AL26 - Modelling Study of the Impact of Copper Insert Design on Aluminium Reduction Cell Heat Balance and Voltage

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Abstract

The rapid development of the aluminium industry and tightening environmental regulations require engineers to look for ways to increase reduction cell productivity while reducing their carbon footprint. One universal remedy are copper inserts in a steel collector bars. This paper describes the impact of the copper insert design on aluminium reduction cell performance parameters. A detailed modelling study was conducted to understand the influence of different copper insert designs on various cell KPIs such as cathode voltage drop, cathode current distribution, heat balance, and cell life.

Keywords: Copper insert, Energy saving, Cathode voltage drop, Cell numerical modelling, Cell life, MHD stability.

1. Introduction

Due to its high electrical conductivity, cathode collector bar copper inserts are a common design innovation in modern aluminum electrolysis cells. It is primarily used to reduce cathode voltage drop. However, copper insert design requires an intelligent approach as it can both positively or negatively affect other key performance parameters such as cell heat balance, cathode current density distribution, and cell stability. At the same time, copper is relatively expensive, therefore, any potential improvement it brings has to be evaluated against its cost. Copper inserts in the collector bars are a simple design improvement, and almost all smelters have adopted it.

According to Wiedemann–Franz law, high electrical conductivity in copper is associated with proportionally high thermal conductivity. Because collector bars are major heat sinks in the electrolysis cell, the addition of copper noticeably increases cell heat losses. This is beneficial for amperage increase in existing technologies because it can withdraw additional heat which is generated by increased heat generation in the cell. However, for the heat-deficient cells, there should be an optimal insert size and position for the best electrical gains and minimal heat loss increase, which should allow for higher total energy efficiency.

The introduction of copper not only decreases overall collector bar resistance but also redistributes the current more uniformly on the surface of the cathode carbon blocks. This is advantageous for the magnetohydrodynamic (MHD) stability of the cell and for cell life expectancy due to reduced cathode erosion.

Non-uniform current on the cathode block creates horizontal currents in the metal pad, which interact with a vertical magnetic field (B_Z) to create unfavorable Lorentz forces for metal-bath interface stability. A good copper insert design decreases horizontal currents in the metal pad. Typically, a copper insert can be defined using three major parameters: cross-sectional area, length, and position within the cathode carbon blocks. It is expected that each of these parameters will have a different influence on cell performance, so it is important to understand how they affect it individually as well as in conjunction with each other.

This unique combination of costs, benefits, and restrictions requires a sophisticated multi-parameter optimization of the topology and geometry of the cathode. In this paper, we used the COMSOL Multiphysics software package which uses finite-element modelling. We focus on understanding copper insert design parameters and their effect on cell heat and voltage balance.

Several studies of copper insert designs have been published, including modelling and cell performance [1-3].

2. Model Description

For this study, a steady-state thermo-electrical model was created using the COMSOL Multiphysics software package. The model represents a 3D cell slice of half-cathode block width, including everything below the anode: bath, liquid metal, cathode block and collector bars, lining, potshell, and part of a cathode ring busbar (Figure 1).

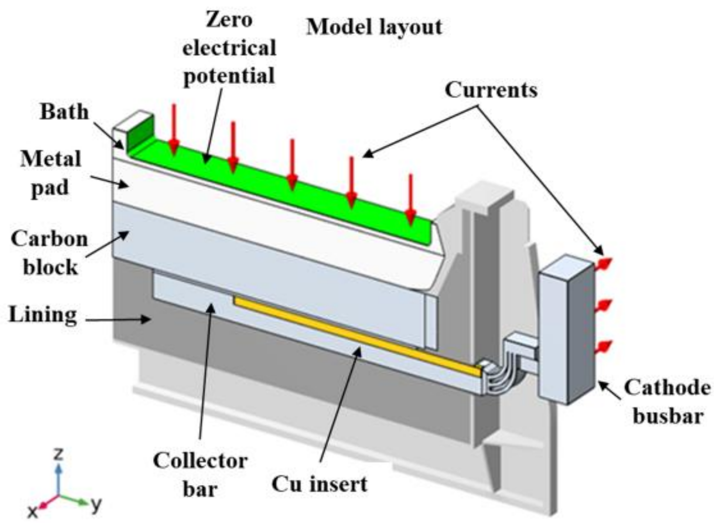

Figure 1. Model layout.

