doi:10.14311/ppt.2023.2.94
Plasma Physics and Technology **10**(2):94–98, 2023

HEAT TRANSFER IN THE SOLID CATHODE OF A HOLLOW CATHODE PLASMA TORCH

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Abstract. After recalling the working principle of hollow cathode plasma torches, we evaluate the heat flux profile on the cathodic arc root. This evaluation takes into account the physics of the cathode sheath. Particular attention is devoted to electron emission from the cold copper cathode. This heat flux profile is then used as a moving boundary condition to obtain the temperature field in the solid cathode with a heat conduction study, with the aim of discussing the problem of its erosion.

Keywords: plasma torch, sheath model, cold cathode, heat conduction.

1. Introduction - Hollow cathode plasma torches

In this study, we address the problem of the erosion of the cathode of hollow cathode plasma torches. A sketch of this kind of plasma torch is presented in Figure 1.

The working principle of these plasma torches and their applications (e.g. studies of heat flux conditions in atmospheric re-entries, but also waste treatment and gas heating, where the thermal plasma generated by the torch replaces usual combustion flames generating greenhouse gases) have already been extensively described in the literature (see e.g. references [1, 2]). We remind however useful elements for the present study. The upstream part of the torch can be assimilated to a hollow cylinder. This part is a cathode and an electric arc moves inside under the action of two forces : (i) gas drag and pressure forces due to the vortex injection of the plasma gas, and (ii) magnetic forces due to a coil installed around the cathode (and of course the "self-induced" magnetic field due to the current in the arc).

The little channel connecting the main (mostly axial) electric arc column and the inner surface is called the arc root. The current circulating in the arc root is thus mostly radial. The action of the axial component of the magnetic field created by the coil on this radial current density is responsible for the apparition of an azimuthal Laplace force. This Laplace force imposes a rotation motion of the arc root around the axis of the torch. Most industrial geometries are designed such that the orientation of this rotation is opposed to the orientation of the vortex gas injection. The axial position of the arc root is stabilized (in principle) in a plane $z = z_{\mathrm{arc}}$, whose position is determined by an equilibrium of drag and magnetic axial forces. The existence of the magnetic axial force is due to the interaction of the azimuthal current density (existing because of the vortex and the rotation of the arc root previously described) and the radial component of the magnetic field created by the coil. More details on this equilibrium can be found in Minoo's paper [1].

Numerical models devoted to the electric arc movements in the cathode part of the torch have been previously published and discussed in the literature (see e.g. [3]). These models are extremely costful numerically. Indeed, the movements of the arc impose a transient study on a 3D geometry and a very small time step should be used since a rotation of the arc root typically happens in 1 ms. Nevertheless, these models enable to obtain the axial position in which the arc root will rotate and its angular velocity.

One of the main issues when using this kind of plasma torch is the fast erosion of the cathode. This erosion is due to the fusion (and vaporization) of the material used [4], usually copper, which happens because of the very high heat flux transmitted to the surface near the arc root. More precisely, the interaction region between the arc root and the surface is made of many tiny cathode spots similar to those of the vacuum arc, and the heat flux due to these cathode spots must be evaluated. The displacement of the arc root due to magnetic forces is supposed to increase the life time of the cathode by spreading the erosion over a larger surface area. To limit the temperature values, the cathode is also water-cooled on its external cylindrical surface. Despite these precautions, erosion still occurs and limits the life time of the cathode.

