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Interpretation of Voltage Measurements in Cutting Torches

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Abstract. Anode-cathode and nozzle-cathode voltages, plenum pressure and gas mass flow measurements in a low current (30 A) cutting torch, operated with oxygen gas, are used as inputs for an electrical model coupled to a simplified fluid model, in order to infer some properties of the plasma-gas structure that are difficult to measure.

Keywords: **Cutting torch, arc voltages, nozzle model.**
PACS: 52.75.Hn; 52.80.-s

INTRODUCTION

Plasma arc cutting process uses a transferred arc between the cathode in a plasma torch and the work-piece acting as the anode. The plasma is created by a narrow constricting nozzle into which the gas-plasma system is injected at a high pressure. A large voltage drop is then produced in the plasma along its length, providing intense heating of the particles and an associated pressure gradient force that accelerates the fluid to large velocities [1]. One of the most commonly employed diagnostic to characterize the torch is the measurement of the anode-cathode and nozzle-cathode voltages [2,3]. The anode-cathode voltage drop admits a simple interpretation in terms of averaged properties of the arc (arc temperature, arc radius and length), but the nozzle-cathode voltage has not been related to any property of the system (the nozzle is electrically isolated from the arc). Here we present a simple electromagnetic model for the nozzle region of a cutting torch that, coupled with a simplified hydrodynamic model for the arc, allows the prediction of the quoted voltages in terms of some plasma properties. The obtained results from this model are compared with voltage measurements in a small (30 A) cutting torch.

MODEL

A scheme of the nozzle region is presented in Fig. 1. Since the arc voltage (V_A) scales as $V_A \sim E_z\, z \sim I\, z / \pi\, R_A^2\, \sigma_A$ (is the axial electric field, I = const is the arc current, σ_A is the arc conductivity and R_A is the arc radius), it is clear that the nozzle is an electrically isolated object facing a plasma with variable voltage. Between the arc and nozzle there is a relatively hot neutral gas with a low ionization degree, so we assume that local currents can circulate from the arc to the nozzle and from the nozzle to the arc, under the condition that the total current must be zero. To evaluate the nozzle voltage it is necessary to know $V_A(z)$.

Since the arc region is a plasma of high electrical conductivity, the electric field outside is normal to its surface (radial direction). The same applies to the metallic nozzle, so that the electric field in the gas region inside the nozzle can be considered mainly in the radial direction. Neglecting the axial component of the electric field $\mathbf{E}$, the charge conservation in the gas region can be written as (σ_G is the electrical conductivity of the gas)

$$\nabla \cdot (\sigma_G \mathbf{E}) = \mathbf{E} \cdot \nabla \sigma_G + \sigma_G \nabla \cdot \mathbf{E} = \sigma_G \nabla \cdot \mathbf{E} = 0 \quad (1)$$

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since $\nabla\sigma_G$ is directed along the axis. The potential in the gas can then be obtained from Laplace equation resulting in

$$\phi(r,z) = \phi_A(z) + \frac{\phi_N - \phi_A(z)}{\ln[R_N / R_A(z)]} \ln[r / R_A(z)] \quad (2)$$

where ϕ_N is the potential of the metallic nozzle, and $\phi_A(z)$ that of the arc. We can now evaluate the electrical current collected by the nozzle as

$$\begin{aligned} I_N &= -\int_0^{L_N} 2\pi r \sigma_G(z) \frac{\partial \phi}{\partial r} dz = \\ &- 2\pi \int_0^{L_N} \sigma_G(z) \frac{\phi_N - \phi_A(z)}{\ln[R_N / R_A(z)]} dz \end{aligned} \quad (3)$$

where L_N is the nozzle length. As the nozzle is electrically isolated the collected current in stationary operation is zero, so that one obtains

$$\phi_N = \frac{\int_0^{L_N} \frac{\sigma_G(z)\phi_A(z)}{\ln[R_N / R_A(z)]} dz}{\int_0^{L_N} \frac{\sigma_G(z)}{\ln[R_N / R_A(z)]} dz} \quad (4)$$

To determine the function $\phi_A(z)$ we write the current along the arc as (we take into account the sign to define positive magnitudes)

$$I = \pi R_A^2(z) \sigma_A(z) \frac{d\phi_A}{dz} \quad (5)$$

so that

$$\phi_A(z) = \phi_{A0} + \frac{I}{\pi} \int_0^z \frac{dz'}{R_A^2(z')\sigma_A(z')} \quad (6)$$

where ϕ_{A0} is the arc potential at the nozzle entrance, which is evaluated as

$$\phi_{A0} = \frac{I\,L}{\pi R_{A0}^2 \sigma_{A0}} + \Delta\phi_C \quad (7)$$

where R_{A0} and σ_{A0} are the arc radius and conductivity above the nozzle, L is the cathode-nozzle length and a voltage drop $\Delta\phi_C$ in the cathode layer was included (all potentials are referred to the cathode potential).

