3D modelling of the cathodic arc root movement in a hollow cathode of a thermal plasma torch

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This paper deals on a 3D unsteady model of an arc in a hollow cathode. In this kind of configuration the gas is injected in vortex, and an external magnetic field is used to produce an arc root movement to diminish the cathode erosion. A 3D model is developed based on the @Fluent software and a physical approach proposed to describe the arc root positions in time following the plasma characteristics. The mathematical developments take in account all the hydrodynamic plasma description and the electromagnetic effects due to the auto induced magnetic field and to the external one. Results are presented in case of an air plasma and a current intensity equal to 260A with an injected mass flow rate of 20g/s. After the presentation of the plasma characteristics in term of temperature, velocity, magnetic field, the obtained mean arc root position is compared to experimental one, and the arc root velocity to literature values deduced from empirical law.

1. Introduction

Thermal plasma torches are widely used for industrial applications like coating, waste treatment or fusion of materials [1]. As shown in figure 1 two great kind of configurations can be found. The first is made of a full cylindrical cathode centred in the anode. The plasma gas is injected around the cathode and constricts the arc on the cathode tip. This kind of configuration is called "Button-Type Cathode" (BTC) torch. In the second case the cathode is a hollow cylinder and the arc root attachment located on the side of it. Generally, this arc root rotates on the side of the cathode under the effect of an external magnetic field. This configuration is called "Well Type Cathode" (WTC) torch. In the two cases, the anode is made of a hollow cylinder enabling the plasma to flow out of the torch.

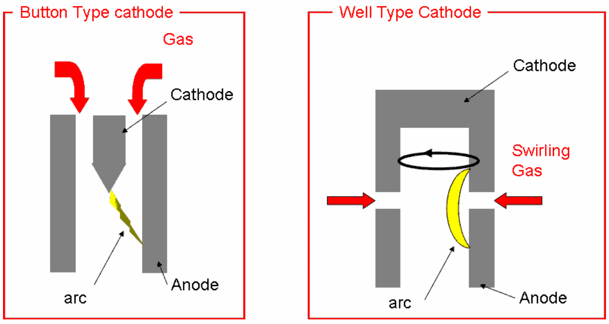

Figure 1 : Two kind or plasma torches.

If a lot of papers exists on the BTC torches ([2] or [3] for instance), nevertheless few works have been made on the WTC ones due to the complexity of their configuration. It exists some experimental studies ([4][5]) but only few theoretical papers are available. The most complete model proposed by Park [6] allows a 3D fluid description of the plasma created by a WTC torch. In its paper, the cathode arc root is assumed to be located in a perpendicular plane of the torch axis. The location of this plane is deduced by considering the velocity field obtained by modelling a cold gas in the geometry.

In this paper, we propose to improve the arc root description in the cathode part of a WTC torch. An unsteady 3D fluid model is developed and used on an industrial torch presenting very large dimensions (the length of the torch is about 1 meter). An approach, initially developed by our team to describe the arc trajectory in low voltage circuit breakers [7] is applied to estimate the arc root movement in the cathode. The properties of the plasma (temperature, voltage) and the results related to the arc root location are presented and discussed.

2. Mathematical model

The model assumes the plasma to be a laminar Newtonian fluid in Local Thermal Equilibrium. The medium is described by the conservation of the mass, momentum and the energy equations written in the conservation form (1)

$$\frac{\partial \rho \Phi}{\partial t} + \mathrm{div}\left(\rho \vec{v} \Phi\right) = \mathrm{div}\left(\Gamma_\Phi \overrightarrow{\mathrm{grad}}(\Phi)\right) + S_\Phi \quad (1)$$

Where Φ is the variable to be solved (velocity component, enthalpy), $\vec{v}$ the velocity, ρ the mass density. Γ_Φ et S_Φ are respectively the diffusive coefficient and the source term. The variable solved are h, the enthalpy, v_x, v_y, v_z the velocity. The plasma temperature T is deduced from the enthalpy and the specific heat Cp. The transport coefficients are those calculated by Bacri [8]. The radiation losses are taken into account by a net emission coefficient calculated by Naguizade [9].

