HYDRODYNAMIC THERMAL MODELING OF 9-CELL ILC CAVITY ELECTROPOLISHING AND IMPLICATIONS FOR IMPROVING THE EP PROCESS *

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Abstract

Multi-cell niobium cavities often obtain the highest performance levels after having been subjected to an electropolishing (EP) process. The horizontal EP process first developed at KEK/Nomura Plating for TRISTAN[1] cavities is being applied to TESLA-style cavities and other structures for the XFEL and ILC R&D. Jefferson Lab is presently carrying this activity in the US. Because the local electropolishing current density is highly temperature dependent, we have created using CFDesign™ a full-scale hydrodynamic model which simulates the various thermal conditions present during 9-cell cavity electropolishing. The results of these simulations are compared with exterior surface temperature data gathered during ILC cavity EP at JLab. Having benchmarked the simulation, we explore the affect of altered boundary conditions in order to evaluate potentially beneficial modifications to the current standard process.

INTRODUCTION

During the electropolishing of 9-cell ILC cavities at Jefferson Lab, several thermocouples were mounted on the exterior of the cavity to monitor the wall temperature during the electropolishing process. Sustained readout from the rotating cavity was accomplished by using a battery operated wireless transmitter. We found the cavity wall temperature to be significantly warmer than the exiting electrolyte and to have periodic time structure corresponding to the revolution frequency.

In an effort to improve our understanding of the internal flow and processing conditions, a full-scale hydrodynamic model was developed to describe the system. The modeling software CFDesign™ was used. The model represents the geometrical configuration of the JLab EP system, with central hollow aluminum cathode supplying fresh electrolyte into each cell through downward pointing holes. Electrolyte exits the cavity symmetrically via supporting Teflon 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.

The work is motivated by recognition that while reproducible and uniform polishing conditions are desired, the local processing conditions are highly temperature and flow dependent. We seek to gain insight into the realized conditions and to subsequently improve process control.

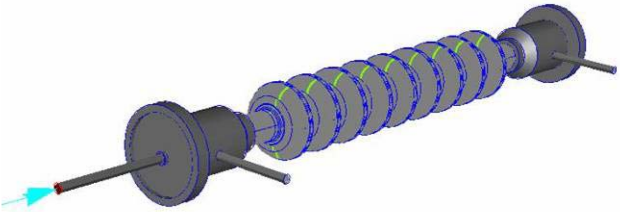

Figure 1. Geometry of model used in the present study.

MODEL PARAMETERS

Material properties

The material properties (thermal conductivity, temperature dependent viscosity and density, specific heat) of sulfuric acid were used for the electrolyte in the absence of more accurate descriptions for the 1:9, HF:H_2SO_4 solution:

- Density: 1.84 g/cc
- Thermal conductivity: 6×10^{-3} W/cm/K
- Specific heat capacity: 1.4 J/g/K
- Mass flow = volume flow * density = 0.17 l/sec * 1840 gm/l = 307 g/s
- Deposited power per degree temperature rise through system = mass flow * specific heat capacity = 307 g/s * 1.4 J/(g-K) = 429 W/K

The 1 rpm revolution of the cavity is included. The thermal boundary conditions applied were a constant 26 C electrolyte supply temperature and a film coefficient external to the niobium approximating mild forced-air cooling with ambient air. The model neglects gravitational effects and any dynamics through the vapor space above the fluid level. Thermal conduction properties of Nb and Al are included in the model.

Heat source in the model

Analysis of the Al-cathode, Nb-anode, HF:H_2SO_4 1:9 system in an instrumented electrochemical cell has enabled separation of the potentials at the cathode, electrolyte, and anode [2]. The potential drop across the electrolyte is a small fraction of the cell voltage and is

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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. In the absence of a clear analysis of the activation energies of the chemical processes occurring at the anode, we take the approximation that the bulk of the potential there when operating in the current plateau region is resistive and contributing local energy flux according to iV_{pa}, where i is the local current density and V_{pa} is the anode polarization potential. 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.

Recognizing that i is itself dependent on the local temperature, the challenge of converging to a self-consistent solution presents itself. Based on recent experimental data for static flow conditions[2], we take the current density for representative conditions and calculate the corresponding heat flux for inclusion as boundary conditions in the hydrodynamic model. See Figure 2. An improved future model will allow local variability as local conditions evolve toward steady state. The dependence of i and thus heat flux on local flow conditions is presently neglected. The present approximation is expected to yield a solution which under-anticipates process variations within the cavity, since local current density has been observed to increase by ~30% in response to representative stirring conditions.