Electrical currents are simulated within the conductive domains using generalized Ohm's law. This is achieved by defining a zero potential boundary at the electrolyte-anode interface and a negative current density on the cross-section of the exit cathode busbar. The interface between cast iron and cathode carbon block, which does not provide perfect contact, is represented by contact resistances on the top and the sides of the collector bar. All models were calculated with the same cell current of 465 kA.

The model simulates heat transfer within all solid components using a steady-state conductive heat transfer equation. This equation uses joule heat sources in electrically conductive materials, coupled with a radiative heat loss model on the outside boundaries, which explicitly evaluates view factors of such shell elements as shell wall, fins, cradles, as well as radiative heat flux between the potshell and the cathode busbar. The heat fluxes from liquid aluminum and electrolyte are approximated as convective heat transfer on cathode and ledge boundaries with homogeneous bath and metal temperature distribution. Heat transfer coefficients from liquids to solids (from liquid aluminium to cathode block, toe, freeze, trench, and bath to the freeze) are fitted to the measured thermal distribution in an industrial cell.

For thermo-electric cell models, the thickness of the frozen ledge is important for accurate heat balance evaluation. In our model ledge domain is deformed until the temperature of the phase boundary reaches liquidus temperatures, which are calculated separately for bath, metal, and toe regions based on their compositions [4]. The deforming domain feature is strongly bi-directionally coupled with a thermo-electric solver and it significantly affects current and heat distribution in the metal pad and the cathode. In order to see the effect of the copper insert on metal currents, the ledge was not deformed when evaluating the following parameters: volume-average of transversal horizontal current (J_y), maximum current per slice, and visualization of horizontal currents in cathode cross-section. In these simulations, the ledge toe was fixed 10 cm inside the anode shadow.

Cathode voltage drop (CVD), cathode heat loss, and temperature contours for the cell cross-section are analysed. Cathode current distribution is represented as a linear plot of the cathode current density, integrated over 10 evenly spaced slices on top the cathode block`s uncovered surface. The cathode top surface except the area covered by the toe is equally divided into 10 slices. The first slice from the toe edge is the slice with maximum current density/maximum current perslice. To evaluate the relative influence of different options (%), in all tables for the first option the maximum current per slice is presented as 100 %. Moreover, the current distribution is illustrated using a contour plot of the Y-component of the current density vector, and by streamlines in the YZ plane.

3. Impact of Copper Insert Cross-Section

Copper insert cross-section has a predominant effect on the thermal and electrical balance of the cell. In this case, both the length and position of the copper insert were held constant at 1.5 m and 61 % overlap with the cathode block. The first model was without copper insert, and for copper inserts, its cross-sectional area was changed from 2500 to 8100 mm^2. The shape of the copper cross-section has no significant effect on cathode assembly, so it was kept square.

The results show strong effect on heat loss and electrical parameters. From the heat loss plot (Figure 2) it can be seen that heat losses increase linearly with copper cross-section at a rate of 9 W/mm^2 or 11 W/kg Cufor the whole cell. As expected, the increase of the copper insert cross-section up to 28 % of the collector bar cross-section significantly affected only collector heat losses. The heat balance on the bottom and walls of the potshell changed by less than 2 % for the whole range of copper cross-sections (Table 1).

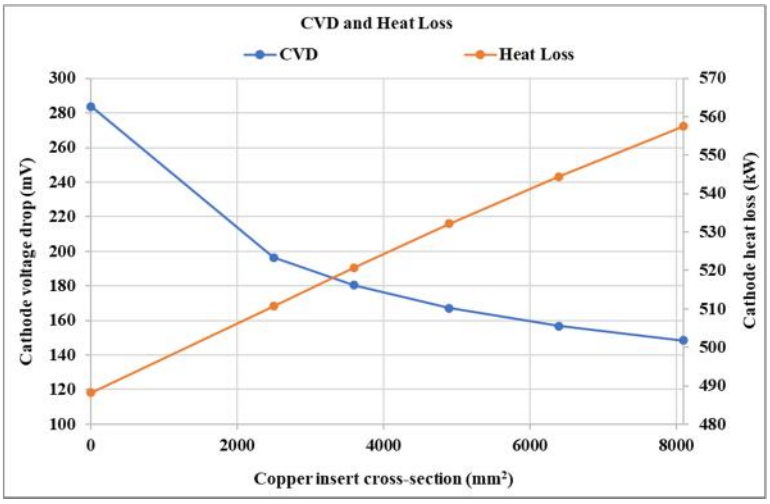

Figure 2. Impact of copper insert cross-section on CVD and heat loss.

