Comparison of CVD, Horizontal Currents and MHD Stability of Different Cathode Designs

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Abstract

MHD stability is known to limit aluminium reduction cell power efficiency. Normally, cell stability is achieved by designing the cell with an optimized magnetic field and electric current distribution in the liquid metal. Modelling of electric current distribution requires a detailed 3D representation of the cell cathode assembly coupled to the liquid metal zone. The modelling software known as MHD-VALDIS is an established tool for MHD stability investigation and cell design. The recent update is described which permits to account for current distribution in liquid metal and coupled cathode features including variable contact resistance along collector bar and carbon, temperature dependent collector bar conductivity variation, carbon block length limitation, ledge profile along cell wall, etc. Cathode voltage drop (CVD) and horizontal current density obtained by MHD-VALDIS software are compared with those obtained using a 3D ANSYS electric software. The impact of reducing both JX and JY on the MHD stability is then analyzed using MHD-VALDIS software.

Keywords: Aluminium reduction cells, MHD stability, Electric current distribution, Cell modelling.

1. Introduction

The present work is a follow up of the work presented at ICSOBA 2023 [1], so it is addressing some of the limitations of the previous work. In this work as in the previous work, CVD and the metal pad horizontal current density in the longitudinal direction (JX) and the transversal direction (JY) are calculated using both a 3D ANSYS finite element based electric model and MHD-VALDIS cell stability software. As its name indicates the main purpose of the MHD-VALDIS software is to analyze the bath-metal interface stability once a perturbation is offsetting it from its steady-state position.

In order to be able to do that, MHD-VALDIS software must first compute that steady-state interface position and in order to do so it must solve for the two liquid phases flow solution under the influence of both the gravity and the Lorentz forces. In order to calculate the Lorentz force field (**F**), the MHD-VALDIS software must calculate first its two components: the current density vector field (**J**) and the magnetic flux density vector field (**B**), both are equally important as the Lorentz force vector field is the vector product of the current density vector field by the magnetic flux density field:

$$\mathbf{F} = \mathbf{J} \times \mathbf{B} \quad (1)$$

Over the years, a lot of work has been done in MHD-VALDIS to improve **B** calculation accuracy that is computed using the very efficient and convenient integral formulation that eliminates the need to mesh the air around the cell to solve for **B** in the bath and metal in the cell considering all the source currents of the full smelter and the shielding effect of the ferro-magnetic steel of the potshell and superstructure of that cell [2].

Until recently, less work had been performed in MHD-VALDIS to improve **J** calculation accuracy. The steady state **J** must be calculated initially in order to provide the source terms required to calculate the steady state **B** and then the steady state **F**, but it must also be recalculated at each time step during the transient cell stability analysis in order to recalculate **F**, as it is the change of **F** due to the change of **J** that drives the interface displacement, in turn responsible for the change of **J**.

So, it is important to be able to quickly recalculate **J** at each time step, to do so MHD-VALDIS solves a network of discretized conductors using the Kirchhoff's law. Givry was the first to solve for **J** vector field in the metal pad using this method [3]. Figure 1 presents how the end block was discretized and the impact of the end ledge toe on the network current boundary condition. The combination of the offset between the anode shadow and the edge of the end block and the end ledge toe position is having a great influence on the intensity of the longitudinal horizontal current density JX.

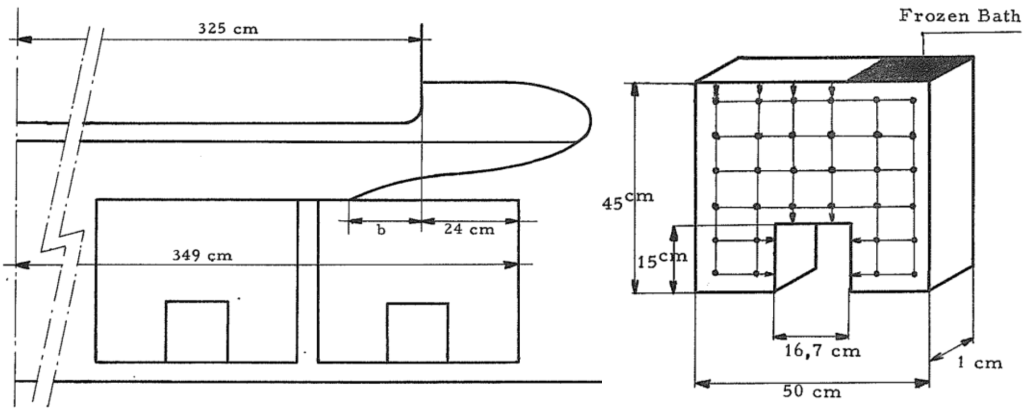

Figure 1. Representation of the end wall cathode assembly and the discretization of the end block by a network of 1D conductors, reproduced from Figure 18 and 20 in [3].

Another way to discretize the cell and to solve for the metal pad current density **J** is to use the finite element method, this has been done for the full cell in 3D using the finite element code ANSYS in [4]. Figure 2 presents the mesh of such a 3D finite element model for the case of the TRIMET cell geometry that will be used again in the present work, as it was used for the first time in [5]. As we can see in Figure 2, the geometry of the TRIMET cell is similar to the geometry presented in Figure 1, the end block exceeds significantly the anode shadow of the end anode.

As already explained in [1], contrary to **B** that can be measured, it is not practically possible to measure **J** in the metal pad. It is well known that horizontal current densities JX and JY are detrimental to cell stability, and great effort have been made to reduce JY principally by the introduction of copper inserts in collector bars, but JX that is as important has not been studied much. One of the reasons is that in order to calculate JX accurately in the metal pad, you need to build a full cell model, calculate the collector bar current pickup, and this requires to model and solve for the current in the busbar network between cells.

Since the TRIMET 3D ANSYS electric model is not representing the busbar network, the current pickup is a boundary condition in the model. The usual boundary condition is to impose a uniform current pickup which is a good boundary condition if the busbar network is well balanced, but it is not actually the case for the TRIMET cell case. So, for the purpose of the comparison of **J** in the metal pad between MHD-VALDIS and ANSYS, the current pickup calculated by MHD-VALDIS (that includes busbar in the calculation) will be use as a boundary condition in the ANSYS model in the current study, this was not done in our previous work [1].

