Spectroscopic Diagnostic and Electrical Characteristic of a Converging-Diverging Plasma Torch at Low Pressure Condition

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Abstract. A new anode nozzle with converging-diverging shape designed for low pressure condition used to produce the plasma jet. The emission spectroscopy diagnostic method is applied to calculate the electron temperature by Ar I neutral species’ Boltzmann plots. The efficiency and voltage-current characteristic of the plasma torch were studied. The results showed that with the increase of the current intensity the electron temperature increase a lot. With the increase of the input power the efficiency of the plasma gun rise a little bit and the electric characteristic of the plasma gun is dependent on the content of hydrogen.

1. Introduction
Plasma spraying is a process that the metallic and ceramic powders heated and accelerated in the plasma jet impinges on the substrate to form the coatings. The plasma jet characteristic has a great effect on the quality of the coating (Ref 1). According to the chamber pressure, Plasma spraying is categorized as atmosphere low pressure plasma spraying (LPPS) and plasma spraying (APS). Compared to APS, LPPS could enhance the bond strength between the substrate and the top coating due to reduce the reactions with oxygen during spraying. So LPPS has attracted extensively research interest (Ref 2-3). Plasma jet characteristic is dependent on gas composition, arc current, plasma torch geometry and the injection gas mode. Compared to APS, the characteristic of the low-pressure plasma jet is very different. In LPPS conditions, the plasma plume was enlarged in length and diameter. The plasma jet characteristic investigations have been performed by means of the emission spectroscopy method. The electron temperature can be measured based on the Boltzmann method from the Ar I species (Ref 4). Qing-Yu Chen et al. (Ref 5) measured the electron density and electron temperature in the plasma jets produced under very low-pressure condition by using the intensity ratio of the Hβ and Hα. They found the value of the electron density is higher than the critical value, which is the criterion standard of partial local thermodynamic equilibrium.

In this paper, the properties of a new low-pressure plasma torch jet were investigated. The current-voltage characteristic of plasma arc was analyzed with the different hydrogen volume percentage. The central axial electron temperatures were calculated by applying the Boltzmann plot method.
2. Experimental setup

2.1. Plasma spray System for very low-pressure condition
A plasma spraying equipment for very low-pressure condition was developed by the Thermal Spraying Center of the Dalian Maritime University (Ref 6). The pressure in the vacuum chamber could be changed between 100Pa to 10000Pa. Fig.1 shows the schematic sketch of the plasma torch anode. Inside diameter of the anode is 6mm and a length of 20mm, and the diameter of the single tungsten cathode is 9mm, and the inside diameter of the nozzle is 8mm.

![Schematic sketch of the nozzle and anode](image)

**Figure 1.** Schematic sketch of the nozzle and anode

The photos of the plasma jets is shown in figure 2 at different current intensity under LPPS (1000Pa, Ar 40L/min, H₂ 5L/min, 700A). Compared to APS, the lower chamber pressure is, the longer plasma plume is. The structure of the plasma jets exhibit the fetures of an under-expanded jet. Compared to 400A current intensity, the plasma jet is much longer at 700A current intensity. Detection parameters were listed in table 1.

**Table 1.** Experiment condition

| Spraying parameters |      |
|---------------------|------|
| Chamber pressure (Pa)| 3000 |
| Current intensity (A)| 400, 700 |
| Argon (L/min)       | 40   |
| Hydrogen (L/min)    | 8    |
| Detection distance (mm) | 10-250 |

![Photos of plasma jet under LPPS](image)

**Figure 2.** Photos of plasma jet under LPPS: (a) 400A; (b) 700A;
2.2. **Optical Setup for Emission Spectroscopy**

Figure 3 shows the experimental setup for spectroscopic measurements of plasma temperature. The data of the spectrum was analyzed by using the PlasusSpecline to identify the atomic lines. In the experiments, the spectrum of the plasma jets is acquired by OES (optical emission spectroscopy), which is made by Avantes in Netherlands, and the type of the spectroscopy is AvaSpec-2048-4-USB2, multichannel. Figure 4 shows the typical spectral emission at 200A with the pure argon.