Cathode voltage drop (CVD) savings change with a diminishing effect, starting from -0.05 mV/kg Cufor the 0-9 % and tapering off at -0.007 mV/kg Cu for the 22-29 % of copper to collector cross-section ratio.

Table 1. Reasults for copper insert cross-section variation. Base case 1.0 is steel collector bar.

Parameter	Unit	Case					
Data:		1.0	1.1	1.2	1.3	1.4	1.5
Copper insert area	mm^2	-	2500	3600	4900	6400	8100
Copper length	mm	-	1500	1500	1500	1500	1500
Copper mass per bar	kg	-	33	48	65	85	108
Heat loss:							
Total cathode heat loss	kW	488	511	521	532	544	558
Including:							
Potshell	kW	337	332	331	329	328	327
Underneath shell	kW	60	60	60	61	61	61
Collector bar	kW	91	119	130	142	155	169
Temperature:							
Collector bar temperature	°C	295	346	362	380	397	414
Max potshell temperature	°C	446	443	443	443	443	443
Electrical:							
CVD	mV	284	197	180	167	157	148
CVD difference from base case	mV	-	87	103	117	127	135
Volume average of J_y in the metal	kA/m^2	6.6	4.5	4.1	3.7	3.3	3.1
Max current per slice	%	100	85.8	82.7	80.0	77.7	75.9

In addition to the thermal and electrical effects described above, the copper insert also increases the uniformity of the vertical current density on the cathode surface, reducing maximum vertical current by up to 25 % (Figure 3), thereby reducing the cathode wear. The addition of the copper insert reducing J_y horizontal current by 50 % (Figure 5). This should increase cell MHD stabilityHowever, for large copper cross-sections, the increased heat loss through the collector bars, unless it is compensated by better lining insulation, will increase freeze toe on the cathode blocks, which may may make the MHD stability worse.

Also, for large copper cross-sections, the increased heat loss through the collector bars, shifts solidus isotherm 850 °C inside the cathode block (Figure 4) which can potentially lead to cathode block cracking through crystallization of absorbed bath components as well as collector bar and potshell corrosion through sodium ooze.

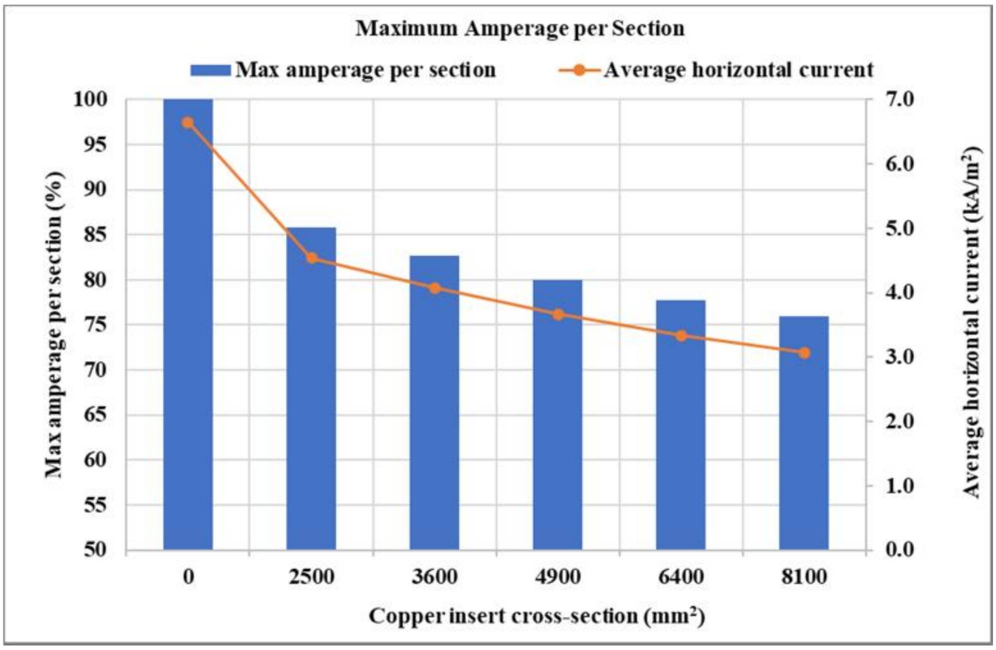

Figure 3. Maximum amperage per slice (section).