For the electrical plasma properties, the Poisson equation for the electrical potential V and the Maxwell's law for the potential vectors (A_x, A_y, A_z) are used. For these electrical properties, the plasma is assumed to be quasi stationary. The components of the magnetic field B_x, B_y, B_z induced by the arc and the current densities j_x, j_y, j_z are calculated respectively from the vector potential and the scalar potential. These quantities enable to estimate the Joule and the Laplace forces respectively in the energy and momentum conservation equations. More detail can be found in [10].

CFD code Fluent V6.2 is used to solve the differential system of equations [11]. Additional users functions (UDF) are developed to take into account the properties of the plasma, electrical equations and the coupling between them and flow equations. The system of equations is solved in a Cartesian repair (x, y, z).

3. Geometry of the torch – operating conditions

A schematic geometry of the torch is presented in figure 2.

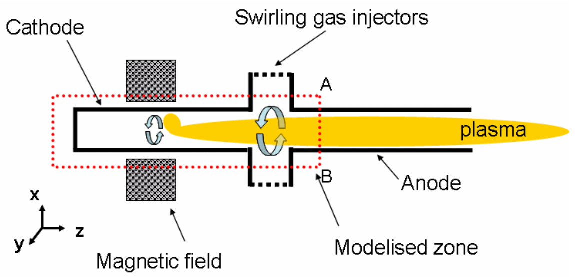

Figure 2: Scheme of the torch.

The torch used is composed by a hollow cathode and anode. The total length of the torch is close to one meter for an internal diameter around 5 centimetres. Air gas is injected in the torch through vortex injectors located between the anode and the cathode. The gas flow rate can be adjusted from 20g/s to more than 90g/s and the DC current intensity used is in the range 260A and 500A. For this paper we used in the simulation a current intensity equal to 260A and a mass flow rate value of 20g/s. In a part of the cathode an axial magnetic field with a magnitude of 125mT is created. This measured magnitude decreases to zero near the injectors. The evolution of the magnetic field for the simulation is given in figure 3. We assume that the magnetic field is constant on a radial section.

In this paper, we are interested by the movement of the cathodic arc root. So, the modelled zone is reduced to: the cathode, the injectors, and a small part of the anode. These zones are delimited by the dashed line in figure 2. An unstructured grid is used leading to a computed domain divided in 770000 cells.

A pressure boundary condition is imposed at the injectors to obtain a mass flow rate equal to 20g/s. Segment AB is considered like an outlet.

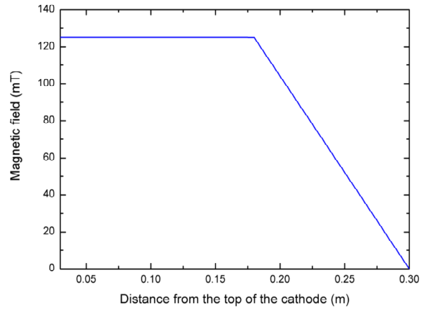

Figure 3 : Magnitude of the magnetic field in the cathode

The temperature is imposed to 300K on all the walls excepted near the arc root. For the electrical potential, a zero reference value is assumed on segment AB i.e. a porous anode condition [10]. For potential vector components, a Neumann condition is used for all the boundaries.

4. Condition for the cathodic root.

At a given location P_0 of the cathodic root, a parabolic current density profile is imposed.

$$j_r(r) = J_{max}\left(1-\left(\frac{r}{R_c}\right)^2\right) \qquad (2)$$

j_r is the current density parallel to the cathode wall. J_{max} is the centre value of the profile. A value of 1.2. 10^8 A/m^2 is chosen. r is the distance between a point P(x,y,z) and the location of the arc root $P_0(x_0,y_0,z_0)$. R_c is such that $j_r(R_c)=0$. The value of R_c was chosen in order to obtain the total intensity I in the torch.

