EXPLORATION AND COMPARISON OF HYDRODYNAMIC AND THERMAL PROPERTIES OF HORIZONTAL AND VERTICAL ELECTROPOLISHING CONFIGURATIONS WITH VARIOUS BOUNDARY CONDITIONS*

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Abstract

Extending initial efforts reported at the 2007 SRF Workshop, a system for modeling the thermal and hydrodynamic flow conditions internal to an electropolishing niobium cavity has been developed using the commercial code CFDesign™. Building upon parametric studies with small niobium samples that highlighted the process sensitivity to both local temperature and fluid flow conditions, we seek to gain predictive insight into processing methods which assure uniform controlled polishing – in both the traditional rotating horizontal configuration as well as the potentially more convenient vertical orientation. For present modeling runs, the experimentally measured temperature-dependent viscosity of the standard HF/H_2SO_4 electrolyte has been included. For the horizontal configuration, we have modeled the recent JLab-adopted reduced temperature and flow conditions used for ILC cavity processing and find corroboration of improved thermal control and uniformity. For vertical EP, the amplitude and pattern of nominally steady-state internal convective flow under conditions of external wall cooling and no electrolyte circulation has been observed for vertical EP for both single-cell and 9-cell cavities. Opportunities for modeling an integrated next-generation system are being explored.

INTRODUCTION

Electropolishing of niobium SRF cavities has been found to yield superior performance over other preparation techniques. The majority of this experience base is empirical. The press of potential applications which could utilize the maximum capability of niobium motivates increasingly detailed analysis of processing conditions and their effects. The expectation is that improved insight will indicate a path toward secured control of peak performance.

Chemical removal of surface material from as-fabricated niobium cavities is necessary to assure that the rf surface is both adequately contamination free and geometrically smooth. Electropolishing, at least in principle, provides for diffusion-limited electrolytic removal of the surface. The details of diffusion of the

chemically active species determine the scale factors involved in the desirable leveling and brightening of the surface. Such diffusion characteristics are functions of electrolyte composition and local temperature, and are also effectively influenced by local bulk convective flow.

While research proceeds on characterizing the diffusion related properties via controlled small-sample tests, we also seek to improve our understanding of actually applied process conditions internal to multi-cell cavities and guide future technological development via hydrodynamic modeling. As reported previously [1], a full-scale hydrodynamic model has been developed to describe a horizontal electropolishing system for multi-cell cavities. The modeling software CFDesign™ was used to find steady-state solutions to defined boundary conditions. The model represents the geometrical configuration of the JLab EP system, with central hollow aluminum cathode supplying fresh electrolyte into each cell. Electrolyte exits the cavity symmetrically via supporting plastic headstock attached to each beamtube. See Figure 1. The model attempts to replicate key elements of the fluid and heat flow dynamics that are present during the electropolishing of the 9-cell niobium cavities.
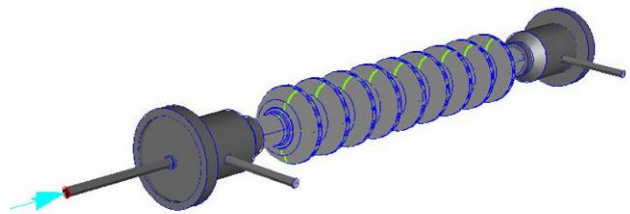

Figure 1: Geometry of model used in the present study.

In addition, after benchmarking the code with the existing horizontal EP configuration, we have begun using it to model hypothetical vertical EP configurations.

MODEL PARAMETERS

Material Properties

Reference material properties of sulfuric acid were used for the electrolyte in the absence of accurate descriptions for the 1:10 $HF:H_2SO_4$ solution. The recently measured temperature dependent viscosity[2] of this electrolyte has been incorporated into the model. This allows the viscous drag effects associated with the 1 rpm rotation of the horizontal configurations to be better modeled.

Thermal conduction properties of Nb and Al are included. A variety of thermal boundary conditions have been applied. Having recognized the importance of controlling the temperature of the cavity/electrolyte interface, the flowing electrolyte supply temperature was lowered to 15°C, reflecting present JLab practice. A film coefficient for the external surface of the niobium of either 6 W/m^2/K at 23°C or 437 W/m^2/K at 20°C was used, approximating either mild forced-air cooling with ambient air or external water bath cooling, respectively.

Heat Source in the Model

Analysis of the Al-cathode, Nb-anode, HF:H$_2$SO$_4$ 1:10 system has enabled separation of the potentials at the cathode, electrolyte, and anode [3]. The potential drop across the electrolyte is a small fraction of the cell voltage and is thus neglected in this study. The potential drop at the cathode appears to be purely associated with the hydrolysis production of hydrogen gas, thus contributing negligible thermal load. As described in [1], we take the local heat flux at the niobium/electrolyte interface to be 0.2 W/cm^2 when the working temperature is < 30°C. Such an approach is in aggregate consistent with the net temperature rise between supply and return electrolyte observed in the JLab 9-cell EP system.

