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2008 Phys. Scr. 2008 014026

(http://iopscience.iop.org/1402-4896/2008/T131/014026)

Phys. Scr. **T131** (2008) 014026 (4pp) doi:10.1088/0031-8949/2008/T131/014026

On the use of the metallic nozzle of a cutting arc torch as a Langmuir probe

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Received 24 July 2008
Accepted for publication 31 July 2008
Published 5 December 2008
Online at stacks.iop.org/PhysScr/T131/014026

Abstract
The region inside the nozzle (bore diameter ≈1 mm) of a cutting arc torch is inaccessible to most plasma diagnostics, and numerical simulations are the only means to find out the relative importance of several physical processes. In this work, a study of electrostatic (Langmuir) probes applied to the inside of a high energy density 30 A cutting arc torch nozzle is presented. The metallic nozzle was used as a Langmuir probe, so the plasma flow is not perturbed by the probe as a solid body. Biasing the nozzle through an electric circuit that employs appropriate resistors together with the arc power source, the i–V nozzle characteristic was built. It was found that under a large positively biased nozzle, the electron current drained from the arc was relatively small, ≈1 A, notwithstanding the fact that the size of the nozzle was relatively large. On the other hand, an almost linear ion current was found for the ion branch for nozzle voltages well below the floating value. Based on the magnitude of inverse slope of the ion current, an estimation of the average electron temperature of the plasma in the vicinity of the nozzle wall was estimated from an ion sheath resistance model using a non-equilibrium two-temperature Saha-equation. An average electron temperature of about 4200 K and a corresponding plasma density of $4 \times 10^{17}\,\mathrm{m}^{-3}$ were found.

1. Introduction

Plasma cutting is a process of metal cutting at atmospheric pressure by an arc plasma jet, where a transferred arc is employed between a cathode and a work-piece (the metal to be cut) acting as the anode. A high-quality cut requires a narrow, hot and high-velocity plasma, i.e. a high energy density arc jet. To this end, a new generation of cutting torch, the so-called 'high energy density torch' was developed. This new generation of torch is characterized by arc current intensities in the range of 30–200 A, flat cathodes, oxygen as the plasma gas, very small nozzle diameters (≈1 mm) and by the generation of an under expanded supersonic arc jet with a shock wave at the nozzle exit [1].

Due to the smallness of the nozzle bore, and the hostile conditions prevailing inside such atmospheric arc torches, access to information about the plasma is inaccessible to most plasma diagnostics, and numerical simulations are the only means to find out information on the plasma structure. Most of the numerical simulations are based on the local thermodynamic equilibrium (LTE) [1, 2]. However, substantial deviations from LTE will occur in the arc fringes inside the torch, where the electron density n_e is much lower than $10^{23}\,\mathrm{m}^{-3}$; which is the lower limit for the existence of such an equilibrium (in accordance with Griem's criterion [3]).

Recently, Ghorui *et al* [4] presented a new two-dimensional (2D), two-temperature, axisymmetric, chemical non-equilibrium model for a 200 A oxygen-plasma cutting torch. It was shown that the electron temperature remained high near the nozzle wall. For instance, an electron nozzle wall temperature T_e of about 12 000 K was found at the nozzle exit (a value much higher than the heavy particle temperature T_h close to the nozzle wall).

In this work, we present an experimental characterization of the plasma flow inside the nozzle of a cutting torch. Emphasis in this work is given to the experimental procedure and experimental results. Also the interpretation of the results in terms of an average electron temperature (along the nozzle wall) of the non-equilibrium plasma is presented.