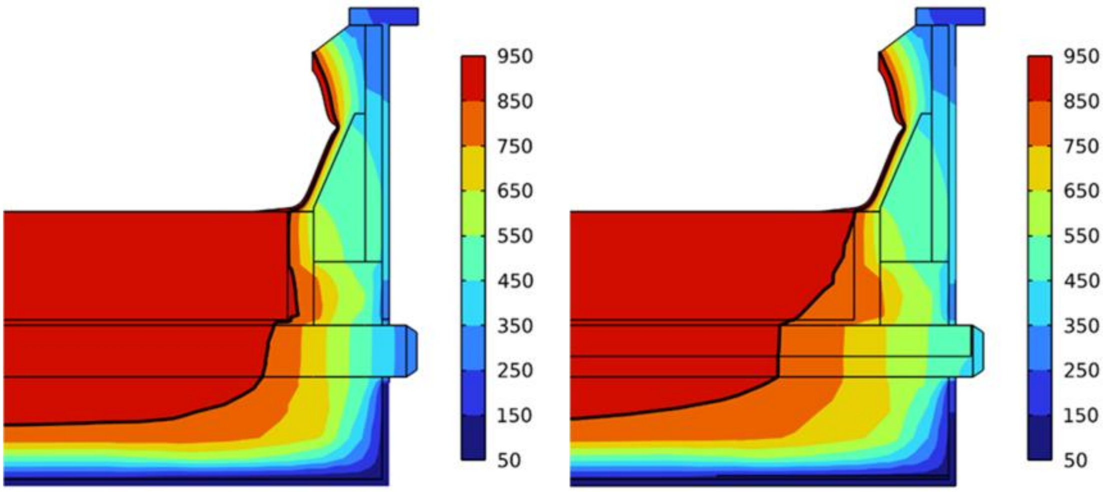

Figure 4. Impact of the copper insert length on solidus isotherm (black line) and end of collector bar temperature (°C). Left: steel collector bar; Right: copper cross-section area 8100 mm².

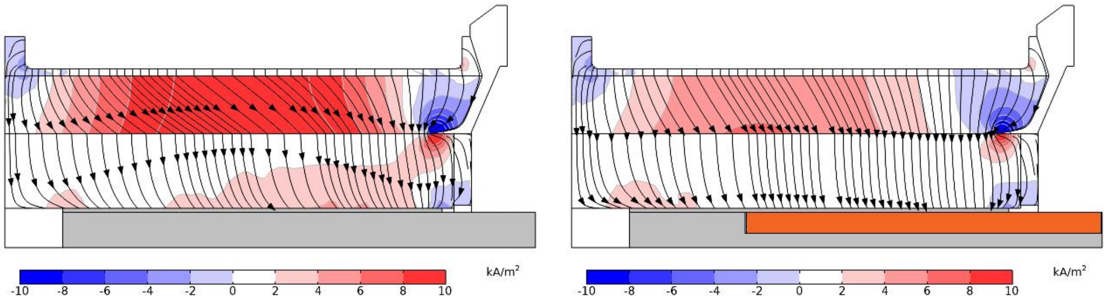

Figure 5. Impact of the copper insert cross-section on horizontal current in the metal (kA/m^2). Left: steel collector bar; Right: copper cross-section area 8100 mm^2.

4. The Impact of Copper Insert Length

In order to understand the influence of copper length on cathode performance, a number of simulations with varying lengths of copper insert were carried out. In these simulations, the outer end of the copper insert was anchored at the end of the collector bar, while the copper insert was extended toward the center of the cell (achieving a 45 % to 77 % overlap with the cathode block). All simulations were performed for the copper cross-section of 2500 mm^2.

Increasing the amount of copper in an area with a very low thermal gradient and low current density is expected to have minimal impact on the thermo-electrical parameters of the cell. The modelling results support this as it can be seen in Figure 6. As a result, temperatures of the collector bar and flexible connection, as well as the magnitude of heat loss, do not change much (within 2.5 % or 5 °C), making no impact on collector corrosion by sodium ooze (Figure 8).

Table 2. Results for copper insert length variation.

