Influence of the Laminar Plasma Torch Construction on the Jet Characteristics

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Abstract Based on two typical laminar plasma torches (LPT), i.e. a multi-electrode plasma
torch (MEPT) with segmented anode structure and a two-electrode plasma torch (TEPT) with
conventional structure, this paper studied the influence of the LPTs construction on the jet char-
acteristics. Experiments were designed to measure their arc voltage, jet length, thermal efficiency
and specific enthalpy using a home-made data acquisition system. With them, the jet character-
istics of the two different LPTs were compared in detail. Results show that different plasma torch
construction leads to distinctively different characteristics of the generated plasma jet. Based on
the different jet characteristics, a plasma torch with appropriate construction could be used to
meet the different application requirements.

Keywords: laminar plasma torch, jet characteristics, thermal efficiency, specific enthalpy

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(Some figures may appear in colour only in the online journal)

1 Introduction

Due to its special jet characteristics, the DC plasma
torch has found multiple applications [1], e.g. plasma
spraying [2], plasma cladding [3], synthesis of nanopar-
ticles [4–6], plasma welding [7], waste treatment [8], etc.
However, the plasma jet generated by most DC plasma
torches tend to entrain much of the surrounding at-
mosphere, resulting in a turbulent flow which is char-
acterized by short jet length, non-uniform radial tem-
perature distribution and high axial temperature gra-
dient [9]. Such a plasma jet is named the turbulent
plasma jet (TPJ). Compared with the TPJ, the lami-
nar plasma jet (LPJ), generated by a laminar plasma
torch (LPT) with two typical constructions [10]: seg-
mented anode structure and conventional structure, en-
trains little of the surrounding atmosphere, leading to
favorable characteristics such as longer jet length, lower
axial temperature gradient, higher controllability and
lower noise. Thus, some researchers [11–13] have de-
digned different LPTs to generate LPJ to make up for
the disadvantages of the TPJ and studied the charac-
teristics of the LPJ (jet characteristics) with different
plasma torch constructions. Pan et al. compared the
characteristics of LPJ and TPJ [14] and studied the in-
fluences of the diameter of the insert-electrode on the
jet characteristics of a LPT with a segmented anode by
experiments [12]. Osaki et al. [13] studied the arc volt-
age, thermal efficiency and jet length of a LPT with
a segmented anode. Miao et al. [15] studied the arc
voltage and jet length of a LPT with a conventional
structure.

Although the effects of the working parameters of the
LPT on the jet characteristics have been studied [11–15],
there is no comparative study on the influences of the
LPT construction on the jet characteristics. Therefore,
two LPTs with different constructions, i.e. a multi-
electrode plasma torch (MEPT) with the segmented an-
ode structure and a two-electrode plasma torch (TEPT)
with the conventional structure, were designed for car-
rying out experimental study on the influence of the
LPT construction on the jet characteristics. Based on
the different jet characteristics, plasma torch with the
appropriate construction could be used to meet the dif-
f erent application requirements.

2 Materials and methods

2.1 Experimental setup

Experiments were carried out on the experiment
setup shown in Fig. 1, which consists of a power source
unit, a gas supply unit, a cooling unit and a LPT. The
power source unit uses an IGBT-based DC power source
with a conversion efficiency >90% and current fluctu-
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The gas supply unit accurately supplies working gas to the plasma torch using a mass flow controller with flow rate < 25 L/min. The cooling unit supplies cooling water with a specified temperature to cool the LPT and the power source.

![Fig.1 Schematic diagram of the experimental setup](image)

Fig.1 Schematic diagram of the experimental setup

![Fig.2 Schematic diagrams of the LPTs used in the experiments: (a) MEPT, (b) TEPT](image)

