Analyzing the Stability of Aluminium Electrolysis Cells Using a Mechanical Model

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Abstract

The magnetohydrodynamic (MHD) stability of an aluminium (Al) electrolysis cell is important for overall stable operation at a lower anode-to-cathode distance (ACD). In particular, it is beneficial to understand the influence of changing cell parameters such as the ACD and cell amperage on the stability of the cell, which can be quantified by the growth or decay rate of the interfacial waves on the Al-electrolyte interface. This can be done by running a suite of numerical MHD simulations with different cell parameters and then using the resulting interface evolution to find the growth/decay rates. However, with many combinations of cell parameters to test, such an endeavor will often be expensive and time consuming. In this work, we utilize the mechanical model of MHD instabilities in Al cells presented in [1] to analyze the stability of a TRIMET 180 kA Al cell for different combinations of ACD and cell amperage. We first show that the model's stability and growth/decay rates can be found quickly by solving an algebraic equation for the complex frequencies of oscillation. Then, we calibrate the model to the parameters of the TRIMET 180 kA cell and study its stability at different ACD and cell amperage combinations. We show a 2D stability map of the growth/decay rates and a 3D stability surface. For a few ACD and anodic current density (cell amperage) combinations, we simulate the TRIMET 180 kA Al cell using MHD-Valdis to find the Al-electrolyte interface growth/decay rate. We show that the growth/decay rates from the mobile model match those from MHD-Valdis simulations. Our results show the value of using the mechanical model as a complement tool to MHD simulations, where it can be used to rapidly narrow down the combinations of cell parameters to be simulated numerically.

Keywords: Magnetohydrodynamic instability, Aluminium cell modelling, Metal pad instability

1. Introduction

The overall stability of aluminium (Al) electrolysis cells relies on the stability of three coupled dynamical phenomena: magnetohydrodynamic (MHD), chemical, and thermal [2]. This stability must be maintained as cell parameters are changed for better energy and current efficiency. In particular, the cell's energy efficiency can be improved by reducing the electrolyte's thickness, quantified by the anode to cathode distance (ACD) [1]. However, reducing the ACD negatively impacts the MHD stability of the cell, and it could go unstable [3-4], where disturbances on the Al-cryolite interface are amplified reducing the cell's current efficiency and possibly shorting it [2-4]. This MHD instability, known as the metal pad instability (MPI) [4], is a result of horizontal electromagnetic forces in the molten Al coupling orthogonal interfacial wave modes (orthogonal standing waves) having close frequencies [1, 5].

The MPI is influenced by many cell and design parameters such as the ACD, cell amperage, molten Al metal level, vertical magnetic field, and cell aspect ratio [3-4]. Thus, to maintain cell stability, it is important to know how the MHD stability is affected by changing these parameters. To do so, we can numerically simulate the cell using specialized software such as MHD-Valdis [5-7] to check whether a cell is stable/unstable for a given set of cell parameters. We can quantify how stable/unstable the cell is by looking at the evolution rate of the waves on the Al-cryolite interface [4], which if positive indicates growth (instability) and if negative indicates decay (stability). This would allow us to compare the relative stability between any two groups of cell parameters. However, as the number of cell parameter combinations increases, the time and computational costs of simulations become large. This makes it difficult to scan a large parameter space with tens of cell parameter combinations.

A mobile model was presented in [1] as a mechanical analogue of the MPI, and it exhibited stability and instability at realistic cell parameters of a TRIMET 180 kA Al cell. Beyond a binary stable/unstable result for a given set of cell parameters, we wanted to see if the mobile model can accurately capture how stable/unstable the cell is. More specifically, if the growth/decay rate of the mobile model would be similar to that of the Al cell's interface. In this work, we use the mobile model to explore the growth/decay rate of a TRIMET 180 kA cell at different combinations of ACD and anodic current densities (cell amperage). We first show that the stability of the mobile model can be studied directly, in a way that the growth/decay rates can be extracted directly without solving for the mobile's motion. Then, we calibrate the mobile model to a critically stable TRIMET 180 kA cell having the cell parameters in Table 1. We use the calibrated mobile to find the growth/decay rates at over 100 combinations of ACD and anodic current densities, creating a 2D stability map. Finally, we simulate the TRIMET 180 kA cell for a few combinations (see Table 2) in MHD-Valdis [5-7] and compare the interface growth/decay rates to those from the mobile model.

Table 1. TRIMET 180 kA cell parameters, reproduced from [1].

J_0 (A/cm^2)	B_z (T)	h_0 (m)	L_x (m)	L_y(m)	H (m)
0.8	0.003	0.043	7.92	3.57	0.17

where:

J_0	Nominal current density in bath, A/m^2
B_z	Vertical constant and uniform magnetic flux density, T
h_0	Thickness of the cryolite or ACD, m
L_x	Length of the Al plate in the x direction, m
L_y	Length of the Al plate in the y direction, m
H	Thickness of the Al plate (analogous to metal pad height), m.

2. Mobile Model

2.1 Brief Description

The mechanical model of the MPI given in [1] is a mobile, shown in Figure 1. It consists of a broad and thin rectangular Al plate (representing the Al layer) that has a variable center of mass (COM) and it is subjected to a damping torque. The Al plate is connected to a fixed ceiling (representing the anodes) by a massless, rigid strut, and can swing about the x and y axes (horizontal axes) with the pivot as shown in Figure 1. The gap between the Al plate and the fixed ceiling is filled with massless and frictionless cryolite (representing the electrolyte layer) creating a path for a steady and uniform current density of magnitude J_0 to pass vertically downwards from the fixed ceiling to the Al plate. The entire mobile is subjected to an external constant and uniform vertical magnetic flux density of magnitude B_z.

4. Conclusions and Future Work

We used the mobile model of the MPI in [1] to investigate the stability of the TRIMET 180 kA Al cells at over a hundred different combinations of ACD and anodic current density combinations (cell amperage). We first used stability analysis to derive an algebraic equation that can be solved to find mobile's growth/decay rate directly, without having to solve for the mobile's motion explicitly. Then, we calibrated the mobile to the parameters of a critically stable TRIMET 180 kA and used it to find the growth/decay rates at different ACD and J_0 values.

The ACD-J_0 stability map showed that increasing the ACD improves stability while increasing J_0 worsens it, as expected. Finally, for six different ACD and J_0 combinations, we compared the mobile model rates to those from simulating a TRIMET 180 kA Al cell with the same parameters in MHD-Valdis. Our results showed that the mobile rates are in good agreement with those from the MHD-VALDIS simulation. This is promising as it has the benefit of rapidly narrowing down the combinations of cell parameters to be simulated numerically, reducing the computational expense.

Our results only compare the growth/decay rates when two parameters are changed: ACD and J_0. It is important to compare rates when other parameters are changed, such as the metal height or magnetic flux density magnitude. Also, the mobile model matched the growth/decay rates of the TRIMET 180 kA cell remarkably well. It would be interesting to see if the mobile model can achieve such good results with other cells, which has a different aspect ratio than the TRIMET 180 kA cell, and likely has a different mode coupling for the MPI.

Moving forward, we plan on using the mobile model to explore the phase space of the dynamic stabilization of the cell [4, 10]. In particular, we are interested in looking at the stabilization effect of adding an oscillating vertical magnetic flux density at different oscillation frequencies and amplitudes.

5. References

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