The problem is to determine the location of point P_0 for a time t. We propose to use a method already developed by our team [7] and validated by the community in low voltage circuit breakers [7] [12]. It consists to separate the geometry in some sectors on which we calculate the mean electrical conductivity. We assume then, the cathodic root location being to the sector having the highest mean electrical conductivity.

For the WTC torch, we define a section like proposed in figure 4. The sector is the grey part in the ring between R_1 and R_2. The sector is defined by its height h, the two radius R_1 and R_2, and θ, the azimutal position of the centre of the sector and Δθ the azimutal width of the sector.

For our geometry, we have chosen R_2 equal to the diameter of the cathode (around 20mm) and R_1 equal to 15mm. h and Δθ are chosen in order that the whole current density profile (2) can be contained in a sector. We have defined a sector each millimetre along z axis, and equal on the azimuthal direction to one degree.

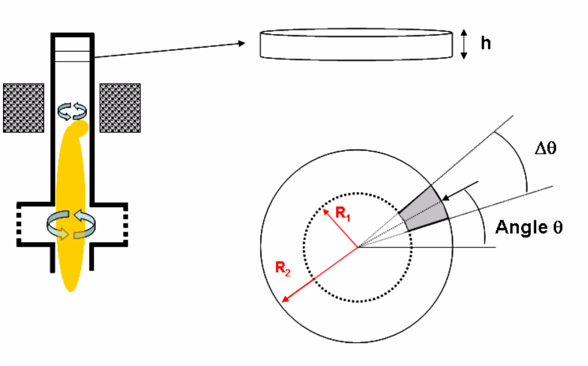

Figure 4: Section definition for the arc displacement

4. Numerical considerations – initial case

Numerous tests have been made, on the time step Δt for the simulation. The optimal one (independence of the results with Δt and highest value) is equal to 5µs. The same time step has been used by Park[6].

In time dependant simulations, the problem due to the high coupling between the equations is to initialize the calculation with a "good solution". As the arc ignition is not described, we have chosen to use the following procedure:

- Obtaining a stationary result in a cold gas.
- Assuming a constant electrical conductivity in a small canal like depicted in figure 5.
- Unsteady resolution of all the equations during 75µs.

The small canal has the form of a cane. Its radius is chosen equal to 3mm. The foot of the cane is located very close to the injectors at 0.290m from the bottom of the cathode. The constant value of the electrical conductivity is chosen equal to 2000S/m. A constant voltage is found equal to -545V for 260A. The total power injected in the initial solution is then 23W. The arc calculation begins from this solution.

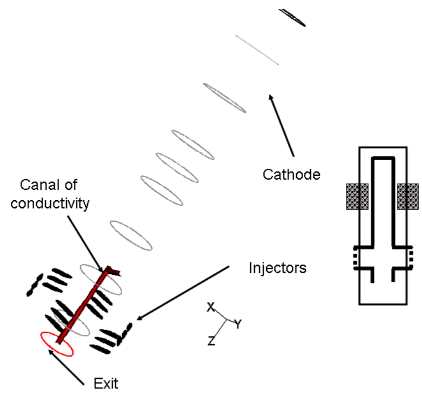

Figure 5 : Initial solution for the unsteady simulation.

5. Results

The total time simulation is 0.01s, corresponding to 2000 time steps. The computed time is about 1.5hour/Nb of processor by time step.

5.1 Movement of the arc root

The axial and azimutal positions of the arc root versus time are plotted in figure 6.

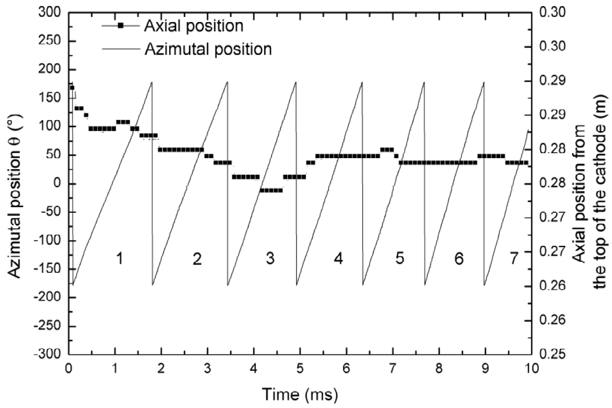

Figure 6 : Evolution of the arc root position versus time.