![Experimental setup of the emission spectroscopy](image)

**Figure 3.** Experimental setup of the emission spectroscopy

![Spectra emission in the plasma jet](image)

**Figure 4.** Spectra emission in the plasma jet

3. **Results and Discussions**

3.1. **Emission spectroscopic measurement**

The absolute intensity of an atomic is written as:

\[
\epsilon_l = \frac{1}{4\pi}A_{r,s} n_r g_{r,s} \frac{Z_r}{E_r} \exp\left(-\frac{E_{r,s}}{k_B T}\right) h\nu
\]  

(1)

Where \(A_{r,s}\) is the corresponding transition probability, \(n_r\) is the population density of the atoms, \(g_{r,s}\) is the statistical weight, \(\epsilon_l\) is the energy of emitted photons, \(Z_r\) is the partition function, \(E_{r,s}\) is the excitation energy, \(h\) is the Planck’s constant, \(k_B\) is the Boltzmann constant, and \(T\) is the absolute temperature.

At a fixed axial position from the torch nozzle exit and the integration is performed over the width of the line. According to the Abel inversion for optically thin plasma, the absolute intensity is given as:
\[ I_{t,s} = \frac{l}{4\pi A_s n_0} \frac{g_s}{Z} \exp(-\frac{E_s}{k_B T})h\nu \]  

(2)

Where \( l \) is the depth of the emission source, \( I_{t,s} \) is the absolute intensity of the emission line of s to t. Eq2 taking the natural logarithm yields:

\[ \ln \frac{I_{t,s}}{g_s A_s} = \ln \frac{l h n_0}{4\pi Z} - \frac{E_s}{k_B T} \]  

(3)

All other terms in Eq3 are constants except for \((-E_s/k_B T)\). Eq3 can be simplified as:

\[ \ln \frac{I\lambda}{gA} = -\frac{5040}{T} E + C_1 \]  

(4)

Where \( C_1 \) is constant, and \( E \) has a linear relationship with a slope of \((-5040/T)\) (Ref 14-15). The transition probability, statistical weight, excitation energy of the selected Ar-species is listed in table 2. Based on the Boltzmann method, the electron temperature can be obtained (Ref 7).

Figure 5 shows the Boltzmann plots at a current intensity 700A under different detection distances. The two temperatures’ value obtained at different distances by the method of Boltzmann plots indicates a wide range for temperature measurement in plasma jet.

**Table 2. Parameters of Ar- spectrum**

| \( \lambda/\text{nm} \) | \( A/10^6 \text{s}^{-1} \) | \( E_s/\text{eV} \) | \( g_s \) |
|-----------------|-----------------|-----------------|--------|
| 675.284         | 1.93            | 14.74           | 5      |
| 687.129         | 2.78            | 14.71           | 3      |
| 714.704         | 6.25            | 13.28           | 3      |
| 727.293         | 1.83            | 13.33           | 3      |
| 750.387         | 4.45            | 13.48           | 1      |
| 772.35          | 11.7            | 13.32           | 3      |

**Figure 5.** The plots of Boltzmann distribution at current intensity of 700A: (a) 150mm; (b) 30mm

The axial distribution of electron temperature is shown in figure 6 in the centerline of the plasma jet. At current intensity of 700A, the temperature decreases rapidly along the axis from the nozzle exit with increasing downstream distance and the temperature closest to nozzle exit situated near \( z=5 \) mm.
is 12150 K, while, at z=120 mm downstream regions of the plasma jet, the temperature is 7231 K. At the axis position ranged from z=25 mm to z=65 mm, the electron temperatures are almost the same (about 10700K), and then, a gradually decay of temperature with increasing downstream distance was shown in Fig.6. When the current intensity decreased to 400A, the electron temperature is much lower, but the axial variation of electron temperatures is similar to the one at current intensity of 700A. For 400A operating condition, figure 7 also shows the axial temperature slowly decay rate at the axis position from 15 mm to 45 mm due to the change of locations of the expansion and compression zones.