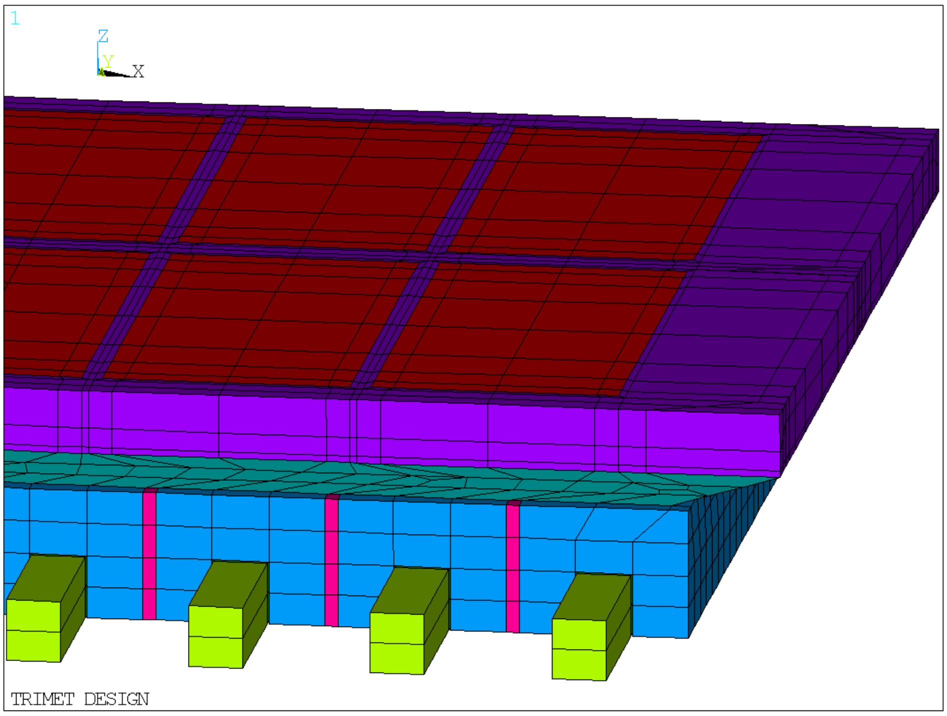

Figure 2. Mesh of the TRIMET cell 3D ANSYS electric model.

2. MHD-VALDIS Current Density Results for the TRIMET Cell Base Case Design

The TRIMET cell base case design is inspired from the real cell operated by TRIMET in Hamburg, Figure 3 is a recently published picture of the potroom. The ledge toe is assumed to be covering 6 cm of the block edge both on the side and on the end as displayed in Figure 2.

Figure 3. Hamburg TRIMET smelter potroom.

The busbar network was presented in Figure 3 of [1], it is a very simple busbar design that is not producing a very uniform collector bar current pickup. The collector bar current pickup resulting from this busbar network design is presented in Figure 4 as calculated by MHD-VALDIS.

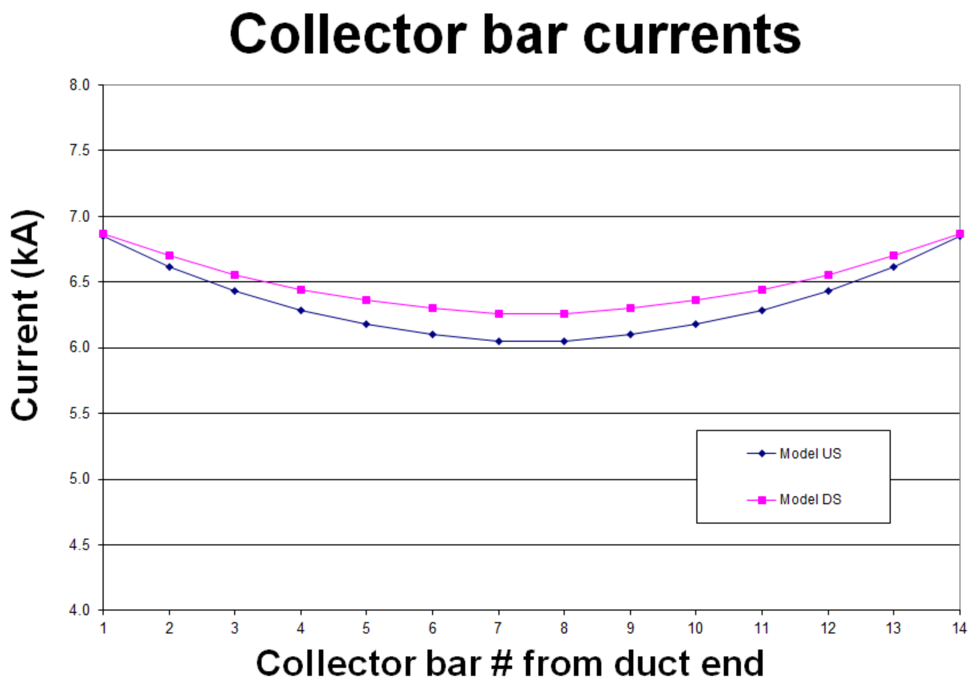

Figure 4. Collector bar current pickup calculated by MHD-VALDIS.

That collector bar current pickup plus the offset of the end cathode edge to the end of anode edge and the end ledge toe position are all influencing the metal pad horizontal current densities in the cell longitudinal direction (JX). The JX calculated by MHD-VALDIS is presented in Figure 5 for that base case design. Metal pad horizontal current densities in longitudinal X-direction are rarely presented and discussed but they are as detrimental to the cell stability as the horizontal current densities in the cell transversal direction (JY). The JY are also affected by the offset of the side cathode edge to the side anode edge and the side ledge toe in addition to be influenced by the bar size, resistivity and the contact resistance between the bar and the block. Figure 6 is presenting the JY calculated by MHD-VALDIS.

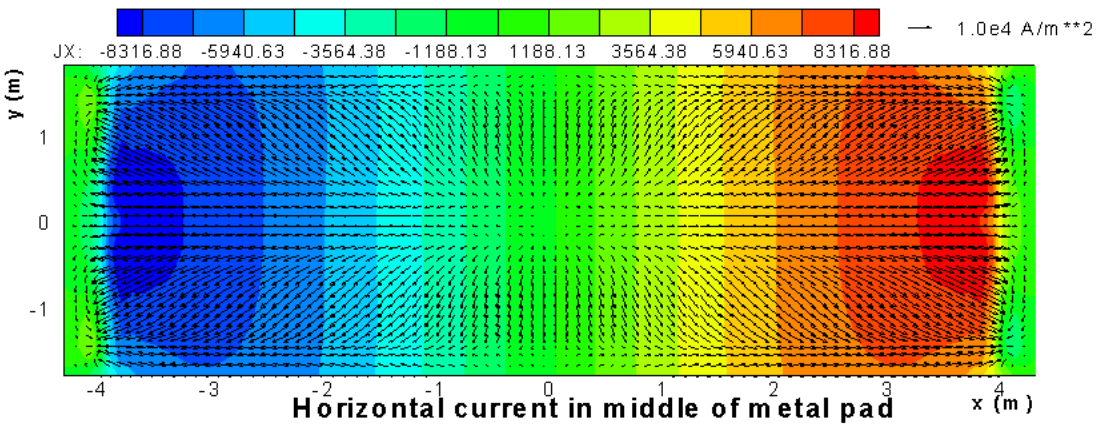

Figure 5. MHD-VALDIS calculated horizontal current density in the metal pad in the longitudinal direction JX.