In addition, 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.

OBSERVATIONS FROM STEADY-STATE SOLUTION

Flow patterns

The scale of interest for considering the electrolyte flow patterns in the 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 temperature input flow rate of 10 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.

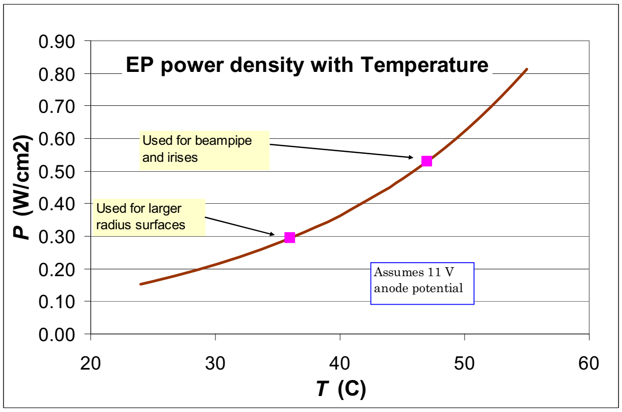

Figure 2. Derived heat flux as a function of local temperature.

Figure 3 graphically depicts the steady-state velocity magnitude of the fluid in the cavity model. Three elements are combined in this graphic: 1) vectors showing the location and orientation of flow at 1 cm/sec,

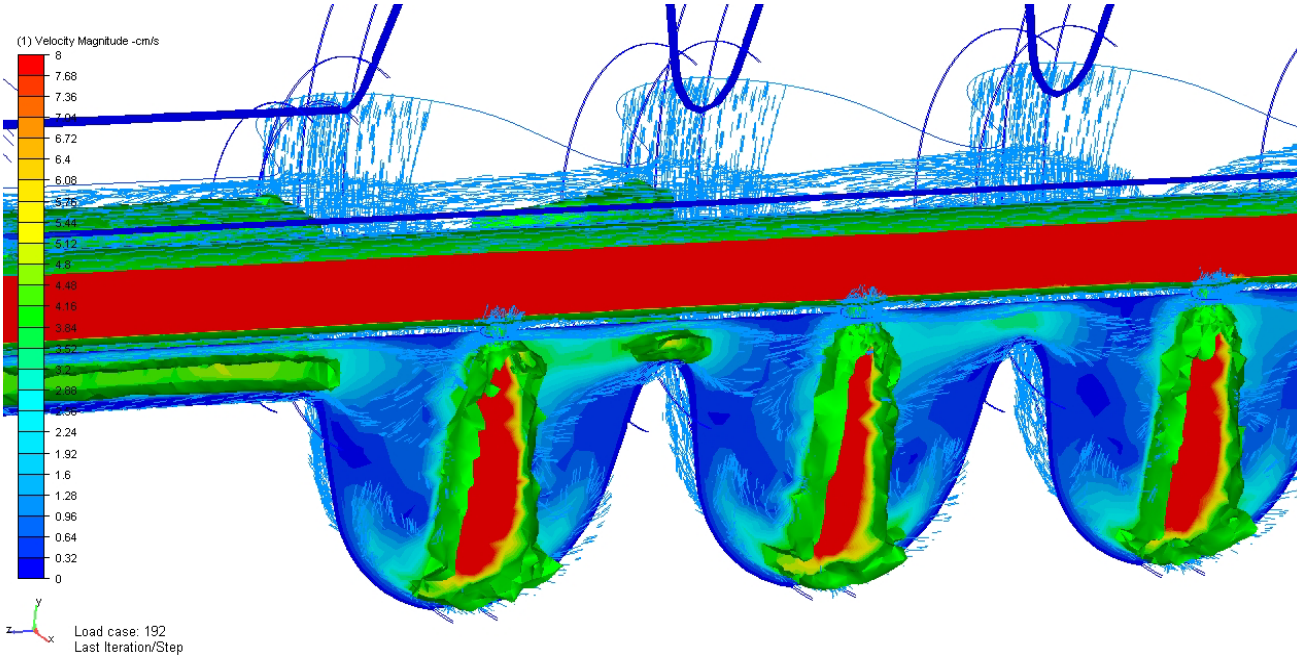

Figure 3. Steady-state electrolyte velocity magnitude in three end cells and beamtube, with 10 lpm total supply flow.