![Figure 6. Evolution of electron temperature with detection under different current intensity](image)

The more distant axial positions are from the nozzle exit, the less intense is the collision frequency of the electron, atom, and iron, and the particle population of the excited state decreases, resulting in the decrease of energy density. Due to the surrounding cold gas engulfing into the plasma jet, the plasma temperature is substantially reduced. The current intensity has a great influence on the electron temperature axial variation in the plasma jet. The current intensity increase enhances the energy density of the plasma jet, which results in the bigger population densities due to the more collision among high-energy electrons, atoms and ions. So, the higher is the current intensity, the higher the electron temperature in the plasma jet centerline is.

3.2. Thermal efficiency and current-voltage characteristics
The low-pressure DC plasma plume was operated at 3000Pa of chamber pressure and the flow of argon was kept at 40 liters per minute. The total coolant losses were stated as follows:

\[ Q = m_w c_p (\Delta T_f - \Delta T_o) \]  \hspace{1cm} (5)

Where \( m_w \) is the flow rate of the water mass, \( c_p \) is the specific heat of the water, \( \Delta T \) is the water temperature rise, the suffix f is the with arc operating, the suffix o is the without arc operating. The thermal efficiency of the plasma torch is defined as:

\[ \eta = \frac{IU - m_w c_p (\Delta T_f - \Delta T_o)}{IU} \]  \hspace{1cm} (6)

Where \( I \) am the current intensity, \( U \) is the arc voltage.

Figure 7 shows effect of the current intensity on efficiency of plasma torch. The thermal efficiency of the plasma torch was kept at about 43%, and the most quantities of energy in the plasma jet were transmitted to the cooled walls. With the increase of current intensity, the efficiency increases. The current increase improves the energy of the plasma plume, which result in enhancing the arc self-magnetic compression effect, so the energy diffusion of the plasma jet decreases. At the same time, the thermal conductivity of the plasma increases due to the plasma temperature increase resulted from the
increase of current intensity, so the heat exchange with the coolant strengthened. Based on the above reasons, the efficiency was kept about the same.

![Figure 7. Effect of the current on the plasma torch thermal efficiency](image)

The voltage-current characteristic of the plasma torch is shown in figure 8. The voltage of the plasma torch was measured using digital multi-meter, and the measurement accuracy is approaching up to 0.1V. The measurement value of arc voltage was actually an average value.

For argon plasma electric arc, with the increase of the current intensity the voltage will rise. For the argon-hydrogen plasma electric arc, in lower current intensity the voltage will decrease with the increase of the current intensity. The current intensity is about 200A when the arc voltage reaches the minimum. But for argon arc, the inflection point was not observed in figure 8. And at very low arc current, the minimum of the arc voltage could occur.

![Figure 8. The voltage-current characteristic of the plasma torch](image)

The thermal conductivity has a great effect on the current-voltage characteristic. Argon is characterized by relatively low thermal conductivity (0.6W/m·K at 10,000K), while hydrogen has a high thermal conductivity (3.7 W/m·K at 10,000K). So, the thermal conductivity of hydrogen is much higher than that of argon. The hydrogen percentage increase greatly promotes the enhancement of the arc voltage (Ref 8). The change trend of current-voltage characteristic can be explained by the differential Ohm’s law. The “rising” or “dropping” of the arc voltage depends on the relative speed of the current density and electric conductivity increase. In the low current intensity, the current increase leads to the rapid increase of the electric conductivity, and the increase speed of the electric conductivity is higher than that of the current density. So, the arc exhibits a “falling” current-voltage characteristic. With the further increase of the current intensity, the temperature of the arc column does not increase, so the electric conductivity was kept about the same. In this condition, the increase speed of the electric density is higher, which results in a “rising” current-voltage characteristic.
4. Conclusion
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