As a first approach of these very complex problems, we propose in this paper to try to analyse how erosion can occur and to evaluate an average flux profile on the cathode spots by a model. This flux profile will then be transposed to the actual hollow cathode geometry with the moving arc root. A heat conduction study of the cathode, similar to that of Teste [5] will be performed in order to obtain the temperature evolution in the cathode body. The working parameters

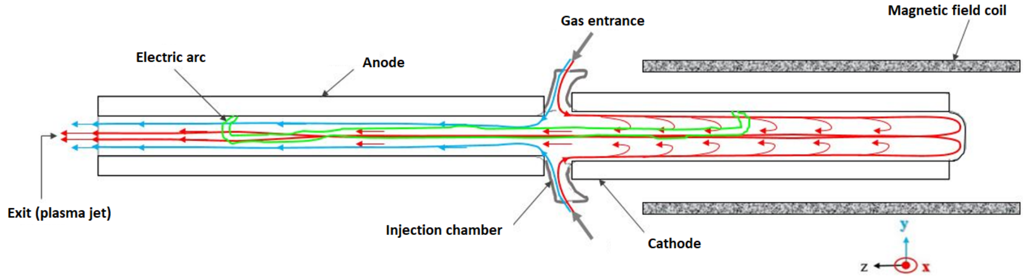

Figure 1. Sketch of the hollow cathode plasma torch working principle

of the plasma torch are the same as Sambou's. The electrical current in the arc and the coil is 260 A and the air mass flow rate is 37 g/s. With these parameters, the experimental voltage of the torch is about 1000 V.

2. Modelling of the cathode heating

2.1. Heat flux profile received on the averaged cathode spot

To understand the cathode erosion, the heat flux inside each cathode spot should be evaluated. Pratically, this evaluation requires the detailed description of the cathode sheath connecting the plasma and the cathode, in terms of particle fluxes and the energy that these fluxes carry. It also requires the description of the evaporation of the cathode with a Knudsen layer. Even though models of the cathode spot exist in the context of the study of vacuum arc cathode spots (see e.g. Beilis' kinetic model [6]), they still depend on experimental parameters such as the current per spot (or equivalently, the number of spots that will appear on the surface depending on the total current). Moreover, it is not clear whether the theories for vacuum arc can be extended to a surrounding plasma gas such as air at atmospheric pressure. Instead, we have chosen, as a first rough approach, to describe this situation with time-averaged heat flux and current density profiles to obtain an average description of the arc attachment. We will thus assume that the time-averaged current density profile on the cathode due to the spots is the same as the current density profile in the plasma. This seems reasonable since the life time of a spot is very short (at most a few µs) compared to other time scales (precised below). Consequently, we have chosen to adapt a model initially developed for refractory cathodes and to make the necessary modifications to handle the case of a copper cathode.

The model that we have developed and used is strongly inspired from the one developed by Cayla et al [7] and Gonzalez et al [8], themselves inspired from Benilov and Marotta's 1995 model [9]. This model takes 4 particle fluxes into account in the sheath : emitted electrons, ions, back-scattered electrons and secondary electrons, as illustrated in Cayla et al.'s paper [7].

Several modifications regarding electron emission were made to adapt this model to a copper cathode. Indeed, the low boiling point of this material (1350 K) indicates that the predominant electron emission effect is field electron emission and not thermionic emission as was assumed by Cayla et al. and by Gonzalez et al, who were studying refractory cathodes. Thus, the law describing electron emission is given by the Murphy-Good equation [10] rather than the usual Richardson-Schottky equation.

Moreover, the electron emission from cold cathodes is extremely complex, and many effects are known to enhance electronic emission with respect to that described by the Murphy-Good equation [11]. In addition, surface roughness and the presence of an oxide layer are known to enhance the surface electric field [11]. To take these complex phenomena into account, we introduce a field enhancement factor $\beta > 1$ which multiplies the electric field calculated from the Poisson equation. This factor will also effectively take into account deviations from the Murphy-Good equation which result in an enhancement of electronic emission.

The model is used on a simple geometry with a flat electrode (circular surface of a cylindrical electrode of radius and height 5 mm). The value of the field enhancement factor is taken uniform on the cathode surface. A parametric study is performed on this parameter and the value retained is the one which gives the closest results to the experiment conducted by Landfried et al. [12], in terms of maximal temperature reached on the cathode surface after 4 ms of heating. Then, the value of β chosen should enable us to reach the right energy transmitted from the plasma to the cathode.