Parameter	Unit	Case						
Data:		2.1	2.2	2.3	2.4	2.5	2.6	2.7
Copper length inside the cathode block	%	45	51	56	61	66	72	77
Copper mass per bar	kg	26.7	28.9	31.1	33.3	35.6	37.8	40.0
Heat loss:								
Total cathode heat loss	kW	511	511	511	511	511	511	511
Including:								
Potshell	kW	332	332	332	332	332	332	332
Underneath shell	kW	60	60	60	60	60	60	60
Collector bar	kW	119	119	119	119	119	119	119
Electrical:								
CVD	mV	200	198	197	197	196	195	195
Volume average of J_y in the metal	kA/m^2	5.1	4.9	4.7	4.5	4.4	4.3	4.3
Max current per slice	%	100	99	98	97	97	97	96

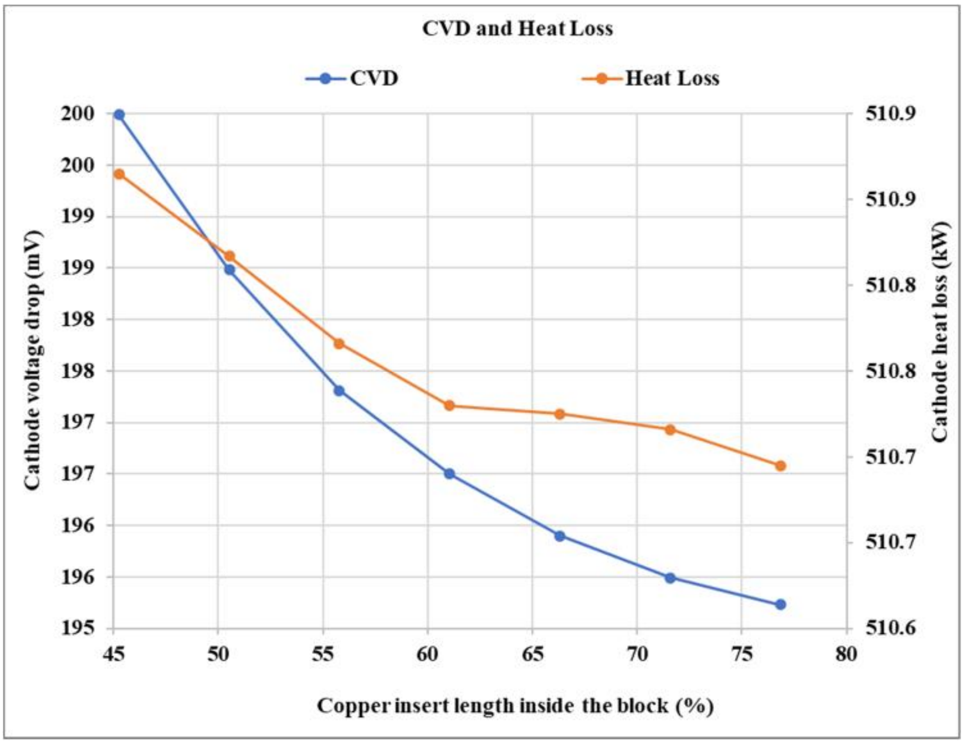

Figure 6. Impact of copper insert length on CVD and heat loss.

At the same time, the copper conductor inside the middle part of the cathode assembly has a significant effect on the current distribution in the metal pad (Figure 7). While the maximum amperage per slice does not change and the cathode surface potential changes very little, the high conductivity of the metal creates a noticeable effect on its horizontal currents. It can be seen from the current vector plot and horizontal current magnitude (Figure 9) that currents in the metal pad and carbon block follow the shorter path to the copper insert.