Model Limitations

This model does not address the particular circumstances presented at the emerging-surface interface, where process conditions may be expected to be unusual due to activity in the drag-out of the viscous electrolyte. Nor does it include fluid flow effects due to buoyancy of hydrogen bubbles that are generated at the cathode surface. In addition, the local current density and thus the local heat generation is a function of the local temperature, a property which tends to reinforce temperature variations and thus non-uniformity in surface processing conditions. The present software is unable to provide locally variable heat flux, so is expected to under-predict temperature variations.

OBSERVATIONS FROM STEADY-STATE SOLUTIONS

Flow Patterns

The flow velocity scale of interest for the electrolyte in the horizontal 9-cell cavity processing is set by the continuous rotation at 1 rpm. For the ILC cavity geometry, this corresponds to motion of the equators at 1 cm/sec. The present model provides for a continuous, fixed 15°C input flow rate of 5 l/min through the center of the aluminum cathode, distributing into each cell. The electrolyte flows outward through the cell irises and exits through both ends of the cavity. The local flow conditions thus vary considerably. The model geometry is left/right symmetric with the exception of the input flow inside the cathode. Left/right thermal asymmetries are due to legitimate heat conduction and temperature-dependent viscosity effects. Use of the flowing electrolyte as the principle process coolant inherently leads to non-uniform processing conditions. The steady-state temperature solution for these conditions is depicted in Figure 2. The corresponding flow velocities are shown in Figure 3. For comparison, Figure 4 depicts the thermal situation with processing parameters used previously: 23°C supply with 10 l/min flow rate. In both cases the temperature in the iris regions is significantly higher than the equators, although the extremes are reduced in the conditions of Figure 2, and overall temperature control is improved.

For comparison, Figure 5 displays process data from the recent electropolishing of an ILC 9-cell cavity at JLab. This was the first run to acquire temperature data from an iris region during horizontal rotating EP. In this case the fifth iris from the supply side was found to be 8°C warmer than the equators, and 13°C warmer than the return circulated electrolyte. Such observations are consistent with the model predictions.
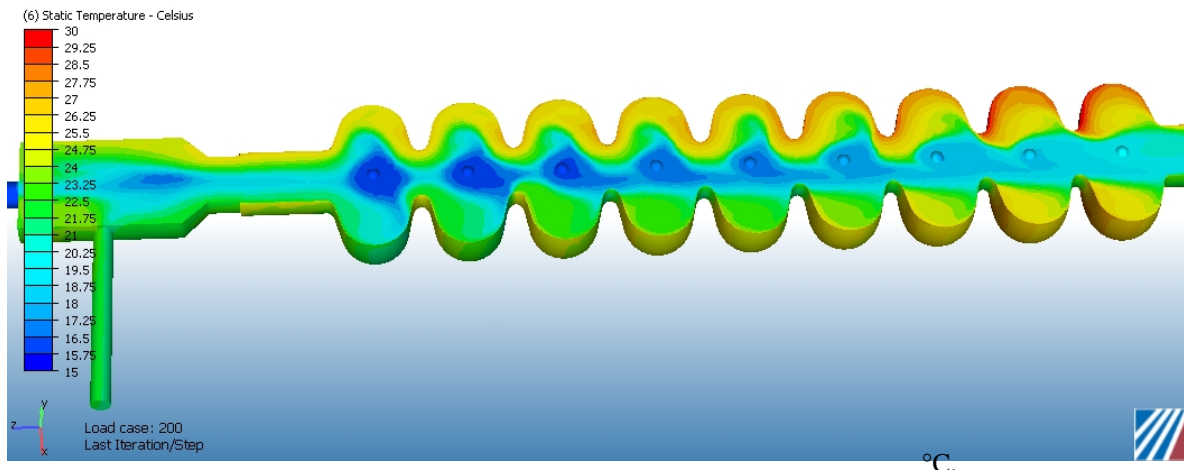