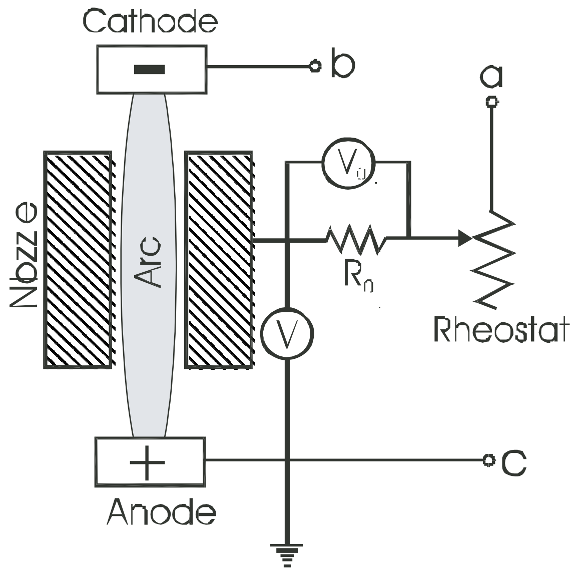

Figure 1. Scheme of the nozzle biasing circuit.

2. Experimental arrangement

The high-energy density cutting torch used in this study consists of a cathode centered above an orifice in a converging-straight copper nozzle. The nozzle consists of a converging-straight bore (with a bore radius $R_N = 0.5$ mm and a length $L_N = 4.5$ mm) in a copper holder surrounding the cathode (with a separation of 0.5 mm between the holder and the cathode surface). To avoid plasma contamination by metal vapors from the anode (usually the work piece to be cut), a rotating steel disk of 200 mm diameter and 15 mm thickness located at 5 mm from the nozzle exit, was used as the anode [1].

By performing a small orifice (1 mm in diameter) on the lateral of the cathode surface, the pressure in the plenum chamber (p_{ch}) was measured by connecting a pressure meter at the upper head of the cathode. The gas mass flow (dm/dt) injected in the torch was also registered. In this experiment, the arc current, the plenum pressure and the gas mass flow were fixed to values of 30 A for the arc current, $p_{ch} = 0.75$ Mpa and $dm/dt = 0.53$ g s^{-1}, respectively.

To obtain the current–voltage nozzle characteristic, it was necessary to bias the nozzle (that under normal arc operation remains floating). The nozzle biasing circuit is shown in figure 1. Different nozzle bias voltages V were obtained using a resistive voltage divider (2 kΩ rheostat), and were registered (with respect to the grounded anode) by using a high-impedance (10 MΩ) voltage meter. On the other hand, the nozzle was disconnected to perform nozzle floating voltage measurements. The nozzle current i was calculated from the voltage drop V_0 through a small resistance R_0.

To build the ion branch of the i–V curve, the rheostat terminal a was connected to the cathode terminal b; while it was connected to the anode terminal c to obtain the electron branch.

3. Experimental results

In figure 2, a typical i–V nozzle characteristic curve is shown. Figure 2(a) shows the whole characteristic, with the electron