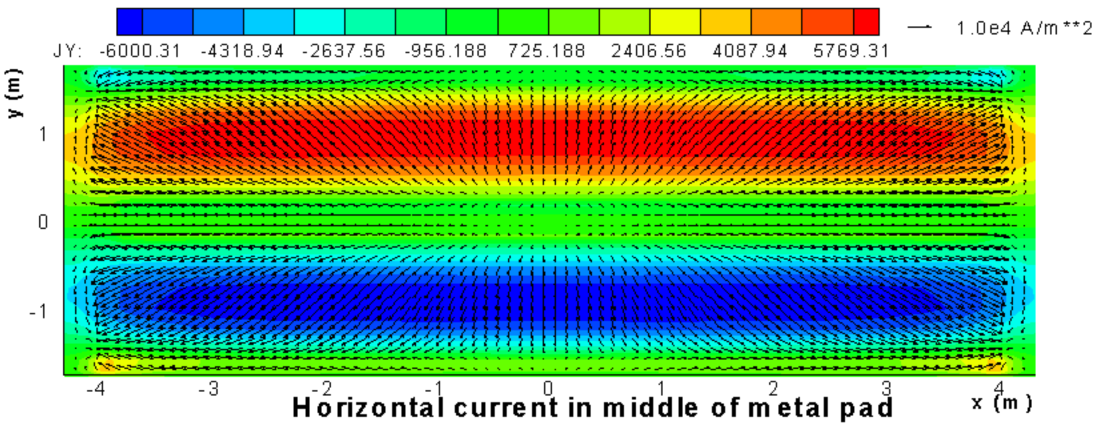

Figure 6. MHD-VALDIS calculated horizontal current density in the metal pad in the transversal direction JY.

As we can see, the JX is calculated to be more intense than the JY, so it can be speculated that they have a quite significant negative influence on the cell stability. This can be studied using MHD-VALDIS, and this result will be presented later. Before that, we want to present and compare the current density results calculated by the 3D ANSYS electric model for the same base case.

3. 3D ANSYS Electric Model Current Density Results for the TRIMET Cell Base Case Design

As already discussed, since the 3D ANSYS electric model is limited to the inside of the cell, the collector bar current pickup is a boundary condition, since we want to compare the JX calculated by MHD-VALDIS with the one calculated by the ANSYS model, we need to use the same collector bar current pickup. So, the one calculated by MHD-VALDIS and presented in Figure 4 is used as boundary condition in the ANSYS model. Figure 7 is presenting the metal pad current calculated by the ANSYS model in all 3 directions.

As it can be seen by comparing Figure 5 to the bottom section of Figure 7 and Figure 6 to the middle section of Figure 7, the horizontal current density results calculated by ANSYS and MHD-VALDIS are very similar. They are not perfectly identical but as already explained in [1], the solution of the metal pad current density is very sensitive to the model setup as the liquid metal electrical resistivity is very low. Any discrepancy between two given models will affect their respective solution of the metal pad current density. The good match in the JX predictions could not have been achieved by assuming uniform collector bar current pickup as boundary condition in the ANSYS model.

Another result that could be compared is the cathode voltage drop (CVD) prediction. MHD-VALDIS is predicting 274 mV of CVD while the ANSYS electric model is predicting 271 mV. The accuracy of MHD-VALDIS CVD predictions has been improved by the addition of the possibility for the user to specify the temperature of the collector bar inside the block in the input file CBARCONTR.txt, the same file that is used to define the Y location dependant contact resistance between the bar and the block. Table 1 is presenting the setup of the CBARCONTR.txt file for the TRIMET base case design which assumes that the collector bar is fully rodded by cast iron along the length of the block.

The CBARCONTR.txt file will be used later to define alternative designs using incomplete rodding or selective rodding in order to reduce the JY intensity and hence increase the cell stability. But in order to be able to compare the cell stability of the TRIMET base case design, the results of the stability analysis of that TRIMET base case design are presented first in the next section.

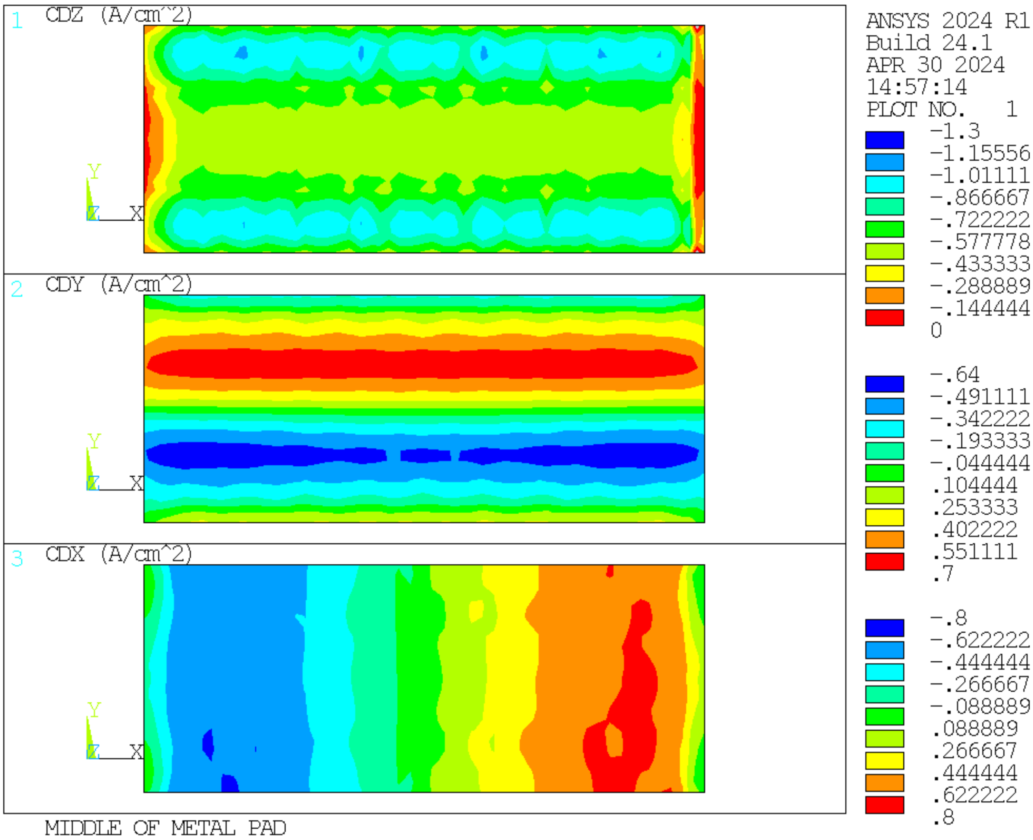

Figure 7. 3D ANSYS electrical model calculated current densities in the metal pad.

