Numerical modeling of the gas breakdown development in the space–charge layer inside the nozzle of a transferred arc torch

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Abstract Double–arcing is a phenomenon that occurs when a transferred arc, flowing inside an electrically insulated nozzle, breaks into two separate arcs: one that connects the cathode with the nozzle, and another that connects the nozzle with the anode. Experimental evidence suggests that the reason for double–arcing is a Townsend like breakdown occurring in the thin space–charge layer, which separates the plasma from the metallic nozzle, due to the high voltage drop across it. Breakdown phenomena in a gas between metallic electrodes have been extensively studied; however the present case involves breakdown of a high–temperature gas between one electrode (the nozzle) and a plasma boundary. A 1–D model of the gas breakdown development in the space–charge layer contiguous to the nozzle of a cutting arc torch operated with oxygen is reported. The dynamics of the discharge is analyzed. The kinetic scheme includes processes of ionization of heavy particles by electron impact, electron attachment, electron–ion recombination and ion–ion recombination.

1. Introduction

The plasma cutting process is characterized by a transferred electric arc that is established between a cathode, which is a part of the cutting torch, and a work–piece (the metal to be cut) acting as the anode [1]. In order to obtain a high–quality cut, the plasma jet must be as collimated as possible. To this end, the transferred arc is constricted by a narrow nozzle (bore of the order of one millimeter).

In the normal mode of torch operation the nozzle is a floating conductor. However, since the metallic nozzle itself is at a constant floating voltage, the zero current balance is fulfilled globally along the whole collecting area of the nozzle, but not locally. This means that one part of the nozzle will collect electrons while the other part will collect ions. Furthermore, due to the fact that the electric current is mostly carried by the electrons, the electron collecting section of the nozzle will be very small as compared to the ion collecting region. Hence, the nozzle floating potential must be close to the arc voltage at the nozzle inlet. In consequence, the voltage drop between the metallic nozzle and the plasma at the nozzle exit reaches a value very close to the total arc voltage drop inside the nozzle [2]. Under certain operating conditions the level of arc stabilization provided by the vortex flow can be

insufficient, and thus the arc, following the path of smallest electrical resistance (the electrical conductivity of the nozzle is much higher than that of the confined arc column), creates two separated arc channels: one from the cathode to the nozzle and another from the nozzle to the anode. Such type of arc instability is called double–arcing. Experimental results [3] suggest that the reason for double–arcing is a Townsend like breakdown occurring in the thin space–charge layer (which separates the plasma from the nozzle wall) at the nozzle exit.

Breakdown phenomena in a gas between metallic electrodes have been extensively studied (e.g., [4]); however, double–arcing involves breakdown of a high–temperature gas between one electrode (the nozzle) and a plasma boundary. A 1–D model of the gas breakdown development in the space–charge layer contiguous to the nozzle of a cutting arc torch operated with oxygen is reported. The dynamics of the discharge is analyzed. The kinetic scheme includes processes of ionization of heavy particles by electron impact, electron attachment, electron–ion recombination and ion–ion recombination.

2. Numerical modeling

2.1. Model geometry
As the Townsend discharge in the space–charge layer likely occurs in the vicinity of the nozzle exit, the 1–D domain is restricted to this region. The model corresponds to a collisional space–charge layer contiguous to the nozzle wall of a 30 A oxygen cutting torch. Since the layer remains thin (about 21 μm [3]) as compared to the nozzle orifice radius (0.5 mm), a planar geometry was used (x is anti-parallel to the radial coordinate at the nozzle exit). The domain is shown in figure 1.
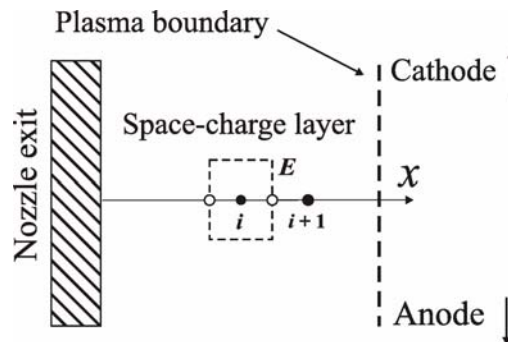
Figure 1. Schematic of the domain.