Finally, the difference of potential between anode and cathode is evaluated assuming constant electrical field E_{out} in the arc outside the nozzle (equal to its value at the nozzle exit), so that

$$\phi_{anode} = \phi_{A0} + \frac{I}{\pi} \int_0^{L_N} \frac{dz}{R_A^2(z)\sigma_A(z)} + E_{out} L_{out} + \Delta\phi_{anode} \quad (8)$$

where L_{out} is the length of the arc outside the nozzle, and a voltage drop $\Delta\phi_{anode}$ in the anode layer was included. To evaluate ϕ_N and ϕ_N from eqs. (4)-(8), it is necessary to know the geometrical parameters of the torch (L, L_N, L_{out} and R_N), the functions $R_A(z)$, $\sigma_A(z)$ and $\sigma_G(z)$, and the parameters R_{A0} and σ_{A0} at the nozzle entrance. We have developed a simplified hydrodynamic model for the pre-nozzle and nozzle regions, that allows to obtain these data in terms of only two parameters of the problem: R_{A0} and the arc temperature at the nozzle entrance T_{A0}.

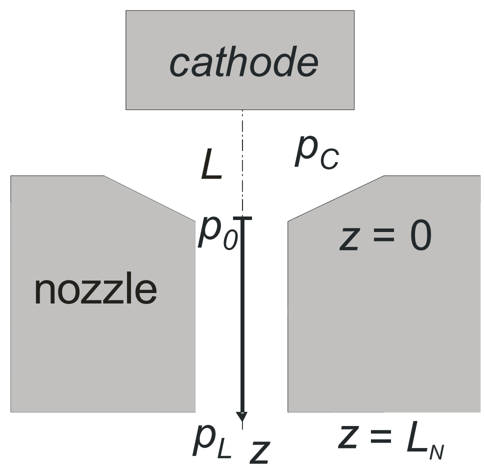

FIGURE 1. Sketch of the cathode-nozzle region of the torch

The model is based on a previously presented one [4], which was extended to allow for mass exchange between arc and gas. Besides, the new model does not require the imposition of sonic conditions at the nozzle exit (used in the previous model), and was also improved in the modeling of radiated power.

The equations of mass conservation, axial momentum and energy for the arc and gas regions, valid inside the nozzle, are (the notation is that used in [4])

$$\rho_A u_A \pi R_A^2 \equiv \dot{m}_A, \quad (9.a)$$

$$\rho_A u_A \frac{du_A}{dz} + \frac{q}{\pi R_A^2}(u_A - u_G) = -\frac{dp}{dz}, \qquad (9.b)$$

$$\rho_A u_A c_p^A \frac{dT_A}{dz} + \frac{q}{\pi R_A^2}\left(h_A + \frac{u_A^2}{2}\right) = u_A \frac{dp}{dz} + \frac{1}{\sigma}\left(\frac{I}{\pi R_A^2}\right)^2 - \chi_A + \varphi_A, \qquad (9.c)$$

$$\rho_G u_G \pi\left(R_N^2 - R_A^2\right) \equiv \dot{m}_G, \qquad (9.d)$$

$$\rho_G u_G \frac{du_G}{dz} - \frac{q}{\pi\left(R_N^2 - R_A^2\right)} u_G = -\frac{dp}{dz}, \qquad (9.e)$$

$$\rho_G u_G c_p^G \frac{dT_G}{dz} - \frac{q}{\pi\left(R_N^2 - R_A^2\right)}\left(h_G + \frac{u_G^2}{2}\right) = u_G \frac{dp}{dz} + \chi_G, \qquad (9.f)$$

where q is the change of mass rates per unit axial length due to mass exchange, modeled as [5]

$$q = \frac{d\dot{m}_A}{dz} = -\frac{d\dot{m}_G}{dz} = 2\pi R_A \rho_G u_G \frac{dR_A}{dz}, \qquad (10)$$

The power radiated by the arc is modeled as [6]

$$\varphi_A = -D(T_A)\left[A(T_A) + \frac{B(T_A)}{R} + \frac{C(T_A)}{R^2}\right]\frac{p}{p_{atm}}, \qquad (11)$$

where p_{atm} corresponds to the atmospheric pressure, and $R \approx R_N$. The functions of the arc temperature A, B, C and D are given in [7].
System (9)-(11) can be integrated numerically if the magnitudes at the nozzle entrance are known, which in turn can be determined modeling the plenum chamber in the following way.

In the plenum chamber we neglect the mass exchange between arc and gas. The conservation of momentum for each region can then be written in integral form as

$$\dot{m}_{G0} u_{G0} = \pi\left(R_{N0}^2 - R_{A0}^2\right)\left(p_C - p_0\right), \qquad (12.a)$$

$$\dot{m}_{A0} u_{A0} = \pi R_{A0}^2\left(p_C - p_0\right), \qquad (12.b)$$

where the sub-index zero corresponds to values at the nozzle entrance, and p_C is the pressure in the cathode region.