Table 1. Content of CBARCONTR.txt file.

N<15	ContRes,Om	Ycoord,m	Tcol,Cdeg
0	0.0	1.60	954.
1	0.000148	0.116129	955.
2	0.000148	0.232258	955.
3	0.000148	0.348387	956.
4	0.000148	0.464516	957.
5	0.000148	0.580645	959.
6	0.000148	0.696774	961.
7	0.000148	0.812903	962.
8	0.000148	0.929032	963.
9	0.000148	1.045161	963.
10	0.000148	1.161290	961.
11	0.000148	1.277419	955.
12	0.000148	1.393548	944.
13	0.000148	1.509677	921.
14	0.000148	1.625806	870.
15	0.000148	1.741935	770.

4. Stability Analysis Results for the TRIMET Cell Base Case Design

As already presented in [1], the TRIMET cell using the base case design model setup produces the magnetic field presented in Figure 4 of [6], the metal pad thickness of 17 cm that produces the horizontal current presented in Figure 5 and 6 and a 4.3 cm electrolyte thickness (ACD) is predicted to be critically stable as presented in Figure 8. As first presented in [7], the MHD-VALDIS software now calculates the bath-metal interface wave stability index which is the negative of the wave growth rate. That stability index is calculated to be -0.9587E-04 that is very close to zero. Since it is negative, it is predicted to be on the unstable side. This means that the wave amplitude is growing very slowly even if this is not explicitly visible in Figure 8.

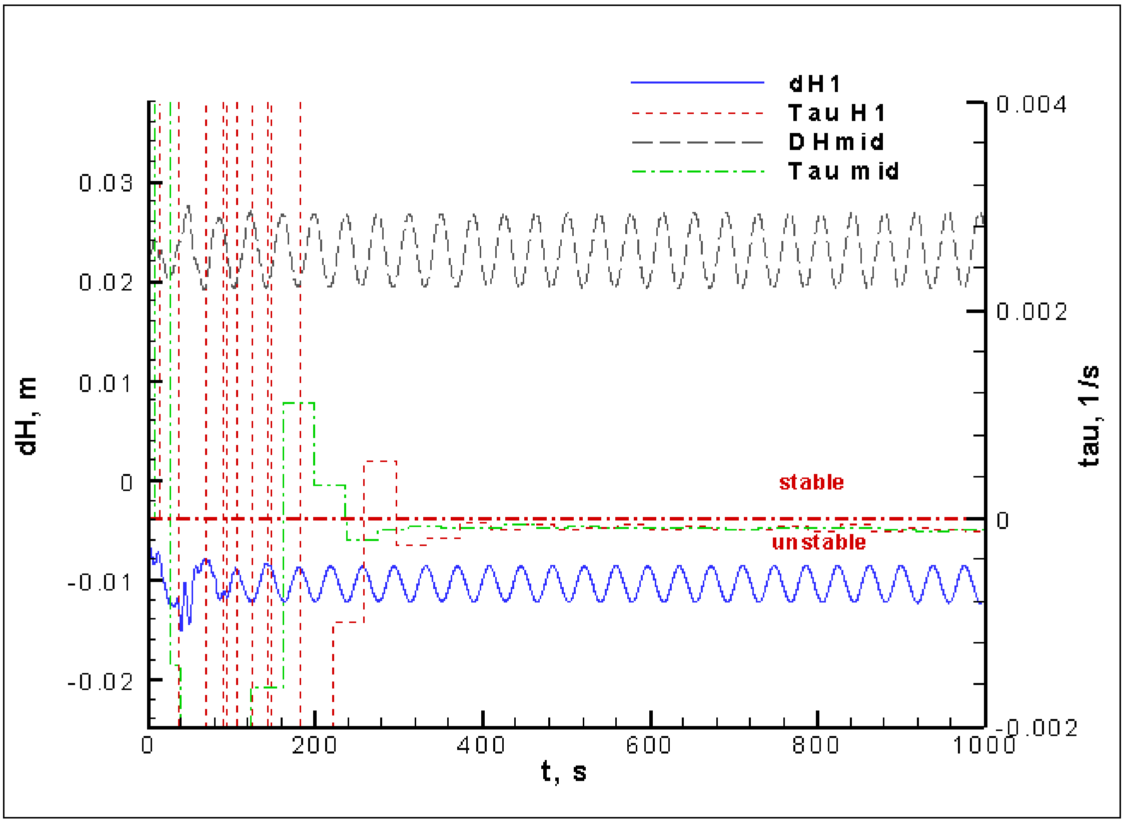

Figure 8. Results of the TRIMET base case design stability analysis performed by MHD-VALDIS.

5. MHD-VALDIS Current Density Results for a TRIMET Cell Design Reducing JX

In the previous publication [1], we investigated the design changes permitting to reduce JY and compared the JY and the CVD predicted by MHD-VALDIS and the 3D ANSYS electric model. Then we performed the stability analysis in MHD-VALDIS to see the impact of that JY reduction on the cell stability while having the insurance that the JY change calculated by MHD-VALDIS was accurate enough.

It was expected that the cell stability will continue the improve as the JY is reduced more and more but the results presented in [1] did not match that expectation. It was speculated that the presence of a JX could confuse the issue, so in the present work, a design change aiming at reducing the JX will be performed first.

In order to reduce as much as possible the JX without changing too much the cell or the busbar design, the MHD-VALDIS input file flexes.txt was used. The purpose of this file is to add a contact resistance between the end of the bar and the flexes and this contact resistance can be adjusted for each bar. After adding the contact resistance in the bars of the first and last block the current pickup of these bars was significantly reduced. This results in a significantly reduced JX as presented in Figure 9. The JY was not affected so it will not be presented again.

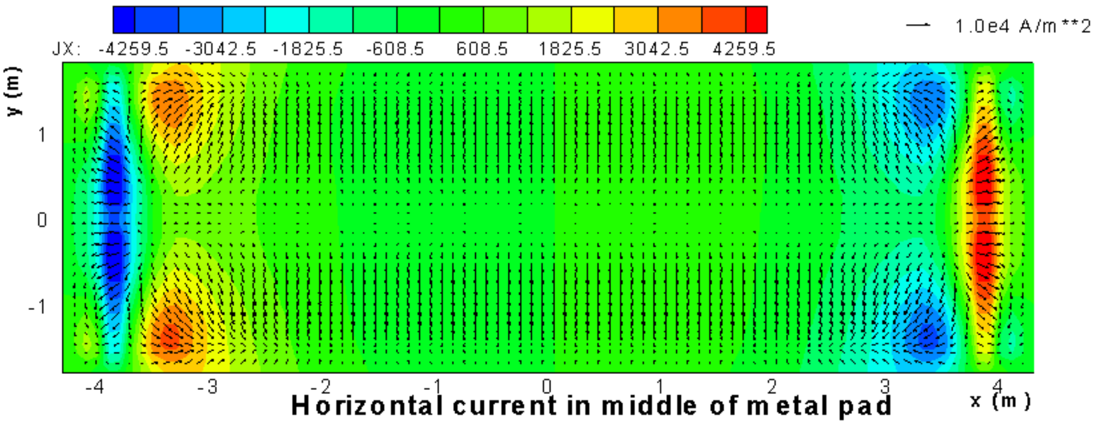

Figure 9. MHD-VALDIS calculated horizontal current density in the metal pad in the longitudinal direction JX, after JX reduction.