Figure 2: Steady-state temperature with 5 l/m supply flow at 15 °C.
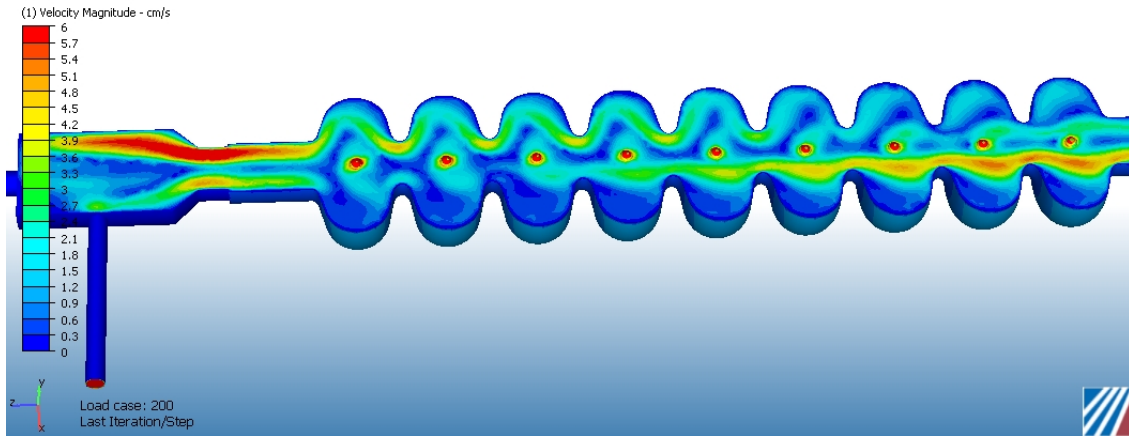
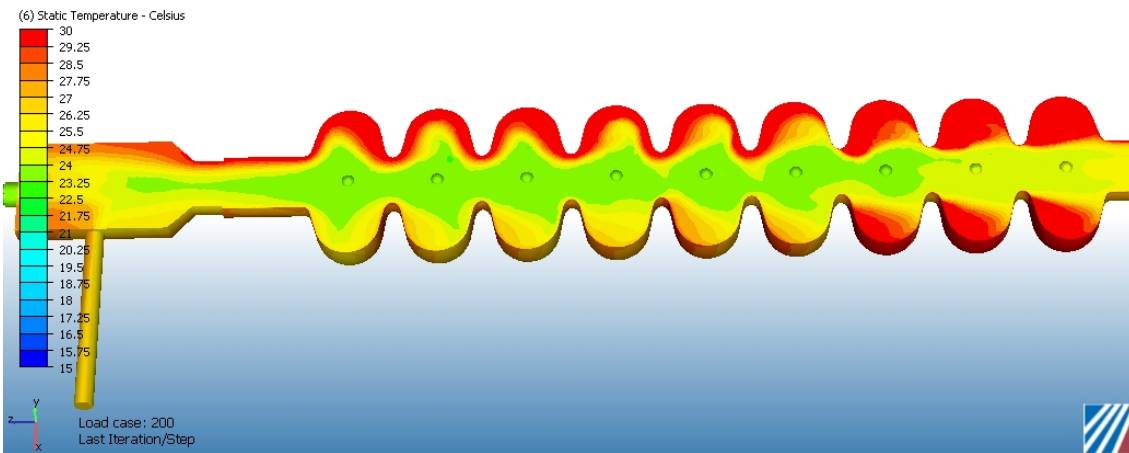Figure 3: Steady-state flow velocity with 5 l/m supply flow at 15°C.

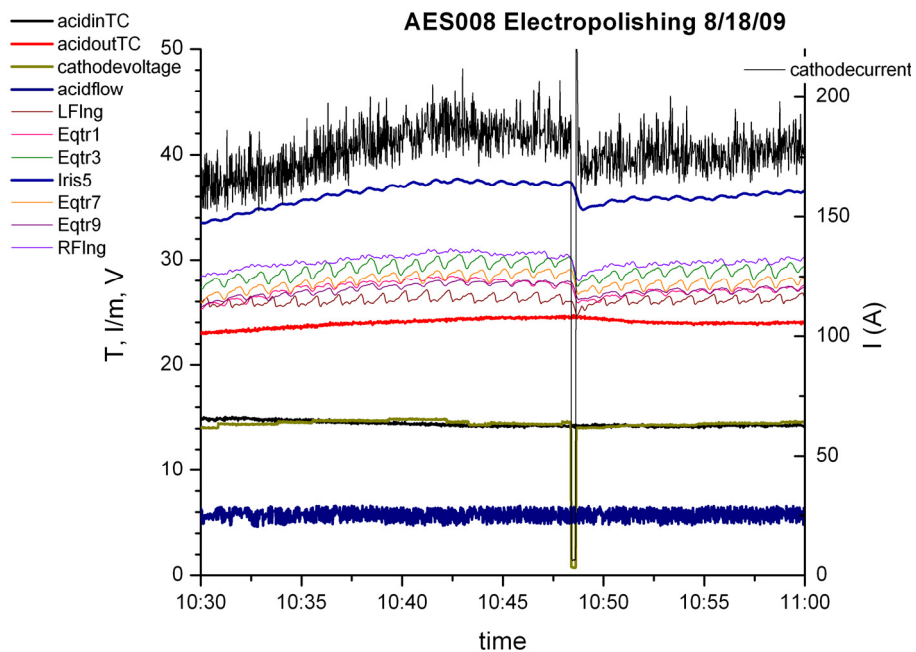Figure 4: Steady-state temperature with 10 l/m supply flow at 23°C.