We also have

$$\dot{m}_{A0} + \dot{m}_{G0} = \dot{m}, \qquad (12.c)$$

$$\dot{m}_{A0} = \pi R_{A0}^2 \rho_{A0} u_{A0}, \qquad (12.d)$$

$$\dot{m}_{G0} = \pi\left(R_{N0}^2 - R_{A0}^2\right)\rho_{G0} u_{G0}. \qquad (12.e)$$

The total energy equation is, neglecting the kinetic energy in the cathode region and considering the arc temperature as constant,

$$\dot{m}_{A0}\left(h_{A0} + \frac{u_{A0}^2}{2}\right) + \dot{m}_{G0}\left(h_{G0} - h_{GC} + \frac{u_{G0}^2}{2}\right) = \frac{I^2 L}{\pi R_{A0}^2 \sigma(T_{A0})} - \varphi_{A0} \pi R_{A0}^2 L, \qquad (12.f)$$

where L is the distance between cathode and nozzle entrance. Given the equations for the pressure one can obtain from system (12) T_{G0}, $\dot{m}_{G0}/\dot{m}$ and p_0 for given values of R_{A0} and T_{A0}, while $\dot{m}$ and p_C are obtained from the measurements.

In this way, for given values (R_{A0}, T_{A0}) we solve the nozzle model and evaluate ϕ_N and ϕ_{anode} using eqs. (4)-(8). An initial guess (R_{A0}, T_{A0}) is systematically corrected until the measured values of $\phi_N = \Delta V_{NC}$ and $\phi_{anode} = \Delta V_{AC}$ are obtained. The whole process can be easily implemented in any symbolic-mathematics software and takes typically a couple of minutes in a Pentium IV processor.

RESULTS

In Table I we present the measured quantities, and in Table II some of the obtained results for the three cases of Table I are shown. These results refer to the values of the hydrodynamic quantities at the entrance (z = 0) and at the exit ($z = L_N$) of the nozzle. The values of R_{a0} and T_{a0} presented in the Table were selected to fit the experimental values of ΔV_{AC} and ΔV_{NC} within less than 2 %. In performing that fitting, a total voltage drop of 8 V in the cathode and anode sheaths was assumed [8]. From Table II, it can be seen that there is a pressure drop between the cathode tip and the nozzle entrance of about 0.1 Mbar (first two columns of the Table). On the other hand, T_{a0} results in a constant value of 16 kK while R_{a0} presents a smooth decrease with $\dot{m}$. At the entrance of the nozzle, almost 98 % of the total mass flow is carried by the gas, but along the nozzle the arc mass flow is practically two-fold increased. Also, there is an increase in both temperatures and axial velocities (gas and arc) along the nozzle. The radial current density distribution in the gas inside the nozzle changes direction at some z value, as a consequence of the condition of zero current collected by the nozzle. Most of this current circulates in the lower region of the nozzle, were the gas is hottest. In any case, the total current circulating in each direction is completely negligible as compared with the arc current, being of the order of 10^{-4} A. The charge carriers, mostly negative oxygen ions, are provided by electrons dragged from the arc or by photoelectrons ejected from the nozzle, according to the direction of the radial electric field.

p_C (MPa)	$\dot{m}$ (g/s)	ΔV_{AC} (V)	ΔV_{NC} (V)
0.70±0.05	0.33±0.05	175±5	78±3
0.64±0.05	0.29±0.05	166±5	70±3
0.47±0.05	0.18±0.05	142±5	55±3

TABLE I. Measured quantities in the torch experiment.

CONCLUSIONS

We have presented a study of several properties of the plasma generated in a low current cutting torch (30 A) operated with oxygen gas. The measured quantities (anode-cathode and nozzle-cathode voltages, plenum chamber pressure and gas mass flow) were coupled to a simplified model for the plasma-gas structure in order to infer some properties of the arc that are difficult to measure. The model includes an electrical calculation inside the nozzle that allows us to predict the nozzle-cathode voltage with reasonable assumptions. To our knowledge, the relation between that voltage and some properties of the plasma-gas system is for the first time reported.

On the basis of the presented results, the following picture on the origin of the nozzle voltage can be depicted: a strong Joule heating of the arc occurs in the pre-nozzle due to the relatively low electrical conductivities in that region. The increase in current density due to flow contraction in the nozzle increases Joule heating that raises further the arc temperature until the electric conductivity is high enough for additional heating to be important. As a result, the gas is heated by heat transfer from the arc until its electrical conductivity is relatively high, close to the end of the nozzle, so as to set the nozzle potential in the manner discussed above. The nozzle potential is in this way determined directly by the gas-plasma structure inside the torch, resulting in a useful diagnostic tool in an operating device.

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p_0 (MPa)	p_L (MPa)	T_{A0} (kK)	T_{AL} (kK)	T_{G0} (kK)	T_{GL} (kK)	R_{A0} (mm)	R_{AL} (mm)	u_{A0} (m/s)	u_{AL} (m/s)	u_{G0} (m/s)	u_{GL} (m/s)
0.43	0.33	16	18.5	0.43	1.48	0.25	0.26	900	2500	90	400
0.40	0.31	16	17.7	0.39	1.52	0.26	0.27	780	2300	75	380
0.31	0.24	16	15.5	0.30	1.97	0.30	0.32	600	1900	50	410

TABLE II. Theoretical values obtained from the model for the experimental values of TABLE I at the entrance (z = 0) and at the exit ($z = L_N$) of the nozzle