6. 3D ANSYS Electric Model Current Density Results for a TRIMET Cell Design Reducing JX

The introduction of a contact resistance between the bar and the flexes only affects the collector bar current pickup boundary condition of the 3D ANSYS electric model, so the same model was solved again using the new collector bar current pickup values obtained from MHD-VALDIS. The resulting metal pad current distribution is presented in Figure 10.

Again, the results obtained by MHD-VALDIS and by the ANSYS model are similar, JX have been eliminated in the bulk of the cell, only a limited JX remain around the first and last blocks. The average CVD is not much affected by the local addition of contact resistances, MHD-VALDIS is computing 274 mV CVD while the ANSYS model is computing 270 mV CVD.

7. Stability Analysis Results for a TRIMET Cell Design with Reduced JX

The reduction of the JX should increase the cell stability even if the JY intensity has remained the same. This has been confirmed by the MHD-VALDIS cell stability analysis. Figure 11 presents the cell stability analysis results; the stability index is now 0.8090E-03, above zero meaning that the wave is damping, clearly indicating that the reduction of the JX intensity improved the cell stability.

8. MHD-VALDIS Current Density Results for a TRIMET Cell Adding an Incomplete Rodding to the Previous Design

Since the JX has been reduced, the same two cathode block rodding design aiming at reducing the JY [1] are tested again in the present work. The first case is for the incomplete rodding which consists at no rodding up to the edge of the carbon blocks, leaving the last 15 cm without cast iron. This design can now be tested in MHD-VALDIS by using the file CBARCONTR.txt simply replacing the last three contact resistance values by a large value (1.0). The resulting JY is presented in Figure 12.

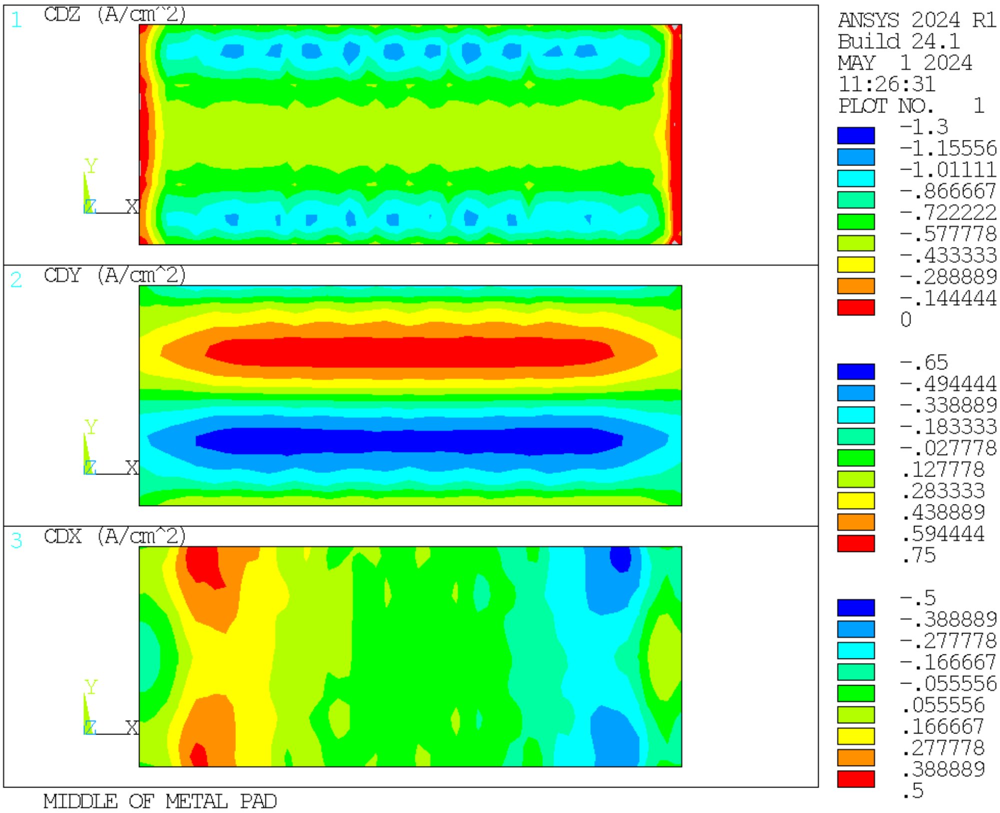

Figure 10. 3D ANSYS electrical model calculated current densities in the metal pad, reducing JX intensity.

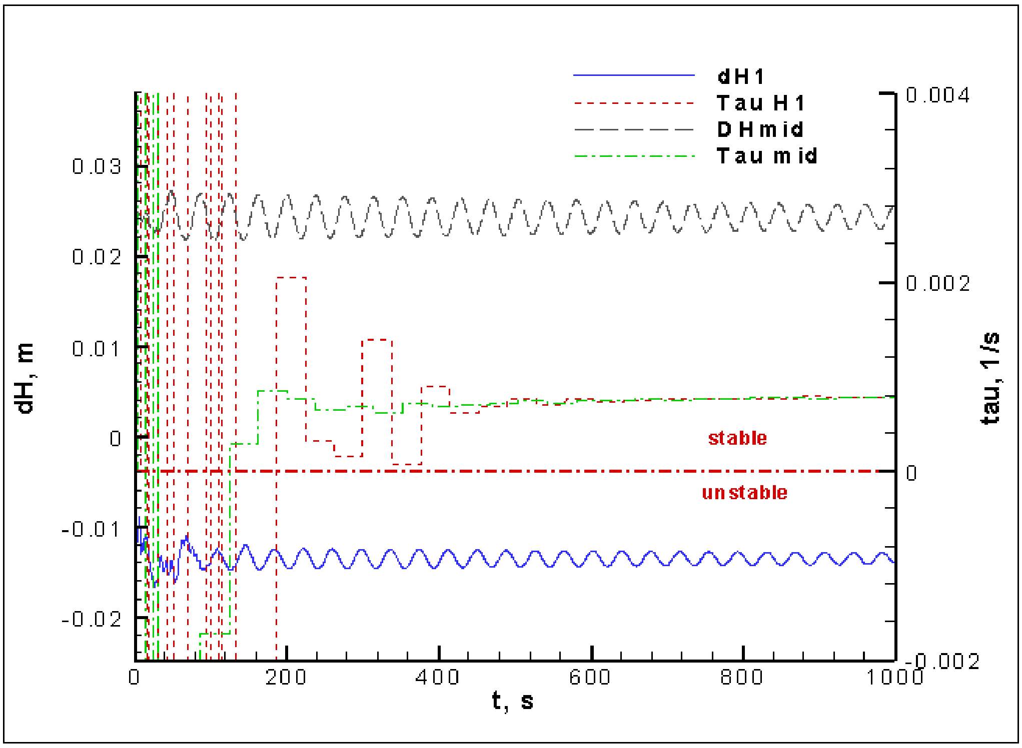

Figure 11. Results of the TRIMET cell design reducing JX intensity stability analysis. performed by MHD-VALDIS.