2.2. Main equations of the layer hydrodynamic approximation
The numerical model includes the following balance equations for charged particles:

$$\frac{\partial N_e}{\partial t} + \nabla \cdot \left(N_e \bar{v}_e - D_e \nabla N_e \right) = k_{ion} N_e N - k_{att} N_e N^2 - k_{rec}^{ei} N_p N_e, \tag{1}$$

$$\frac{\partial N_p}{\partial t} + \nabla \cdot \left(N_p \bar{v}_p - D_p \nabla N_p \right) = k_{ion} N_e N - k_{rec}^{ii} N_n N_p N - k_{rec}^{ei} N_p N_e, \tag{2}$$

$$\frac{\partial N_n}{\partial t} + \nabla \cdot N_n \bar{v}_n = k_{att} N_e N^2 - k_{rec}^{ii} N_n N_p N. \tag{3}$$

Here, N_e, N_p, N_n and N are the numerical densities of electrons, positive (O_2^+) and negative (O_2^-) ions, and neutral (O_2) particles; respectively. v_e, v_p and v_n are the drift velocity of electrons, positive and negative ions, respectively. D_e and D_p are respectively the diffusivity of electrons and positive

ions. k_{ion}, k_{rec}^{ei}, k_{rec}^{ii} and k_{att} are, respectively, the rate constants of ionization, electron–ion and ion–ion recombination, and electron attachment. The equation of state for the pressure (p) was also used

$$\frac{p}{k} = \left(N_p + N_n + N\right)T_h + N_e\,T_e,\tag{4}$$

k being Boltzmann's constant and T_e and T_h the electron and heavy particle temperatures, respectively. The electric field ($\overline{E}$) in the discharge gap is described in terms of the electrostatic potential φ

$$\overline{E} = -\nabla\varphi\tag{5}$$

whose distribution over the gap was determined by solving the Poisson's equation

$$\nabla^2\varphi = -\frac{e}{\varepsilon_0}\left(N_p - N_e - N_n\right),\tag{6}$$

(e is the absolute value of the electron charge and ε_0 the permittivity of free space).

2.3. Kinetic scheme
The following processes were incorporated to the model [4, 5]
Direct electron impact ionization

$$e + O_2 \rightarrow e + e + O_2^+,\tag{7}$$

$$k_{ion} = \exp\left(-13.2 - 21.8/\vartheta\right)m^3s^{-1},$$

where $\vartheta \equiv E/N$ (in units of 10^{-16} V cm^2).
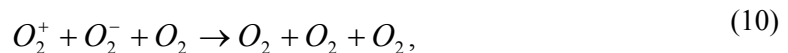Electron-ion recombination

$$e + O_2^+ \rightarrow O + O,\tag{8}$$

$$k_{rec}^{ei} = 2.0\times10^{-13}\left(\frac{300}{T_e}\right)m^3s^{-1}$$

Electron attachment

$$e + O_2 + O_2 \rightarrow O_2 + O_2^-,\tag{9}$$

$$k_{att} = 2.0\times10^{-41}\left(\frac{300}{T_e}\right)m^6s^{-1}.$$

Ion-ion recombination

$$O_2^+ + O_2^- + O_2 \rightarrow O_2 + O_2 + O_2,\tag{10}$$

$$k_{rec}^{ii} = 2.0\times10^{-37}\,m^6s^{-1}.$$

2.4. Initial particle distributions in the layer and boundary conditions
The results were obtained for a gas pressure $p = 0.1$ MPa, a gas temperature of $T_h = 1000$ K, and an electron temperature of $T_e = 5400$ K. [3] The initial profiles of the electron, positive ion, and neutral densities together with the initial voltage distribution were taken from a previously published numerical model of the layer [6]. At the initial time zero level of negative ions was assigned. The nozzle and plasma boundary voltages are held constant at values of -155 and -22 V, respectively. [6]

The nozzle wall was considered as an absorbing surface for the positive ions. The secondary emission caused by positive ions and UV photons was also considered at this surface [7]. The plasma border was modeled as an open boundary for the charged particles.

2.5. Numerical aspects

The governing equations were solved by solving them using a finite difference discretization technique of first-order accuracy in space and time. The domain was discretized into 50 cells. To ensure stability a semi-implicit method was used in which the Poisson equation is first solved using explicitly predicted values of the densities, and the transport equations are then solved implicitly for the densities [8].