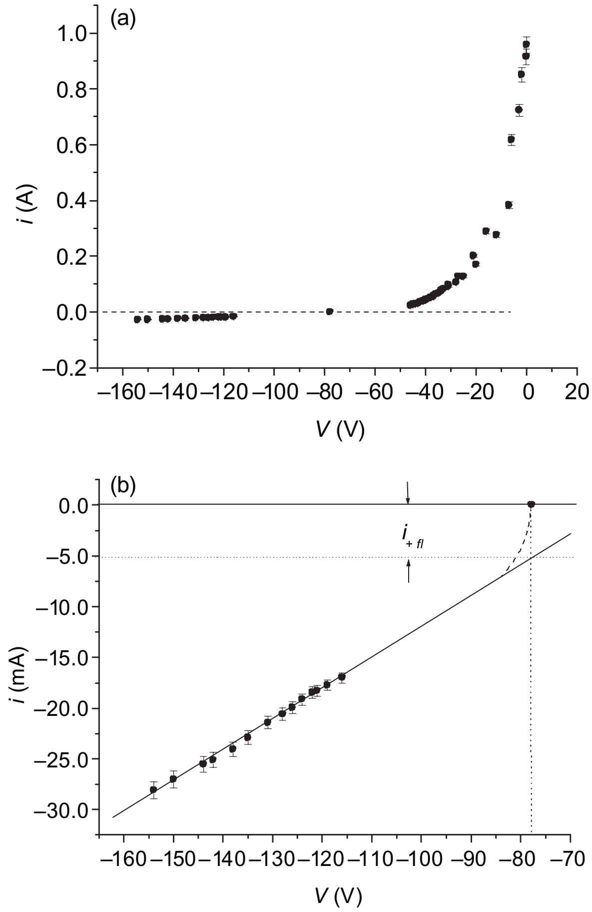

Figure 2. (a) Nozzle i–V characteristic curve. $p_{ch} = 0.75$ MPa and $dm/dt = 0.53$ g s^{-1}. (b) Detail of the ion branch of the i–V characteristic curve. $p_{ch} = 0.75$ MPa and $dm/dt = 0.53$ g s^{-1}. Here i_{+fl} is the pure ion current collected by the nozzle in floating conditions.

current assumed as positive. Figure 2(b) shows a detail of the ion branch with an enlarged current scale. These curves are similar to those reported in wall-stabilized arc experiments without deliberate axial gas flow (see figures 2(a)–(c) of [5]) and with imposed axial gas flow (see figures 2(a) and (b) of [6]).

From figure 2(a), note that under a large positively biased nozzle, the electron current drained from the arc is relatively small, ≈1 A, notwithstanding the fact that the size of the nozzle is quite large. This fact reflects the existence of a very low electron density close to the nozzle wall (that is an essential feature for the correct operation of a transferred arc torch). Also note the great difference between the intensities of the ion and electron collected currents, indicating that in these experimental conditions electron attachment is not present.

The solid curve in figure 2(b) represents a linear fitting of the experimental points. It can be seen that the fitting with a straight line is quite good for voltages well below the floating value, showing that the ion current grows linearly with the nozzle voltage. At voltage values close to the floating value, the straight-line behavior is lost due to the electron contribution to the current. The intersection between the straight fitting line with the vertical line corresponding to the floating potential value can be interpreted as the pure ion current collected by the nozzle in floating conditions ($i_{+\mathrm{fl}}$, see figure 2(b)).

It should be noted that in this kind of cutting torch, the arc is extremely constricted, resulting in high pressures, high current densities and correspondingly high temperatures in the arc axis, even at relatively low arc current values (≈10 A). Then, the radiative arc loses are a significant fraction of the electrical power input, and it is found that the spectral contribution at wavelengths less than 200 nm (photon energy of about 6 eV) is very important in a wide range of conditions [7]. We found (using the semi-empirical radiative model of [8] and a photoemission coefficient $\gamma_\nu \approx 0.001$ [9]) that the photoemission from the nozzle surface yields an electron current of ≈10 mA, i.e. of the order of the ion current. However, the photoelectron current is not dependent on the nozzle voltage, and only produces a parallel displacement of the characteristic curve without changing the slope of the fitting straight line.

4. Interpretation of the results

A simple probe theory is not applicable to the actual situation, because of the collision-dominated regime of the plasma, and the analysis is further complicated by the presence of the axial potential drop in the arc column along the equipotential nozzle surface. Since the nozzle floating voltage is close to the plasma potential at the position of the nozzle inlet [5] and the axial drop of the arc column voltage is of the order of $10\,\mathrm{V\,mm^{-1}}$, there is a considerable variation in the potential difference across the sheath layer from the inlet to the exit of the equipotential nozzle.

However, according to the linear fitting previously shown in figure 2(b), a possible ion current functional dependence like $i \propto V^{1/2}$ (sheath convection regime [10]) is not observed; but this linear fitting suggests that the analysis applied in [5] results in a plausible method to analyze the ion branch.

If, for convenience, we take the point of floating V_{fl} as the potential origin, the fitting straight line is given by the equation

$$i = R^{-1}\tilde{V} + i_{+\mathrm{fl}}, \tag{1}$$

where R is the inverse slope $(\mathrm{d}V/\mathrm{d}i)$ of the line, and represents an effective ion sheath resistance for nozzle voltages much larger than the floating value (and consequently for ion currents much larger than $i_{+\mathrm{fl}}$). From figure 2(b), the inverse slope of the ion branch results $R \approx 3.3\,\mathrm{k}\Omega$ (a value of $\approx 5\,\mathrm{k}\Omega$ was found for a 25 A wall-stabilized, N_2 atmospheric pressure arc [5]).