2.2. Position of the heat conduction problem

Having obtained the heat flux profile at the arc root, we study the dynamics of the temperature field in the torch's cathode. We must now take into account the movement of the cathodic arc root, in the scope of a full 3D model. The hollow cathode is assimilated to a hollow cylinder whose internal radius is R_{int}, external radius R_{ext} and height H. A picture of the geometry modelled is presented in Figure 2.

Results obtained by Sambou et al [3] show that the arc root reaches an equilibrium axial position

Figure 2. Geometry used for the 3D heat conduction study. Only the solid region (in brown) is modelled. The inside radius is R_{int}, the external radius is R_{ext}, and the length of the cylinder is H.

z_{arc} after a few 10 ms. They also show that the arc root has a rotation motion around the axis with a typical period $T_{\mathrm{arc}} = 1$ ms. We will thus assume that the arc root and the associated flux profile move on the surface with these characteristics. More precisely, we assume a circular motion with constant angular velocity $\omega = \frac{2\pi}{T_{\mathrm{arc}}}$ in the plane $z = z_{\mathrm{arc}}$.

The method used to solve this problem is similar to that of Teste [5]. We solve the heat conduction equation in the solid cathode volume:

$$\frac{\partial \rho h}{\partial t} = \nabla.(\kappa \nabla T), \tag{1}$$

where ρ is the mass density of copper, κ is the thermal conductivity, and $h = cT$ is the specific enthalpy of copper (with c the specific heat capacity). Unlike Teste, we use temperature independent material properties (constant and uniform), but we still include the latent heats for fusion and vaporization in the massic heat capacity. This way, if phase changes occur, they will be treated from the thermal point of view.

The water-cooling on the external lateral face is modelled by Newton's law of conducto-convection:

$$q(R_{\mathrm{ext}}, \theta, z) = h(T(R_{\mathrm{ext}}, \theta, z) - T_{\mathrm{fl}}), \tag{2}$$

where θ and z are the cylindrical coordinates naturally associated with the cylinder geometry. The value of the transfer coefficient h is determined by Europlasma Industries from a dimensional analysis and experimental parameters of the cooling. Its value is estimated to 35000 W.m^{-2}.K^{-1}, and the temperature of water at the edge of the thermal boundary layer is $T_{\mathrm{fl}} = 300$ K.

The time dependent boundary condition on the internal cylindrical surface is:

$$q(R_{\mathrm{int}}, \theta, z) = q_{\mathrm{cat}}(\sqrt{(z - z_{\mathrm{arc}})^2 + (\theta - \omega t)^2}) \tag{3}$$

where t is time and q_{cat} is the radial flux profile obtained from the cathode sheath model described above.

This problem is then solved numerically with the software Ansys Fluent 19.2 [13]. Typical geometric parameters are $H = 25$ cm, $R_{\mathrm{int}} = 1.5$ cm and $R_{\mathrm{ext}} = 2.5$ cm. The mesh contains 141960 cells with typical size $\delta = 1$ mm. This choice results from a compromise between precision and calculation time. It may be argued that the flux profile resolution on the surface will be low, but the calculated deposited power with that mesh is correct, and since the solver uses finite volume method, it is conservative by construction. The time step used for this transient simulation is $\Delta t = 10$ µs. This time step is chosen from an estimation of the arc residence time on a cell, knowing that its speed is $v_{\mathrm{arc}} = R_{\mathrm{int}}\omega$, i.e. $\Delta t = \frac{\delta}{v_{\mathrm{arc}}}$. The spatial discretization scheme is the one used by default in Fluent for fluid flow calculation, and is second order upwind. The linear system obtained from the first order implicit formulation that we used is solved with the Gauss-Seidel method.