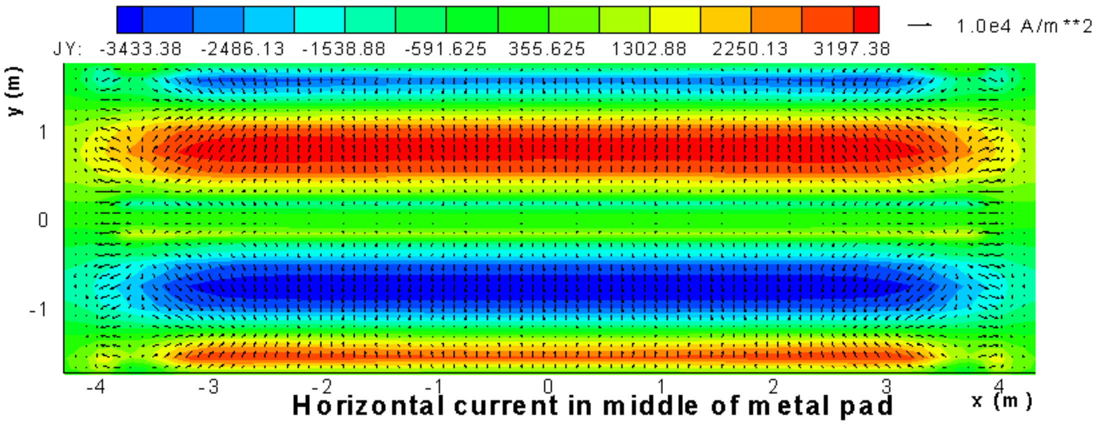

Figure 12. MHD-VALDIS calculated horizontal current density in the metal pad in the transversal direction JY, after incomplete rodding.

9. 3D ANSYS Electric Model Current Density Results for a TRIMET Cell Adding Incomplete Rodding to the Previous Design

Since the option to use incomplete rodding is covered in the 3D ANSYS electric parametric model, it is easy to model this option again. The obtained JY is presented in Figure 13. Those results compare very well with the results calculated by MHD-VALDIS. For the CVD values, MHD-VALDIS is computing 300 mV and the ANSYS model is computing 305 mV. The match between the two results is much better than those reported in [1] due to the addition of the option to specify the bar temperature in the CBARCONTR.txt file in MHD-VALDIS.

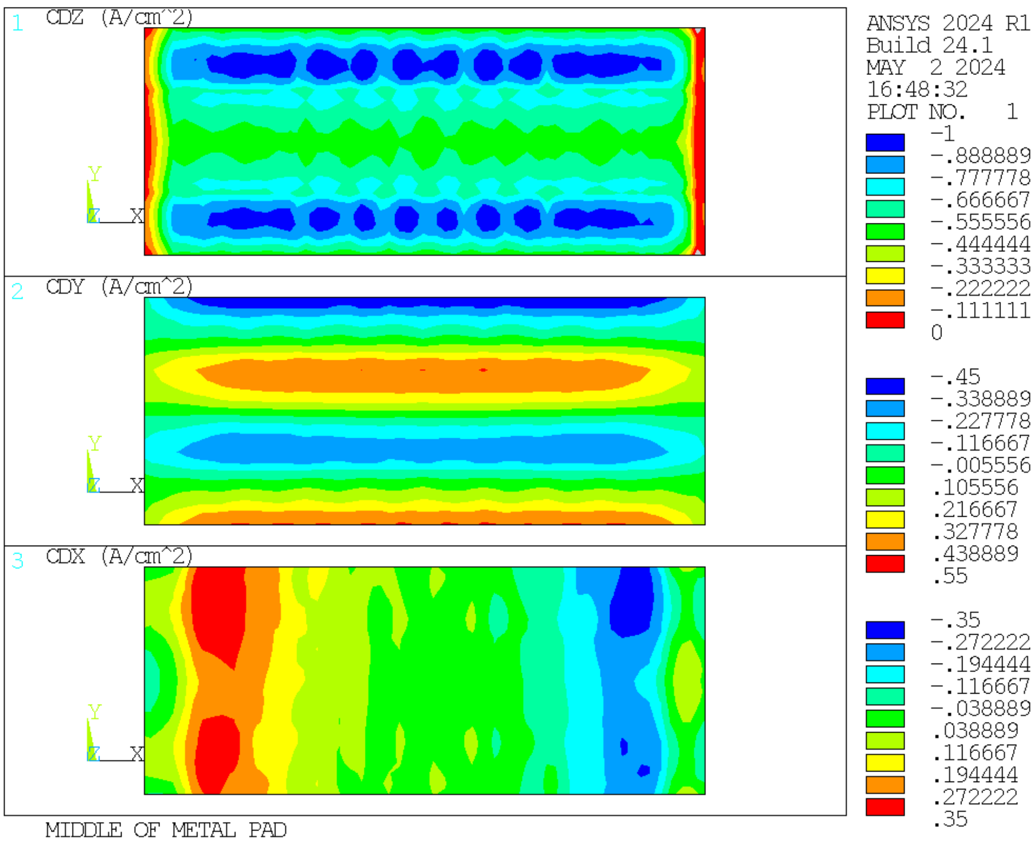

Figure 13. 3D ANSYS electrical model calculated current densities in the metal pad.

10. Stability Analysis Results for a TRIMET Cell Adding Incomplete Rodding to the Previous Design

Figure 14 presents results of the cell stability analysis when incomplete rodding is added to the previous design reducing the JX, so now, both the JX and JY have been reduced. The stability index has increased to 0.1156E-02 indicating an increased cell stability.