The quoted value of the average ion sheath resistance is difficult to relate to the unperturbed plasma parameters (i.e. the value of the temperature at the sheath edge), due to the complexity of the internal structure of the sheath. The structure of the boundary layer of a high-pressure, collision-dominated plasma (the characteristic probe length ≫ collision mean free path of charged particles) in contact with a metallic wall, depends on the number of collisions within the sheath (with an extension of the order of the electron Debye length λ_{D}). If the sheath is collisional ($\lambda_{\mathrm{D}} \gg$ collision mean free path), then no transitional layer between the sheath and the unperturbed plasma is required, i.e. the sheath edge coincides with the unperturbed plasma [11]. This is the situation implicitly assumed in the analysis of [5].

Numerical models of the collisional plasma sheath [12] show that if the sheath is highly collisional, the average ion kinetic energy at the wall position is slightly greater than the ion kinetic energy at the sheath edge (even at high negative wall potentials); i.e. the electrostatic force and the frictional force almost balance each other. Then (considering that the ion flux toward the wall is almost constant), the ion density within the sheath does not vary too much with respect to the unperturbed value. Then, a rough model of the average ion sheath resistance predicts that the sheath resistance is given by

$$R \approx (2\pi R_{\mathrm{N}} L_{\mathrm{N}})^{-1} \lambda_{\mathrm{D}} (e n_\infty \mu_+)^{-1}, \tag{2}$$

where e, n_∞ and μ_+ are the electron charge, the undisturbed charge plasma density and the ion mobility, respectively. An estimation of the average electron temperature of the non-equilibrium plasma along the nozzle wall at the sheath edge $T_{\mathrm{e}\infty}$, can be derived from (2) if the average pressure value inside the nozzle is known and by using the plasma state equation and an appropriate statistical-equilibrium equation. As substantial deviations from the LTE equilibrium will occur in regions of low electron density (thus producing an appreciable deviation between the actual and the LTE predicted electron densities), we have adopted in this work a generalized Saha equation for a two-temperature plasma [13].

For an average sheath resistance of about $R \approx 3.3\,\mathrm{k}\Omega$, for a typical average pressure value of about 0.3 MPa [1, 4] and for an average ion heavy particle temperature (close to the nozzle wall temperature [4]) $T_{\mathrm{h}} \approx 1000\,\mathrm{K}$; an electron average temperature at the sheath edge of around $T_{\mathrm{e}\infty} \approx 4200\,\mathrm{K}$ was obtained. At this electron temperature, the average electron density along the nozzle wall is around $4 \times 10^{17}\,\mathrm{m^{-3}}$, a value much smaller than Griem's criterion value for the validity of the LTE equilibrium.

It should be noted that although the average nozzle pressure value is somewhat uncertain, considerable variations in this value (up to 60%) render only small changes in the electron temperature value (3%). Also, in spite of the use of a very simplified model of the ion sheath resistance (2), since at $T_{\mathrm{e}} \approx 4000$–$5000\,\mathrm{K}$ n_{e} grows steeply as T_{e} increases; a good estimate of the electron temperature along the nozzle wall is obtained regardless of the precise estimation of the average ion density within the sheath.

Concerning the validity of the collisional sheath assumption, the ratio of the Debye length to the ion mean free path λ_+ is $\lambda_{\mathrm{D}}/\lambda_+ \approx 20$, showing that the above-mentioned assumption is satisfied.

There are no experimental data available on temperature measurements inside the arc torch. However, a recent non-equilibrium model for a oxygen-plasma cutting torch [4], shows that the electron temperature remains high near the nozzle wall. In particular, an electron temperature of about 12 000 K was found for a 200 A torch at the nozzle exit. Although this value is larger than that reported in this work, the difference between the arc currents is also very marked.

5. Final remarks

In this work, we have developed an experimental technique to estimate the average (along the nozzle wall) electron temperature of the non-equilibrium plasma of a cutting torch in the vicinity of the nozzle wall. As an example, the practical application to a 30 A oxygen high energy density cutting torch was presented and discussed.

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