2) iso-surfaces locating contours with velocity magnitude of 4 cm/sec, and 3) a vertical half-plane slice indicating local flow magnitude. They share a common color scale. While likely not unexpected, several features may be easily observed. The higher velocity flow conditions on the cavity are present directly under the inlet flow and in the outboard irises and beampipes. In addition, one may note the location of nodes in the flow patterns. Such locations may be expected to be less well cooled.

Thermal pattern

Use of the flowing electrolyte as the principle process coolant inherently leads to non-uniform processing conditions. Figure 4, below, shows two views of the temperature of the surface of the electrolyte, a view from above which includes the temperature of the niobium in the plane of the fluid surface and the interface with the niobium viewed from below.

The relatively high viscosity of sulfuric acid and the rotation of the cavity creates horizontal asymmetry as viewed down the cavity centerline. Heat generated at the active surface tends to accumulate as the surface moves through the electrolyte. In the JLab configuration, with its downward flow of the incoming fresh electrolyte in each cell, this accumulation is partially disrupted, keeping the cavity cooler than would be expected otherwise. Figure 5 is the niobium wall temperature in the equatorial plane of the center cell as found by the model. This solution is reasonably consistent with the measured equator temperatures during the 9-cell EP processing at JLab.

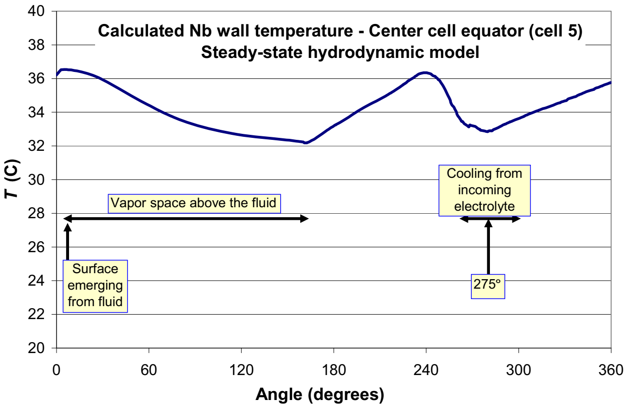

Figure 5. Model temperature variation of the niobium wall at the equator of the center cell.

Figure 6 presents the processes conditions during electropolishing of the cavity AES1. The temperatures