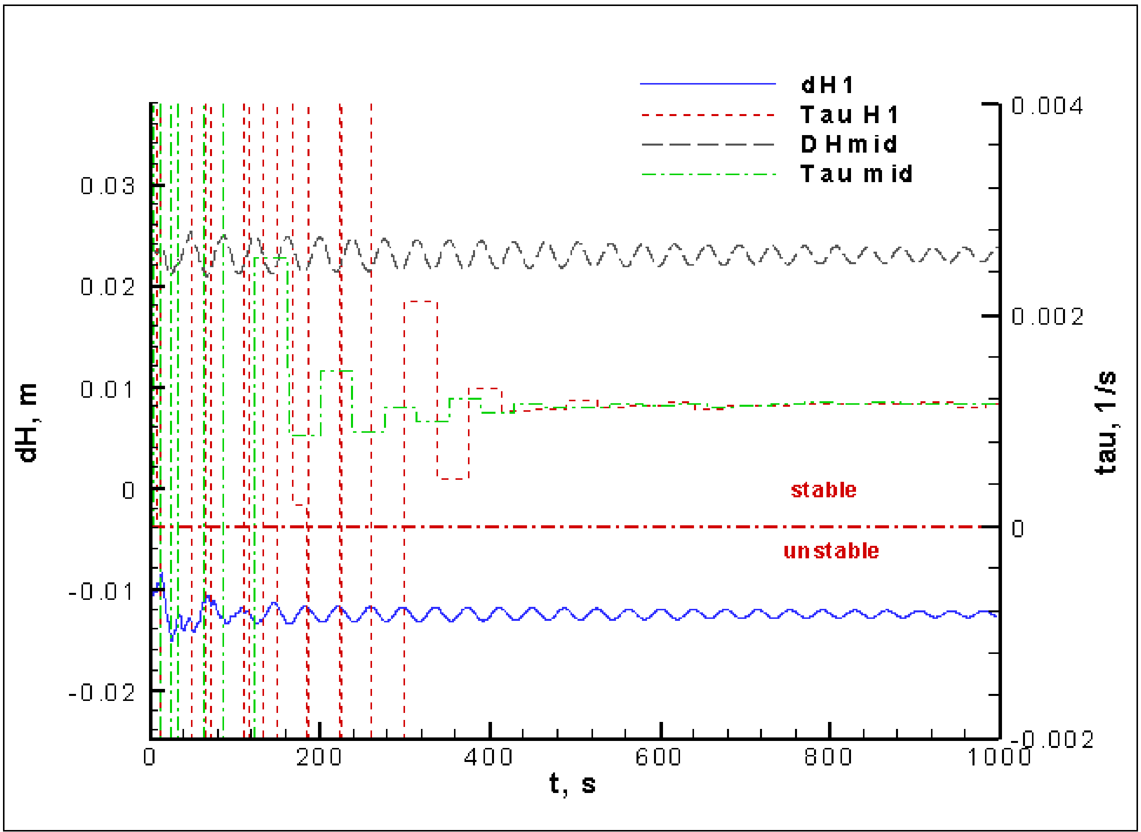

Figure 14. Results of the stability analysis for the TRIMET cell adding incomplete rodding to the previous design.

11. MHD-VALDIS Current Density Results for a TRIMET Cell Replacing Incomplete Rodding by Selective Rodding to the Design Reducing JX

The final design analyzed is the combination of selective rodding to reduce JY and extra resistance in bars to flexes connections of the end blocks to reduce JX. Selective rodding concept was first presented in [8], it consists of rodding the bar per sections, reducing the section length and increasing the gap between sections as you progress toward the block edge. The impact of using selective rodding on cell stability was first analyzed in [1], but in the cited article, nothing was done to also reduce the JX. Figure 15 presents the obtained JY.

As the 3D ANSYS electric model was not designed to support selective rodding designs, that design could not be easily modeled using ANSYS so no comparative results are available for that final design.

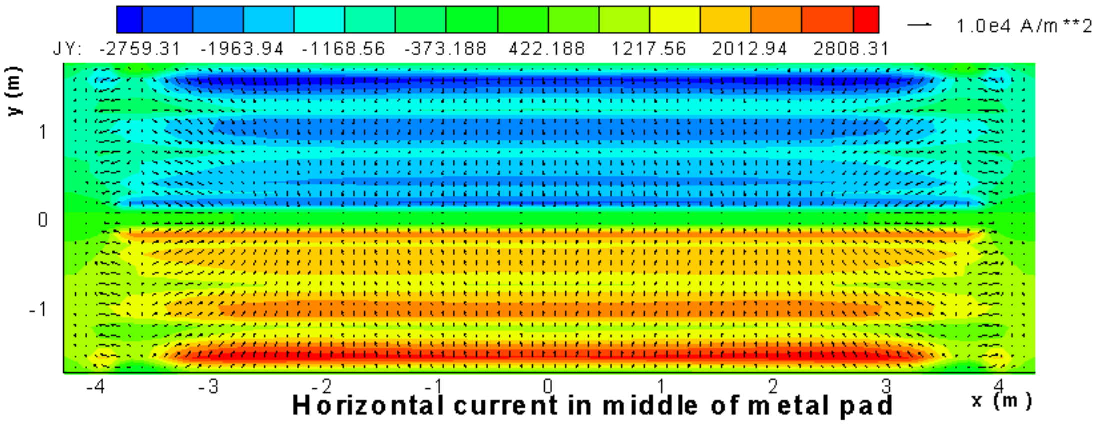

Figure 15. MHD-VALDIS calculated horizontal current density in the metal pad in the transversal direction JY.

12. Stability Analysis Results for a TRIMET Cell Replacing Incomplete Rodding by Selective Rodding to the Design Reducing JX

In this final analyzed design, both the JX and the JY have been significantly reduced so that it should be the design that produces the most stable cell. Figure 16 presents the results obtained; the stability index is now 0.2273E-02 so it is a significant cell stability improvement over the previous case using incomplete rodding.