Figure 5: Logged process conditions during EP of cavity AES8 at JLab.

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VERTICAL EP

For process simplification, it is very desirable to consider electropolishing niobium cavities in a vertical orientation. Development of such a process is underway at Cornell University[4,5] and Jefferson Lab. Complications related to managing the evolved hydrogen bubbles remain, but we have begun to apply the flow modeling to this situation.

Using the same material parameters as used for the horizontal models, we reoriented gravity, filled the cavity with electrolyte, centered the cathode on the cavity axis, and eliminated the supply of electrolyte via a hollow cathode. To provide stabilization of the process temperature, the boundary condition on the outside surface of the cavity was set to simulate the presence of a 20°C water cooling bath by using a film coefficient of 467 W/(m^2-K). Figure 6 shows the thermal solutions with no flow or stirring of the electrolyte and with a simple 2 l/min bottom-to-top flow of electrolyte supplied at 15°C.

Within the factors included in the present model there appear to be no thermal motivations for providing internal stirring if external cooling is in place. Very slight convective circulation is set up in each cell due to electrolyte density variation with temperature. The importance of this as it influences the processing effects on up/down-facing surfaces is under separate investigation. It is possible that other factors such as self-convection of chemical reaction products not included in this model have important effects.
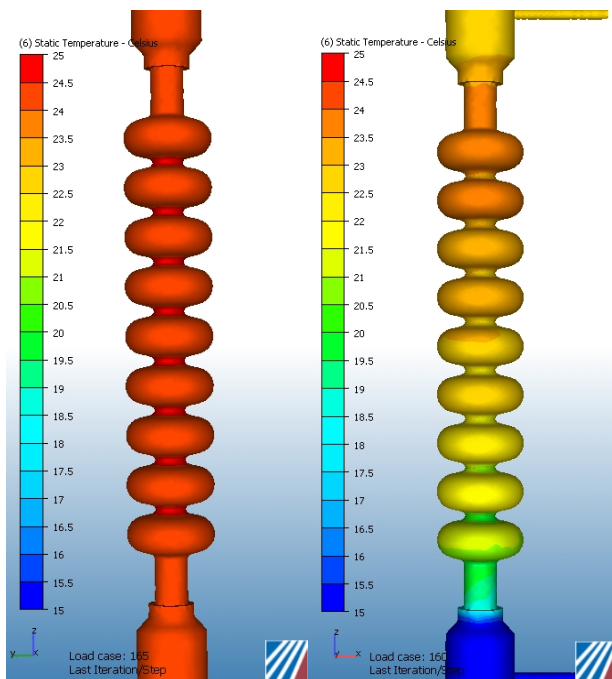

Figure 6: Steady-state cavity/electrolyte interface temperature of vertical electropolishing 9-cell cavity with 20°C external water bath boundary conditions, a) static electrolyte, and b) 2 l/m vertical flow supplied at 15°C.

SUMMARY

Hydrodynamic models have been developed to simulate the thermal and electrolyte flow conditions in the ILC 9-cell cavity electropolish processing system at Jefferson Lab and also in a potential vertical electropolishing configuration. Using approximate material parameters for the electrolyte and averaged heat flux conditions relevant the cavity EP process, solutions are obtained which correspond reasonably well with measured data. The lowered supply temperature and reduced flowrate, compared with former process conditions, yield improved temperature control and process uniformity across the cavity. Significant variations in local temperature and flow conditions yet remain. The model also indicates that providing external water cooling to the cavity during EP processing dramatically stabilizes the thermal conditions and eliminates the need for the circulating electrolyte solution to serve as heat sink, which in turn reduces the internal flow rate variations. We are encouraged to pursue water bath cooling during vertical electropolishing of niobium cavities in our future integrated cavity processing (ICP) systems.

REFERENCES

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[4] See D. Meidlinger, E. P. Chojnacki, J. J. Kaufman, H. Padamsee, A. J. Windsor, "Vertical Test Results for Vertically Electropolished 1.3GHz 5-Cell Superconducting Cavities," contribution TU5PFP049 to PAC2009.

[5] A. C. Crawford and H. Padamsee, "A Procedure for Electropolishing Vertically Oriented Muticell Niobium Radiofrequency Cavities," contribution TU5PFP050 to PAC2009.

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