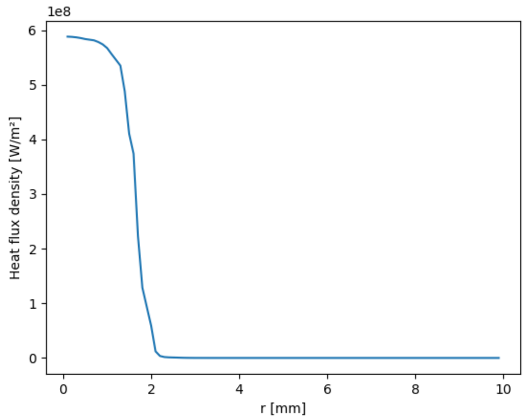

Figure 3. Cathodic heat flux profile for an electric arc in air, with current intensity $I = 260$ A and $\beta = 40$

3. Results

3.1. Arc root flux profile

The retained value of β is that which gives closest results to Landfried's experimental results [12] in terms of maximal temperature reached on the surface after 4 ms of heating (on the simple flat geometry). We find a value of $\beta = 40$. The cathodic heat flux profile associated to this value is represented in Figure 3.

We then transpose this flux profile on the internal cathode surface of the plasma torch as a boundary condition (see Eq 3).

3.2. Temperature field on the cathode surface

The solution of the conduction heat problem set in section 2.2 leads to the temperature fields on the internal cylindrical surface reported in Figures 4 and 5. Note that the space scales in Figure 4 are different from Figure 5, since we have zoomed on the region of interest for the first figure mentioned. For both figures, the cylindrical surface has been "unfolded" (i.e. is represented in cylindrical coordinates). At the beginning of the heating, only a local "spike" of temperature exists at the same position than the flux profile imposed. This "spike" corresponds to the increase of temperature during the transit of the arc root. Of course, one transit is too short for much

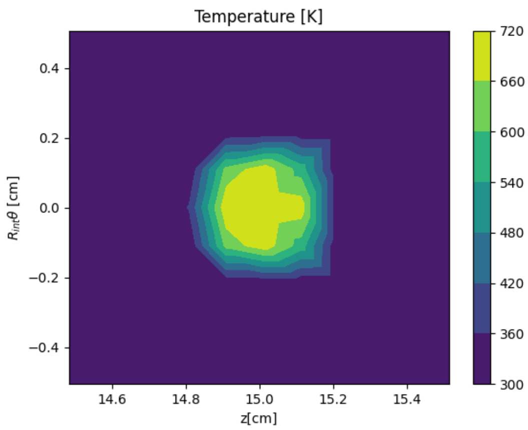

Figure 4. Temperature field on the internal surface of the cathode after 10 µs. This temperature spot moves on the cathode surface in agreement with the flux spot.

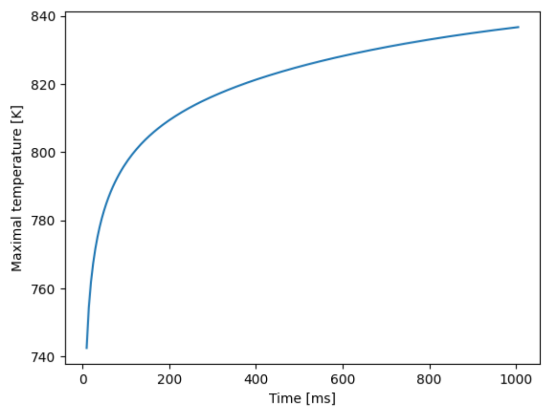

Figure 6. Evolution of the maximal temperature reached on the inner cathode surface for $h = 35000\ W.m^{-2}.K^{-1}$.

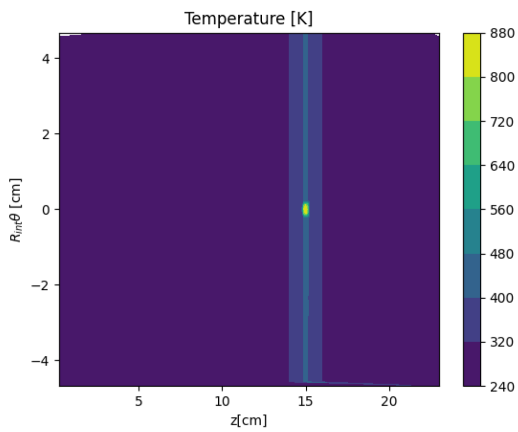

Figure 5. Temperature field on the inner cathode surface after 1 s of heating.

energy to be deposed on the surface, so the temperature decreases after the arc root is gone. However, when longer time scales are considered, the surface has locally suffered many transits of the arc root, so that much more energy has been deposited on the surface, and a temperature streak appears on its path (visible in Figure 5). This temperature corresponds to a heating with the flux averaged over a rotation period of the arc root.