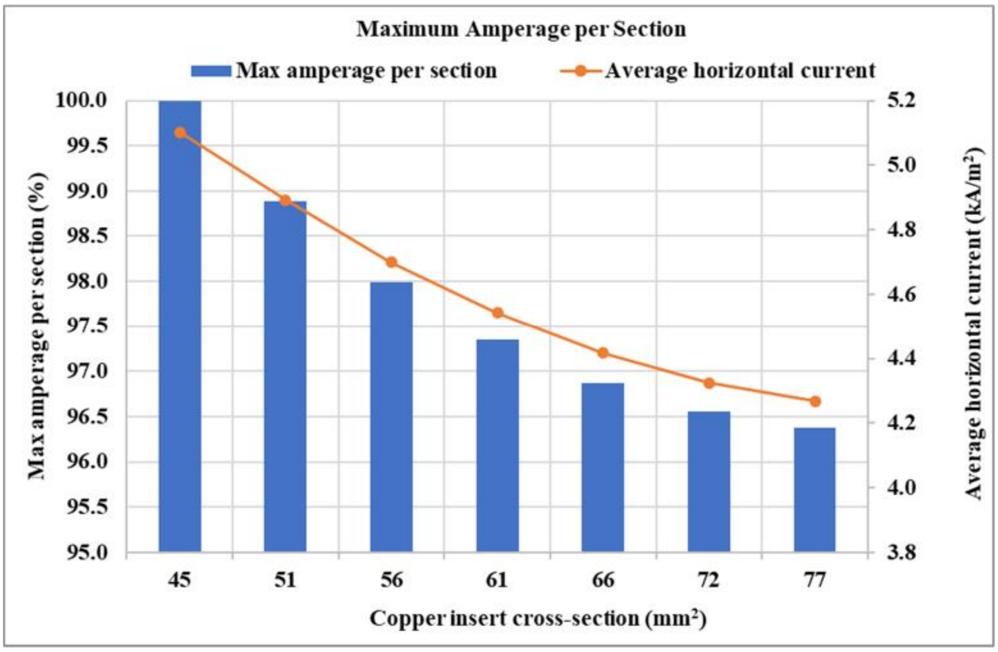

Figure 7. Maximum amperage per slice (section).

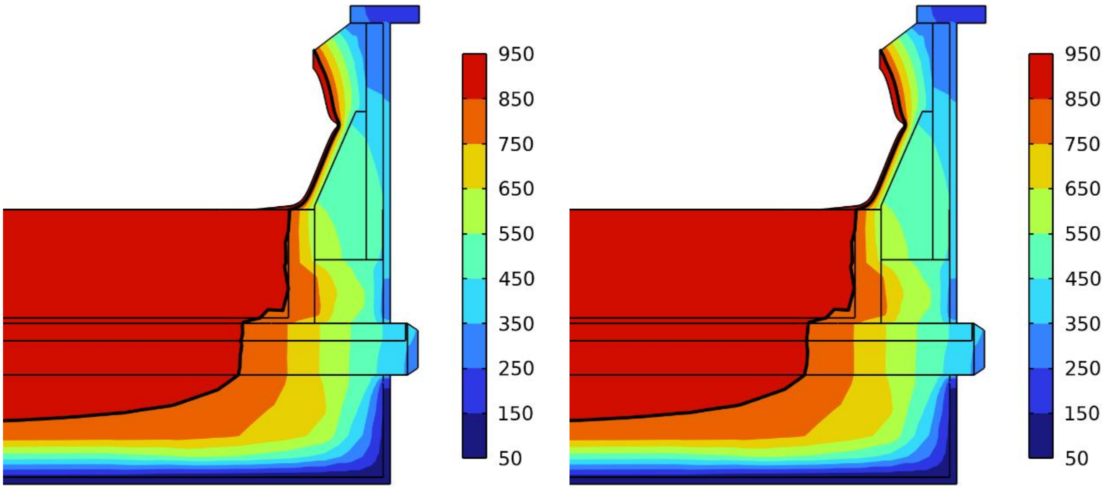

Figure 8. Impact of the copper insert length on solidus isotherm and end of collector bar temperature (°C). Left: copper-carbon overlap 45 %; Right: copper-carbon overlap 77 %.

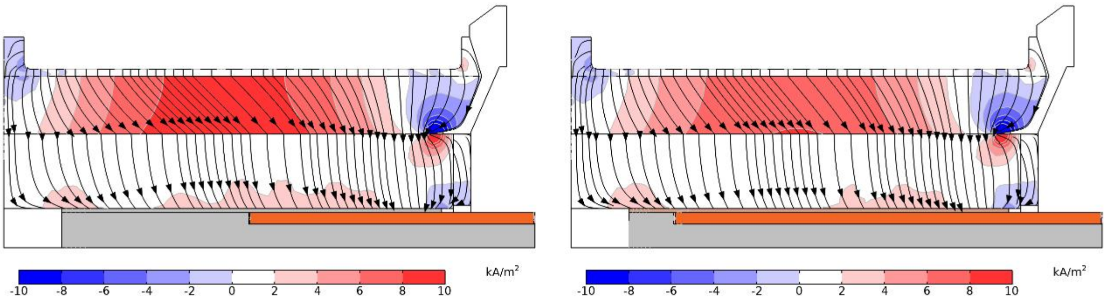

Figure 9. Impact of the copper insert cross-section on horizontal current in the metal (kA/m²). Left: copper-carbon overlap 45 %, Right: copper-carbon overlap 77 %.

