ELECTROPOLISHING SIMULATION ON FULL SCALE RADIO FREQUENCY ELLIPTICAL STRUCTURES

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Abstract

This paper describes a methodology to simulate the electropolishing of a full scale radio frequency (RF) accelerating elliptical cavity through data acquired by means of a rotating disc electrode (RDE) in a three electrode set-up. The method combines laboratorial data from the RDE with computational simulation performed with Comsol Multiphysics® either for the primary and secondary current distribution as well as to account for the local effect of hydrodynamic perturbations. The results are compared with experimental data from the electropolishing of niobium 704 MHz mono and five cell cavities from the Superconducting Proton Linear Accelerator (SPL) R&D project at CERN.

Introduction

The existing electropolishing installation at CERN is a vertical setup, where cavities are assembled upright whilst the electrolyte is circulating upwards inside them [1].

Previous work on the subject of computationally modelling electropolishing has involved efforts to optimise cathode geometry in an attempt to achieve uniform electropolishing, however this work only took into account primary and secondary current distribution where temperature and bath velocity were assumed constant [2]. Besides geometry optimisation, it allowed defining the minimum potential at which the cavity inner surface is under limiting current condition; for this specific surface finishing, it means that the polishing rate is mainly dependent of the electrolyte velocity and temperature.

The fluid dynamics of the process, however, has not been addressed in the previous work. Being able to study the electrolyte flow, and further, quantify its velocity at specific points inside the cavity would enable optimisation of the electropolishing process; such as the chosen electrolyte inlet flow or the cathode geometry and this to achieve a more uniform material removal all through the cavity surface. Of particular pertinence is the desire to ascertain a correlation between the electrolyte velocity within the cavity and current density value. In order to achieve it, a known electrode geometry has been used to supply the necessary data; the RDE. Under limiting current conditions, the main advantage of the RDE is that the convective-diffusion equation (see Eq. 1) can be solved and its solution is known as the Levich equation (see Eq. 2). This equation gives a direct relationship between electrode angular velocity and current.

Equation 1: $\frac{\partial C_j}{\partial t} = -D_j \nabla^2 C_j - v.\nabla C_j$

Equation 2: $j = 0.62\, nFAD_0^{\frac{2}{3}} \omega^{\frac{1}{2}} \nu^{-\frac{1}{6}} C_0^*$

Methodology

The method described hereafter assumes that the entire surface to be processed is under limiting current. It can be resumed to two main steps: perform fluid dynamics simulation and conversion of electrolyte velocity data from simulation into current density.

The fluid dynamics simulation was made through COMSOL Multiphysics®. The used geometry included the cathode defined by the optimisation of primary and secondary current distribution simulation on a five cell cavity) and the cavity itself (see Fig. 1). From the fluid dynamics simulation, it was possible to acquire data that defined a boundary layer through the cavity length. This boundary was defined by the distance to the cavity wall at which the electrolyte velocity was 1% of the maximum velocity.

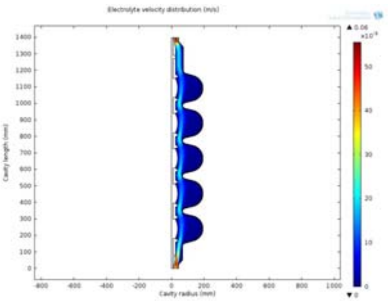

Figure 1: Electrolyte speed distribution in an axisymmetric cut of a SPL five cell cavity assembled with its cathode.

The conversion of electrolyte velocity, collected through the fluid dynamics simulation, into current density was made by coupling the solution of the hydrodynamic equations and that of the convective-diffusion equation for the RDE. The first will provide a relation between radial (see Eq. 3) or normal velocity (see Eq. 4) with the angular velocity; this is of utmost importance, as it provides the means to make a bridge between RDE and cavity geometries; the second, as already mentioned, will provide the relation between angular velocity and current density as defined in figure 2.

Equation 3: $v_r = 0.51\, \omega^{\frac{3}{2}} \nu^{-\frac{1}{2}} r y$

Equation 4: $v_y = 0.51\, \omega^{\frac{3}{2}} \nu^{-\frac{1}{2}} y^2$

In order to ascertain whether the conversion is an accurate representation for that which occurs during electropolishing, the values calculated for current density were compared with those found in reality. Finding the real current density distribution on the five cell cavity was achieved through measuring the thickness of the cavity wall before electropolishing and after, and by converting the change in thickness into current density through the Faraday law of electrolysis.

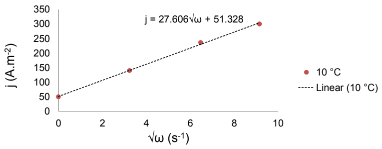

Figure 2: Experimental data acquired through the RDE shows the linear relation defined by the Levich equation between limiting current density and the square root of the angular velocity.