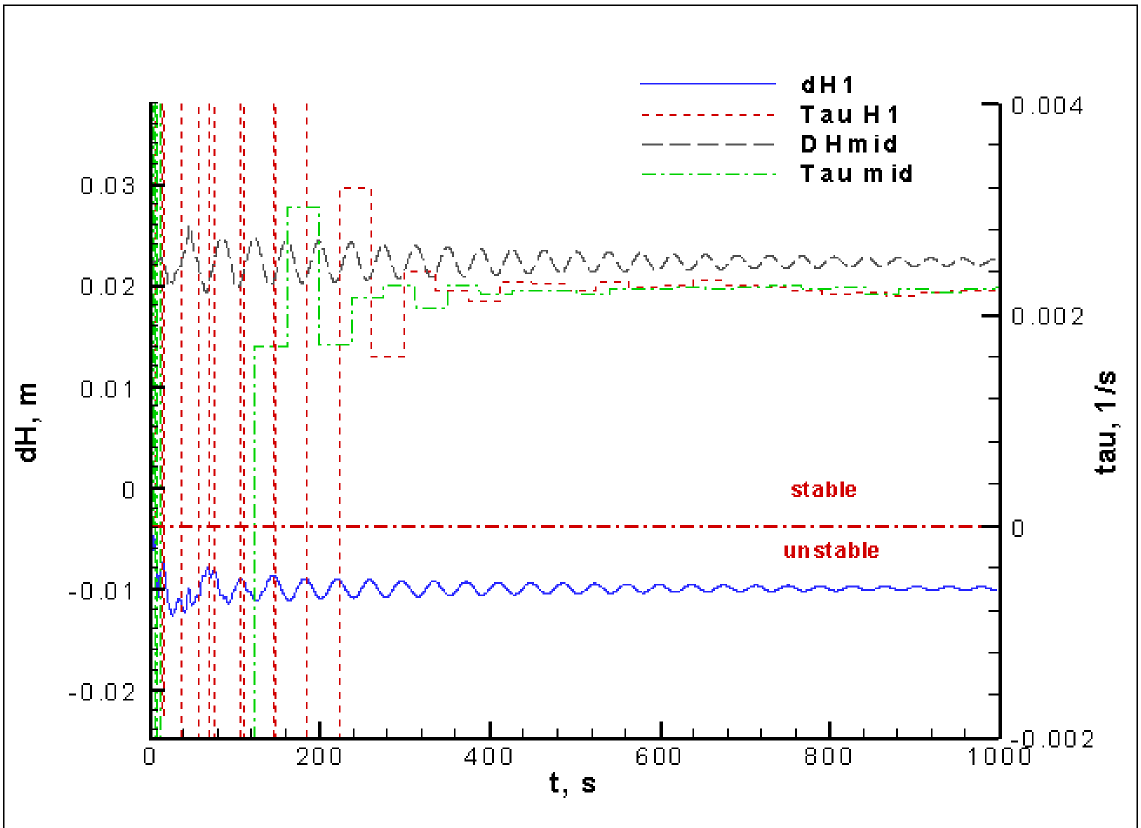

Figure 16. Results of the stability analysis for the TRIMET cell replacing incomplete rodding by selective rodding to the design reducing JX.

13. Impact of Changes of Metal Pad Current Density on the Bath Flow and Dissolved Alumina Concentration in the Bath

Design changes aiming to reduce the horizontal current intensity in the metal pad do not only affect the cell stability. They primarily affect the steady state Lorentz forces which in turn affect the steady state bath and metal flow. In turn, the MHD bath flow affects the way the alumina particles fed to the cell circulate around and eventually dissolve.

For any given bath flow and set of feeder locations, there is a pseudo steady state alumina concentration pattern that get established with often zone(s) of very low alumina concentration responsible for continuous (low voltage) PFC emissions.

MHD-VALDIS also has an alumina dissolution module that has been used to calculate the alumina concentration in the bath for all 4 cases studied above. Figure 17 presents the results obtained after 1 hour of feeding stating from a uniform 2.5 % alumina concentration.

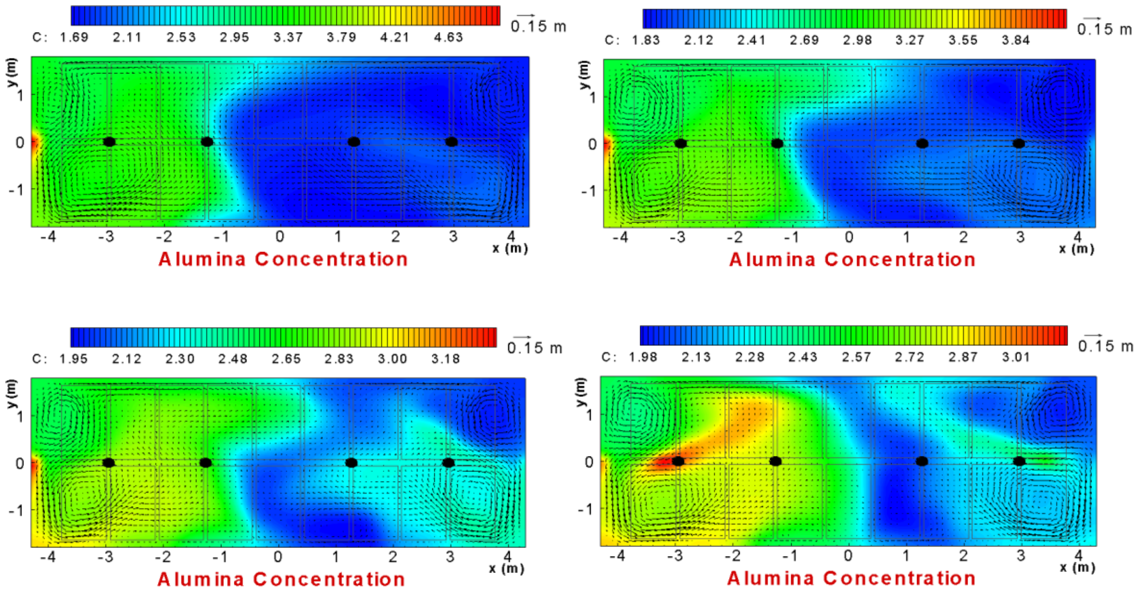

Figure 17. Results alumina concentration gradient in the bath after 1 hour of feeding Top left: base case, top right: reduced JX, bottom left: reduced JX plus incomplete rodding, bottom right: reduced JY plus selective rodding.

Even if it was not the aim of the design changes, it turned out that reducing both the JX and JY intensity produced a more symmetric bath flow that in turn considering the symmetric position of the feeders produces a more uniform alumina concentration in the bath. Those results are only indicative as no validation work has been done on those alumina concentration model predictions.

14. Conclusions

The recent MHD-VALDIS software improved method to compute the metal pad current density that let the user define the collector bar temperature inside the blocks and the length of the blocks, in addition to the possible variation of the contact resistance along the bar/block connection has been tested again. The improvement also involves the computation of the horizontal current density in the cathode block in the Y direction. Metal pad current density and CVD results obtained using MHD-VALDIS have been found to be quite comparable with those obtained using a 3D ANSYS electric model.

The subsequent cell stability analysis has demonstrated that it is as important to reduce the JX as it is important to reduce the JY in order to increase cell stability. By combining with the results presented in [1], we can conclude that when intense JX are present, continuous reduction of the JY intensity may not result in continuous increase of the cell stability. Hence it is important to reduce both JY and JX intensity to maximize cell stability.

Finally, the reduction of the horizontal current densities also affects the steady state Lorentz force field which in turn affects the steady state bath and metal flow pattern. Since the bath flow pattern affects the path of dissolving alumina particles added into the bath, a change of bath flow pattern will also affect the pseudo steady state alumina concentration gradient present in the bath responsible for continuous PFC emissions in region(s) of very low alumina concentration. For the series of the four analyzed design changes, the modifications aiming at reducing the horizontal current in the metal pad also resulted to the reduction of the alumina concentration gradient in the bath.

15. References

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