5. Impact of Copper Insert Position

Cathode performance can be controlled without changing the mass of the copper insert by modifying its position within the collector bar. In this scenario, the length and cross-section of the copper insert were held constant at 1500 mm and 2500 mm² respectively, but its overlap with the cathode carbon block was adjusted, ranging from 61 % to 74 %.

The properties of the collector end have a strong impact on the thermal and electrical performance of the cell, as it is the area with the highest current and heat flux densities. The simulation results reveal a significant effect of the copper position on both CVD and heat balance as shown in Figure 10. Specifically, a 250 mm displacement of the copper insert results in a 13 % CVD increase. This is because full collector bar current passes through increasingly long part of the stee collector bar without Cu insert. Heat loss through collector also decreases by 4 % for the same reason. (Table 3 and Figure 10).

On the other hand, the results indicate that the position of the copper insert has only a minor impact on the current distribution in both the cathode block and metal pad, as illustrated in Figure 11. This behavior is similar to what is observed when extending the length of the copper, as seen in cases 2.4 – 2.7 (Figure 12).

Table 3. Results for copper insert position variation.

Parameter	Unit	Case				
Data:		3.1	3.2	3.3	3.4	3.5
Copper insert area	mm^2	2500	2500	2500	2500	2500
Copper length	mm	1500	1500	1500	1500	1500
Copper length inside the block	%	61	66	69	71	74
Copper position inside potshel	mm	-50	50	100	150	200
Heat loss:						
Total cathode heat loss	kW	511	500	497	494	491
Including:						
Potshell	kW	332	335	335	336	336
Underneath shell	kW	60	60	60	60	60
Collector bar	kW	119	105	101	98	95
Temperatures:						
Collector bar temperature	°C	343	324	317	312	309
Max potshell temperature	°C	443	444	444	444	445
Electrical:						
Total CVD	mV	197	208	214	220	227
Volume average of J_y in the metal	kA/m^2	4.5	4.4	4.3	4.3	4.3
Max current per slice	%	100	99	99	99	99