The drift–diffusion flux of charged particles was discretized using the Scharfetter–Gummel scheme [9]

$$J_E = \frac{v_E}{\exp\left(\dfrac{v_E\,\Delta x}{D_E}\right)-1}\left[\exp\left(\frac{v_E\,\Delta x}{D_E}\right)N_i - N_{i+1}\right],\qquad(11)$$

where the sub–index E indicates east boundary of the cell (see figure 1). Δx is the cell dimension.
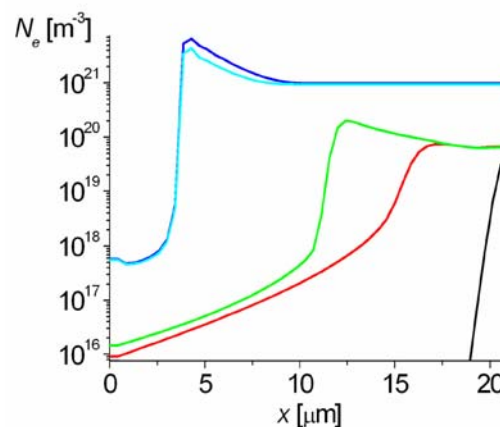
3. Numerical results and discussion

The dynamics of the Townsend breakdown development in the space–charged layer is illustrated in figures 2 to 5. The results show that the breakdown is produced on time scales of the order of 10^{-6} s. The cathode layer of the discharge (with a length scale about 5 μm) in front of the negatively biased nozzle wall is clearly recognized. In this region the positive ion density exceeds the negative charge density, strongly shielding the electric field outside it. The remaining gap region contains quasi–neutral plasma with a weak electric field.

The electrons are lost mostly by electron attachment to O_2 molecules in accordance with the reaction (9).
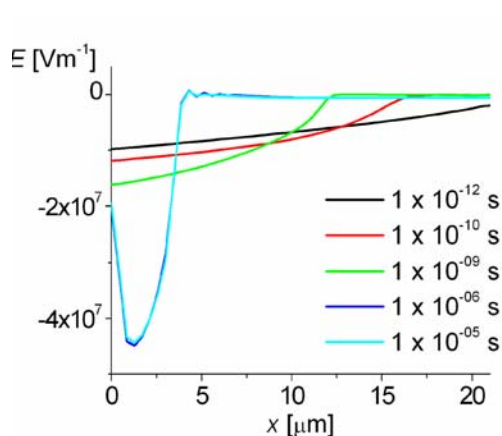

Figure 2. Calculated electric field.

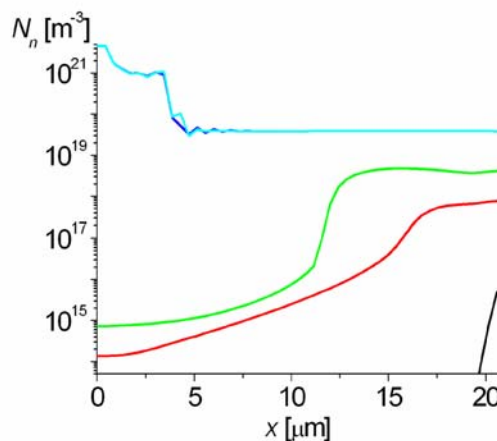**Figure 3**. Calculated electron density.

4. Conclusions

A 1–D model of the gas breakdown development in the space–charge layer contiguous to the nozzle of a 30 A cutting arc torch operated with oxygen was reported. The dynamics of the discharge was analyzed. The kinetic scheme includes processes of ionization of heavy particles by electron impact, electron attachment, electron–ion recombination and ion–ion recombination. The numerical results

show that the Townsend breakdown is produced on time scales of the order of 10^{-6} s. The so–called cathode layer (with a length scale about 5 μm) in front of the nozzle wall was clearly recognized. The remaining gap region contains quasi–neutral plasma. It has been also shown that electron attachment to O_2 molecules plays an important role in the discharge dynamics.
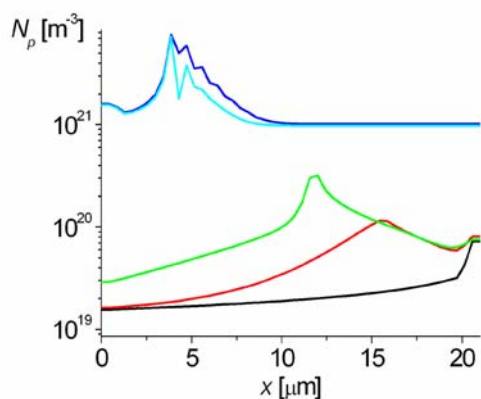
Figure 4. Calculated positive ions density.   **Figure 5**. Calculated negative ions density.

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