During the total calculation time, the arc root makes seven revolutions (numbered 1 to 7 in figure 6) around the cathode. Axially, the root moves from its initial position 0.290m to 0.278m for the last revolutions where equilibrium has been found. The arc root moves in the same horizontal plane at 0.278m. We have calculated the mean rotating velocity per revolution of the arc root. These velocities are presented in table 1.

Rev	1	2	3	4	5	6	7
Velocity (m/s)	82	87	95	99	106	110	111

Table 1 : Mean rotating velocity per revolution

These velocities are difficult to obtain experimentally but some authors have proposed semi empirical relations to deduce the arc root velocity when the plasma is deflected by an external magnetic field. The most recent paper is the one of Essiptchouk [13]. A relation is established between the rotating velocity, the magnetic field, the current intensity and a parameter φ which depends on the axial velocity of the cold gas on the arc root. In our case, this axial velocity is difficult to obtain (which velocity should we taken?: the mean velocity near the arc root, the maximum velocity or the mean velocity of the section?. We have so chosen to use the validated equation established by Kukekov and reported by Essiptchouk [13]:

$$v_0 = 185\left(\frac{I \cdot B^2}{C_x^2 \rho_0^2}\right)^{1/3} \qquad (3)$$

v_0 is the rotational velocity, B, the magnetic field, I, the current intensity, ρ_0 the density of the cold gas, C_x the drag coefficient. The use this formulation with a magnetic field equal to 23mT in the plane z=0.278mm gives a rotational velocity equal to 72m/s which is in the same order of magnitude than the theoretical value found in table1.

Concerning the axial location of the arc root, an experimental observation enables to estimate it to be between 150 and 200mm from the top of the cathode. The theoretical value of 278mm seems so to be quite far from these observations.

Nevertheless it seems that the assumption to take constant along a section the magnetic field produced by the external coil, plays an important role on the arc movement. This point needs to be investigated in future works.

5.2 Arc temperature field

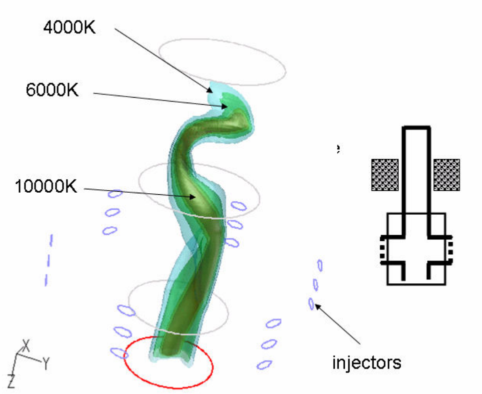

Figure 7 : Temperature field at final time.

The temperature field obtained at final time is presented in figure7. We can see that the arc is twisted by the swirl injection and the rotation force due to the external magnetic field. The total voltage is equal to -245V and a maximal temperature of 17000K is found near the cathode wall. At the exit of the geometry the maximum of temperature is around 14000K and located near the natural axis of the geometry.

6. Conclusion

A 3D, unsteady model of an arc in a hollow cathode has been developed. An original method to represent the arc displacement submitted to an external magnetic field and a swirl injection has been presented. This method enables to predict the rotational velocity of the arc root and its mean axial location. Compared with semi empirical estimations it seems that the prediction of the model gives a good order of magnitude of the rotational velocity. Nevertheless, the mean axial position of the arc is underestimated. We think that this is due to a too much rough description of the external magnetic field created in the cathode and we should study more in detail this point in future works.

7. References

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