.

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Conflicts of Interest

The authors declare no conflicts of interest.

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References

- [1] J. F. Brilhac, B. Pateyron, J. F. Coudert, P. Fauchais, and A. Bouvier, *Plasma Chem. Plasma Process.* 15, 257 (1995).
- [2] P. Fauchais and A. Vardelle, *IEEE Trans. Plasma Sci.* 25, 1258 (1997).
- [3] S. Ghorui, S. N. Sahasrabudhe, P. S. S. Murthy, A. K. Das, and N. Venkatramani, *IEEE Trans. Plasma Sci.* 28, 2179 (2000).
- [4] M. Hur and S. H. Hong, *J. Phys. D: Appl. Phys.* 35, 1946 (2002).
- [5] M. Hur, K. S. Kim, and S. H. Hong, *Plasma Sources Sci. Technol.* 12, 255 (2003).
- [6] J. M. Park, K. S. Kim, T. H. Hwang, and S. H. Hong, *IEEE Trans. Plasma Sci.* 32, 479 (2004).
- [7] K. S. Kim, J. M. Park, S. Choi, J. Kim, and S. H. Hong, *Phys. Plasmas* 15, 023501 (2008).
- [8] K. S. Kim, J. M. Park, S. Choi, J. Kim, and S. H. Hong, *J. Phys. D: Appl. Phys.* 41, 065201 (2008).
- [9] S. L. Camacho, Proceedings of 8th International Symposium on Plasma Chemistry, edited by K. Akahashi and A. Kinbara (Tokyo, Japan, August 31-September 4, 1987), pp. 87-94.
- [10] S. C. Park, D. U. Kim, M. H. Kim, J. H. Seo, and O. B. Yang, *J. Korean Phys. Soc.* 63, 1746 (2013).
- [11] I. M. Yang, M. G. Choi, J. S. Nam, M. Y. Lee, and J. H. Seo, *J. Korean Phys. Soc.* 74, 465 (2019).
- [12] Z. Yin, D. Yu, Y. Wen, Q. Zhang, J. Qiu, and S. Yang, *Plasma Sci. Technol.* 23, 095402 (2021).
- [13] Z. Yin, D. Yu, Q. Zhang, S. Yang, and T. Yang, *Plasma Chem. Plasma Process.* 41, 1471 (2021).
- [14] M. F. Zhukov and I. M. Zasypkin, Thermal Plasma Torches (Cambridge International Science Publishing Ltd., Cambridge, 2007).
- [15] S. Santen, P. Mogensen, M. Kaij, and J. Thornblom, U.S. Patent 4,543,470 (1985).
- [16] I. M. Yang, J. S. Nam, M. K. Choi, J. H. Seo, and S. Y. Yang, *Plasma Sci. Technol.* 22, 015403 (2020).
- [17] R. A. Lampson, R. E. Haun, R. S. Brooks, and R. C. Eschengach, U.S. Patent 6,313,429 (1985).