Fig.2 Schematic diagrams of the LPTs used in the experiments: (a) MEPT, (b) TEPT

The LPT is one of the two typical LPTs, i.e. MEPT and TEPT, whose schematic diagrams are shown in Fig. 2. As shown in Fig. 2(a), MEPT, which adopts the segmented anode structure, consists of a rod tungsten cathode (6), a copper cathode cooler (5), a copper gas injection ring (4), insulator rings (3), an inter-electrode (2) (including an inter-ring (2-1), a constriction ring (2-2) and an ignition ring (2-3)) and a cylindrical copper anode (1) with axial gas injection. An arc is ignited between the ignition ring and the cathode by breaking down the working gas in between using high-frequency and high-voltage pulses, and then switched to the cylinder copper anode. Its average arc length is about 35 mm. The other LPT named TEPT, which adopted the conventional structure, is shown in Fig. 2(b). It consists of a rod tungsten cathode (5), a copper cathode cooler (4), a copper gas injection ring (3), an insulator ring (2) and a taper copper anode (1) with axial gas injection. An arc is ignited and maintained between the cathode and anode directly with an average arc length of about 20 mm. All components are directly cooled by the cooling water to reduce erosion.

2.2 Experimental conditions

To study the LPTs’ jet characteristics, experiments of the LPTs working with the parameters specified in Table 1 were carried out and the corresponding arc voltages, images of the generated plasma jets, temperatures and flowrate of the cooling water were recorded. The parameters shown in Table 1 were selected as the LPTs can work stably.

![Table 1. Working parameters of the LPTs](image)

<table>
<thead>
<tr>
<th>Torch name</th>
<th>Working gas</th>
<th>Anode diameter (mm)</th>
<th>Arc currents (A)</th>
<th>Gas flow rates (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEPT</td>
<td>Pure N₂</td>
<td>5</td>
<td>40, 70, 100</td>
<td>2, 3, 4, 5, 6</td>
</tr>
<tr>
<td>TEPT</td>
<td>Pure N₂</td>
<td>5</td>
<td>40, 70, 100</td>
<td>4, 5, 6, 7, 8</td>
</tr>
</tbody>
</table>

2.3 Measurement system

The arc voltages were measured using a data acquisition module (NI USB-6210). The sampling frequency is 100 kHz. The measured data were averaged to obtain the arc voltage of the LPT working at the corresponding parameters.

The images of the plasma jet generated by the LPTs working with the specified working parameters were recorded by a CCD camera. Then, the jet lengths were obtained by analyzing the RGB values of the images with a MATLAB program.

The temperature and flow rate of the cooling water at the inlet and outlet of the cooling channel of the plasma torch were measured by two thermocouples and a turbine flow meter respectively. Then, the thermal efficiency of the LPT and the specific enthalpy of the LPJ could be calculated using Eqs. (1) and (2) respectively:

\[ \eta = \frac{(UI - cm\Delta t)}{UI}, \]  
\[ h_o = UI\eta/G_{gas}, \]

where \( \eta \) is the thermal efficiency of the LPT, \( c, m, \Delta t \) are the specific heat, the mass and the temperature difference of the cooling water respectively, \( h_o \) is the specific enthalpy of the LPJ, \( U \) and \( I \) are the arc voltage and the arc current of the LPT respectively, and \( G_{gas} \) is the gas flow rate.

3 Results and discussions

3.1 Arc voltage

The arc voltages of the MEPT and the TEPT at different working parameters are shown in Fig. 3. As seen from the figure, the average arc voltage of the MEPT is
higher than 95 V, while that of the TEPT is lower than 70 V, which is much lower than that of the MEPT in the range of the working parameters. The distance between the anode and the cathode of the MEPT is much longer than that of the TEPT, resulting in a longer arc length of the MEPT, and thus a higher arc voltage.

In addition, the arc voltage of the MEPT increases slower than that of the TEPT with increasing the gas flow rate. This tendency may be a result of the different construction of the LPTs. With the increase of the working gas flow rates, the arc length of the MEPT increases slightly because the anode arc attachment of the MEPT is limited on the cylinder anode, whose length is relatively small, leading to a slower increase of the arc voltage. For the TEPT, after the arc is ignited between the cathode and the cone section of the anode, the anode arc attachment travels from the cone section towards the cylinder section of the anode at the effect of the aerodynamic force with increasing gas flow rate. It results in a faster increase of the arc length and thus a faster increase of the arc voltage.

Besides, the arc voltages of the two LPTs increase with the working gas flow rates, while they decrease with the arc currents. The reasons for such a tendency are detailed in Ref. [16].