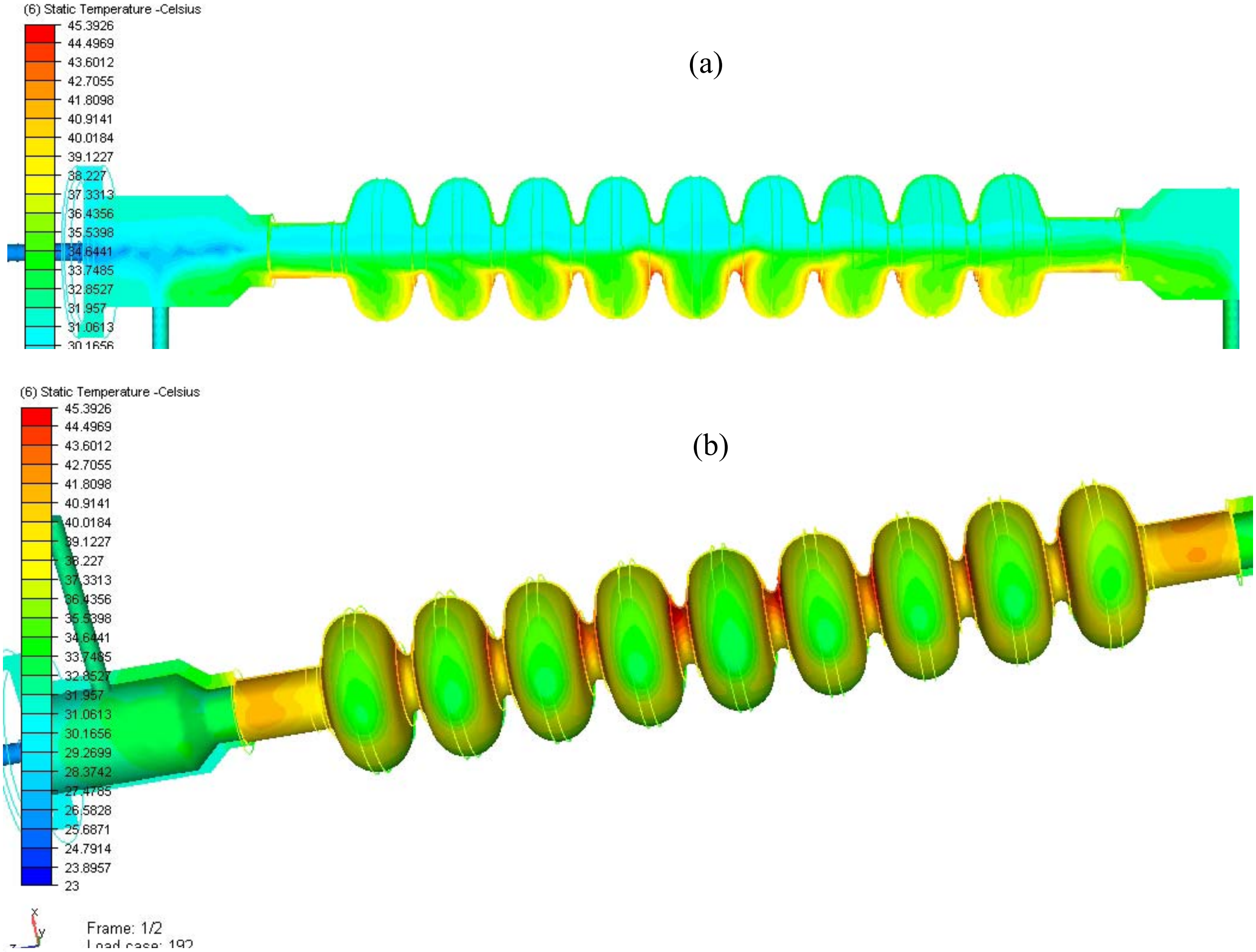

Figure 4. Steady-state solution temperatures at (a) top electrolyte surface and (b) interface with cavity wall.

sensed by three thermocouples on cells 1, 5, and 9 are included. The periodicity is the 1 rpm rotation frequency of the cavity. Figure 7 is similar data from the processing of cavity AES3, with the C1 and C9 thermocouples moved to the nearby beampipes. Note that these sensed temperatures are quite excessive and not fully reproduced in the model. We interpret this difference as due to the fact that the flow rate dependence of the local current density is not included.

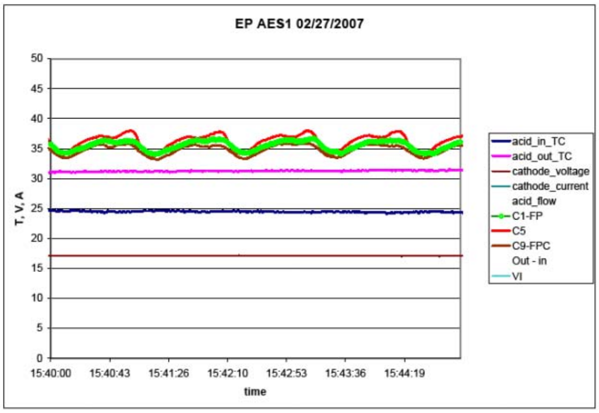

Figure 6. Logged process conditions during EP of cavity AES1 at JLab.

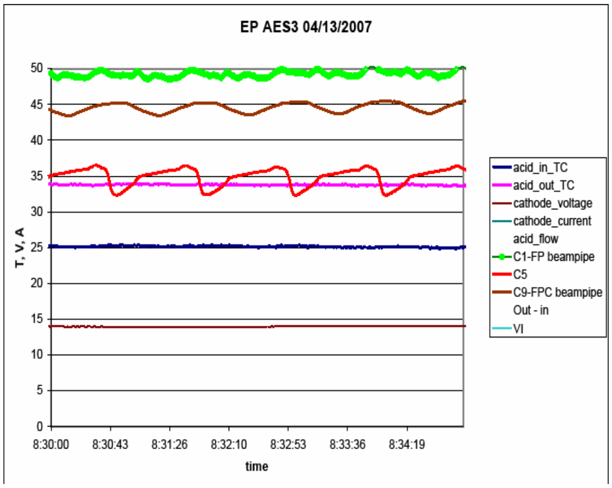

Figure 7. Logged process conditions during EP of cavity AES3 at JLab.