The wall thickness was measured by ultrasonic means, with an accuracy of 1% with respect to the wall thickness, roughly ± 30 µm. This control allows for the amount of niobium taken on the surface to be measured at well-defined coordinates of the cavity wall, and for the uniformity along the five cell cavity to which this has occurred to be assessed. Further to this, the overall current density was also determined from the cavity mass loss; and this after each electropolishing step. This overall value was used as referential of the conversion process.

Conclusions

The accuracy of experimental data acquired based on wall thickness control is not enough to validate the fitting with the simulated values. Nevertheless, the values are close enough to evaluate the optimisation of the electropolishing process in terms of inlet flow and cathode shape.
The methodology applied to convert RDE data to elliptical shaped radio frequency structures gives satisfactory results.

REFERENCES
[[1] S. Calatroni et al., “Status of EP simulations and facilities for the SPL”, LINAC10, Tsukuba, Japan (2010).
[2] L.M.A. Ferreira et al., “Niobium cavity electropolishing modelling and optimisation”, SRF2013, Paris, France (2013).

Results and Discussion

Wall thickness removal measurements of the first run are shown in figure 3 in the form of current density; the solid line refers to the iris position and allows identifying each of the five cells. The dotted line refers to the equator position and allows identifying the top and bottom half-cell for each of the represented five cells. The accuracy of the ultrasonic technique together with the difficulty of positioning the transducer on a non-flat surface, as the one of the SPL cavities, introduced a non-negligible dispersion into the acquired data; the negative values have no real meaning. Nevertheless the overall profile provides already exploitable information; the top half-cells were preferentially etched if compared with the bottom half-cells, i.e. higher current densities.

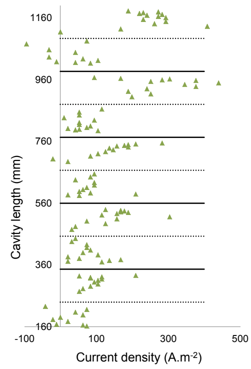

Figure 3: Current density distribution across an SPL 5 cell cavity from wall thickness measurements.

The average current density from the wall thickness data is 119 A/m², where the overall current density determined by weight difference of the full cavity is 115 A/m2; which is considered the real value. Given that the collected data didn’t took into account cut-offs and iris, areas with expected higher current densities, it’s then reasonable to deduce that the collected data values are in average somehow inflated; that is, the dispersion in the measurement is unbalanced to higher values.

The electrolyte velocity distribution given by the simulation allowed to evaluate better the velocity asymmetries inside the cavity; in addition to the obvious velocity profile difference between the iris (small section) and the equator (large section), there is also an asymmetry of the electrolyte velocity above and below the equator (see fig.4); this overall behaviour is in agreement with the current density distribution as it can be seen in figure 3.

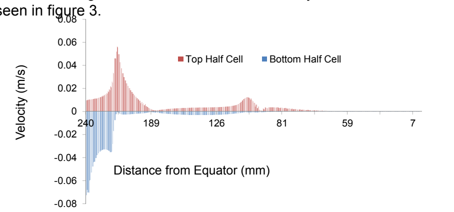

Figure 4: Electrolyte absolute velocity distribution at 5 mm from the cavity wall on a single cell. Negative velocity values are only for presentation purposes.

In figure 5 and 6 are shown the current density distribution across the cavity both from the wall thickness measurements values as the ones from the fluid simulation data. The solid and the dotted lines refer to the same codification as in figure 3. Although the general trend is similar, the current densities on the top half-cell are bigger than the bottom ones; a fitting is not always conceivable.

The overall average current density from simulation data is 208 A/m², which is roughly double the one determined by weight difference. However, this value is statistically inflated as the number of data from the cut-offs is proportionally higher than the ones from the cells; if the data from the cut-offs is not taken into account, the average current density becomes 118 A/m². The actual average values from simulation are somewhere in between; higher than the one from weight difference, but rather close.

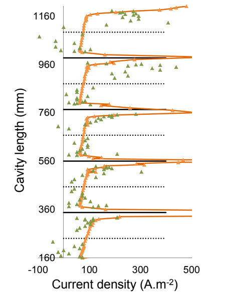

Figure 5: Current density distribution across the SPL five cell cavity for the first run. In green the experimental values and in orange the ones derived from the simulation data.

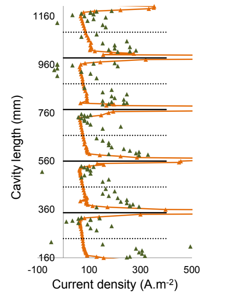

Figure 6: Current density distribution across the SPL five cell cavity for the second run. In green the experimental values and in orange the ones derived from the simulation data.