3.2 Jet length

The jet lengths of the two LPTs at different working parameters are shown in Fig. 4. From Fig. 4, the jet length of the MEPT is much longer than that of the TEPT. There could be three reasons to explain such a difference which are caused by the different plasma torch construction. Firstly, the working gas flow rates of the MEPT are smaller than those of the TEPT, resulting in a smoother flow regime. It is beneficial for generating a longer plasma jet as it entrains less ambient atmosphere air into the plasma jet. Secondly, the arc chamber of the MEPT changes smoother than that of the TEPT in the axial direction. Such torch construction keeps the jet velocity almost along the axial direction and thus increases the axial inertia of the working gas, which may be helpful for the increase of the jet length. Thirdly, the arc length of the MEPT is longer than that of the TEPT. It increases the high arc voltage and then the working power, which may result in a longer jet length when the jet is at laminar status.

Besides, the jet length of the LPTs increases with the arc currents, presenting a tendency of a reversed “V” with the increase of the working gas flow rates, which coincides with the tendency reported by Pan [12].

3.3 Thermal efficiency

The thermal efficiencies of the MEPT and TEPT at different working parameters are shown in Fig. 5. It can be seen that the TEPT’s thermal efficiency is much higher than that of the MEPT. The maximum thermal efficiency of the TEPT is higher than 76% while that of the MEPT is only about 43%. This could be caused by the different torch constructions. Firstly, compared with the TEPT, although the segmented anode structure of the MEPT increases the arc voltage, it also increases the dwell time of the arc in the arc chamber, resulting in more heat loss to the chamber wall and thus lower thermal efficiency. Secondly, the cone anode structure of the TEPT increases the thickness of the cooling layer between the plasma arc and the chamber wall. It reduces the heat loss to the chamber wall, resulting in higher thermal efficiency. Thus, the thermal efficiency of the TEPT is much higher than that of the MEPT.
Besides, the thermal efficiencies of the two LPTs increase when the working gas flow rates increase, which could be caused by the increase of the thickness of cold layer [16].

3.4 Specific enthalpy

The specific enthalpies of the plasma jet (JSE) generated by the LPTs at different working parameters are shown in Fig. 6. From Fig. 6, the JSE of the MEPT is much larger than that of the TEPT. The maximum JSE of the MEPT is higher than 68 kJ/g while that of the TEPT is only 28 kJ/g. The segmented anode structure of the MEPT increases the arc length, leading to an increase of the arc voltage and then the arc power. In addition, the MEPT works with lower gas flow rates than those of the TEPT. Thus, from Eq. (2), the JSE of the MEPT is much higher than that of the TEPT.

![Fig. 6 JSE of the LPTs at different working parameters](image)

It can also be seen from Fig. 6 that the JSE of the MEPT decreases with the gas flow rates while that of the TEPT increases slightly. From Figs. 3 and 5, the arc power and the thermal efficiency of the MEPT increase slightly when the working gas flow rates increase. Thus, from Eq. (2), the JSE of the MEPT decreases. However, the arc power and the thermal efficiency of the TEPT increase obviously, surpassing the effect of the gas flow rate on the JSE. Thus, the JSE of the TEPT increases slightly.

Besides, the JSE of the two LPTs increases with the increasing arc current, which is the result of the increase of the arc power.

4 Conclusions

In this paper, the influence of the laminar plasma torch construction on the jet characteristics has been studied by carrying out experiments on two specially designed LPTs. The study can be concluded as follows:

The arc voltage of the MEPT is much higher than that of the TEPT. Besides, the arc voltage of the LPTs increases with the gas flow rates while it decreases with the arc currents.

The jet length of the MEPT is much longer than that of the TEPT. Besides, the jet length of the two LPTs increases with the increase of the arc currents, presenting a tendency of a reversed “V” when the working gas flow rates increase.

The thermal efficiency of the TEPT is much higher than that of the MEPT. Besides, the thermal efficiency of the LPTs increases when the working gas flow rates increase.

The JSE of the MEPT is much higher than that of the TEPT. In addition, the JSE of the MEPT decreases with the gas flow rates while that of the TEPT increases slightly.

Although the jet characteristics of the two LPTs have been experimentally studied and compared, the construction of the LPTs should be optimized by modeling and simulation studies on the underlying mechanism of the LPTs.

References


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