To date, no monitoring of the iris temperatures during cavity processing has been accomplished. The model predicts at least a 10°C higher temperature in the iris regions, even higher than what is found on the beampipes. This is illustrated in Figure 8 which displays the temperature of the surface of the electrolyte in cells 4 and 5. The model predicts local temperatures as high as 45°C at the irises.

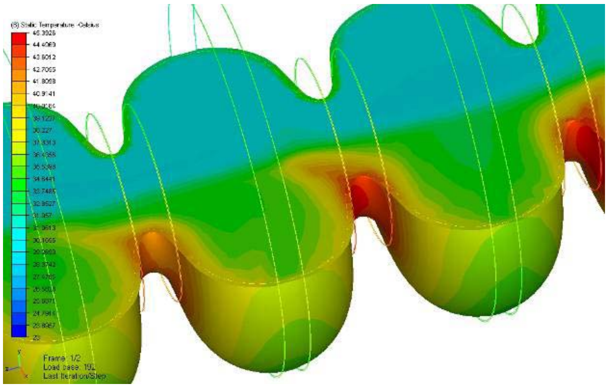

Figure 8. Steady-state temperature in the plane of the electrolyte top surface and at the fluid/cavity interface.

POTENTIAL ALTERNATE COOLING CONDITIONS

As previously noted, the use of the flowing electrolyte as the principle process coolant inherently leads to non-uniform processing conditions. Local heat generation increases with local temperature and local flow rate. This current hydrodynamic model illustrates significant non-uniformity of conditions, even though both of these complicating effects are not included. Past bench measurements which have sought to identify optimum processing conditions for attaining the smoothest surface have all identified 25-35°C as the appropriate control range.

Both the externally monitored temperatures during 9-cell cavity electropolishing and the present hydrodynamic model indicate that the actual applied process conditions is significantly outside the intended operating range and is quite non-uniform. The basis for understanding the attained niobium surface conditions would seem to be significantly compromised.

As a first consideration of an alternative cooling condition, we reran the hydrodynamic model with the change of only one parameter, the film coefficient applied to the exterior of the niobium surface. We simulate the presence of a 30 C water cooling bath by using a film coefficient of 467 W/(m^2-K). The resulting steady-state conditions are depicted in Figure 9, using the same temperature color scale as Figure 8.

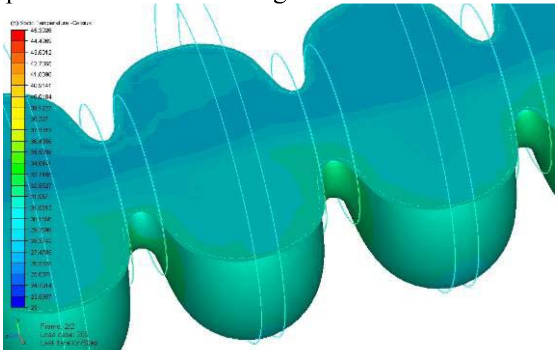

Figure 9. Steady-state temperature in the plane of the electrolyte top surface and at the fluid/cavity interface, with 30°C external water bath boundary conditions.

SUMMARY

An initial hydrodynamic model has been developed to simulate the thermal and electrolyte flow conditions in the ILC 9-cell cavity electropolish processing system at Jefferson Lab. Using what are believed to be reasonable approximate material parameters for the electrolyte and averaged heat flux conditions relevant the cavity EP process, solutions are obtained which correspond well with available process monitoring data. Very significant variations in local temperature and flow conditions have been identified. The obtained steady-state conditions are not with parameters identified as optimum for the desired surface processing of niobium cavities. The model also indicates that providing external water cooling to the cavity during EP processing would dramatically stabilize the thermal conditions and eliminate the need for the circulating electrolyte solution to serve as heat sink, which would enable reduction of the internal flow rate variations.

REFERENCES

[1] K. Saito et al., “R&D of Superconducting Cavities at KEK,” p. 635-694, Proc. 4th SRF Workshop, 1989.

[2] H. Tian et al., “Novel Characterization of the Electropolishing of Niobium with Sulfuric and Hydrofluoric acid mixtures,” contribution WE104 to this Workshop.