Figure 6 shows the maximum temperature reached on the cathode surface as a function of time (i.e. a heating curve of the surface). We can see an increase of the surface temperature due to the many rotations of the arc root. After 1s of heating, the temperature has only reached 840 K which is far below the fusion temperature. The characteristic times for temperature diffusion in the cathode thickness and relaxation to the established regime are respectively $\tau_{\mathrm{diff}} = \frac{\rho c {e_{\mathrm{K}}}^2}{\kappa}$ and $\tau_{\mathrm{rel}} = \frac{\rho c e_{\mathrm{K}}}{h}$ where $e_{\mathrm{K}} = R_{\mathrm{ext}} - R_{\mathrm{int}}$ is the thickness of the cathode. Numerical evaluation of these times gives $\tau_{\mathrm{diff}} = 0.9$ s and $\tau_{\mathrm{rel}} = 1$ s. These results are consistent with Figure 6.

The result obtained from the averaged profile used in the model seems unsatisfactory to describe fully the temperature rise up to erosion.

4. Discussion and conclusion

We have developed and used a model to describe the heating and erosion of a hollow copper cathode of a plasma torch. This model considers a time-averaged description of the cathode spots which exist on the cathode surface. The heat flux in the zone where the cathode spots exist is evaluated thanks to a description of the cathode sheath adapted from a model developed for refractory cathodes. The electron emission law was adapted to take into account the phenomena specific to cold cathodes. The heat flux profile obtained was used as a boundary condition for a heat conduction study of the torch's cathode. The results of the model are in contradiction with the existence of the cathode erosion. Many factors can explain this problem.

First, modelling the cathode spots by an average flux profile using a method developed for refractory cathodes may be a too rough approximation since this will erase the very high heat fluxes (typically 10^{10} W.m^{-2}) that exist on the cathode spots, and lead to the temperature rise up to erosion. A way of improving this description would be to estimate the total surface occupied by spots in order to get a better description for power distribution on the surface. Such an estimation would however use parameters such as the current per spot (in order to determine the number of spots), but also the mean size of a spot and its life time. Indeed, even though the local flux distribution derived from our model is likely incorrect when this problem is taken into account, the total deposited power should be correct, and knowing the time and space scales of the spots would enable to redistribute this total power. This question remains open. The approach could be compared to the experimental erosion rate of the cathode which is around

1 g/h for the considered conditions. At any rate, even though complex models for the cathode spots in vacuum arcs do exist, they consider a single spot and are not integrated in a complete modelling of a dynamic multi-spot arc attachment zone. To authors' knowledge, such a model describing the complete interaction between an electric arc established in atmospheric air with a cold cathode is still lacking in the literature.

Second, the heat transfer coefficient h was set arbitrarily to the value given by Europlasma Industries and may be too high. With the help of a simplified 1D spherical code, we have found that, with the given flux profile and arc root velocity, the value of h should be reduced to around $2700\,\mathrm{W.m^{-2}.K^{-1}}$ in order to reach the fusion temperature. It appears unlikely that the value given by Europlasma Industries was so overestimated. Finally, the real trajectory of the arc root may present stagnations during which the surface temperature may exceed the fusion temperature. With the given flux profile, such a phenomena is also unlikely because the arc root would have to stay in place for at least 9 ms (when starting the heating at the average temperature that exists on the streak), which is much longer than a typical arc root rotation. Therefore, to better understand the erosion of the torch, further studies should be focused on the description of evaporation in the cathode spots.

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