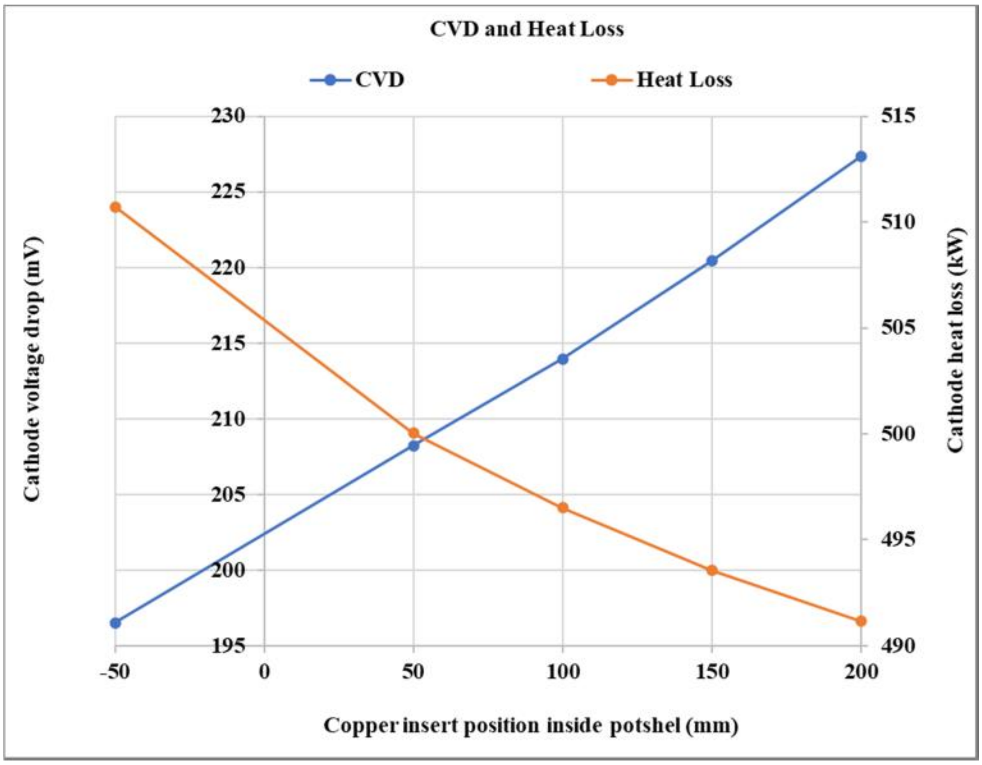

Figure 10. The impact of the copper insert position on CVD and heat loss.

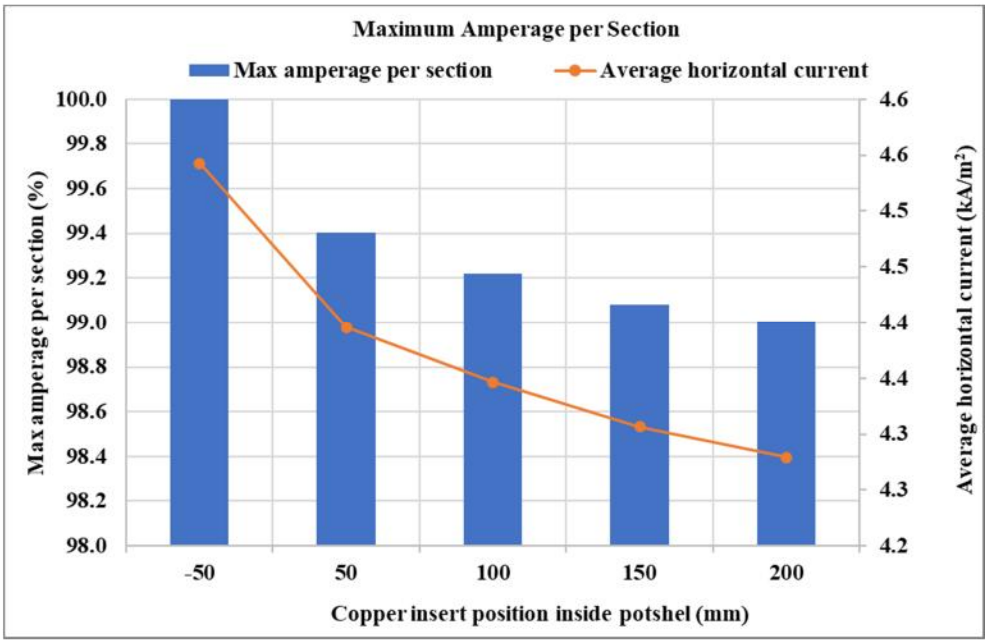

Figure 11. Maximum amperage per slice (section).

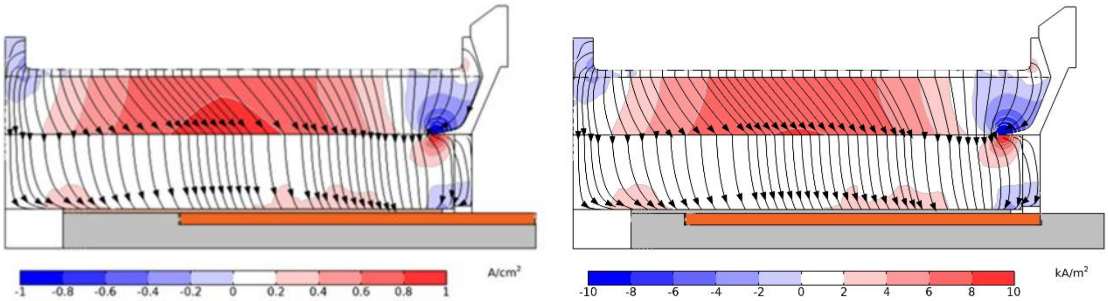

Figure 12. Impact of the copper insert position on horizontal current in the metal. Left (A/cm^2): copper starts 50 mm outside the potshell; Right (kA/m^2): copper starts 200 mm inside the potshell.

While the position of the copper insert does not influence the location of the solidus isotherm, the copper outside of the potshell results in a moderate increase in the temperatures of both the collector bar and the cathode flexible connection (Figure 13). . This consequently increases the risk of collector bar corrosion

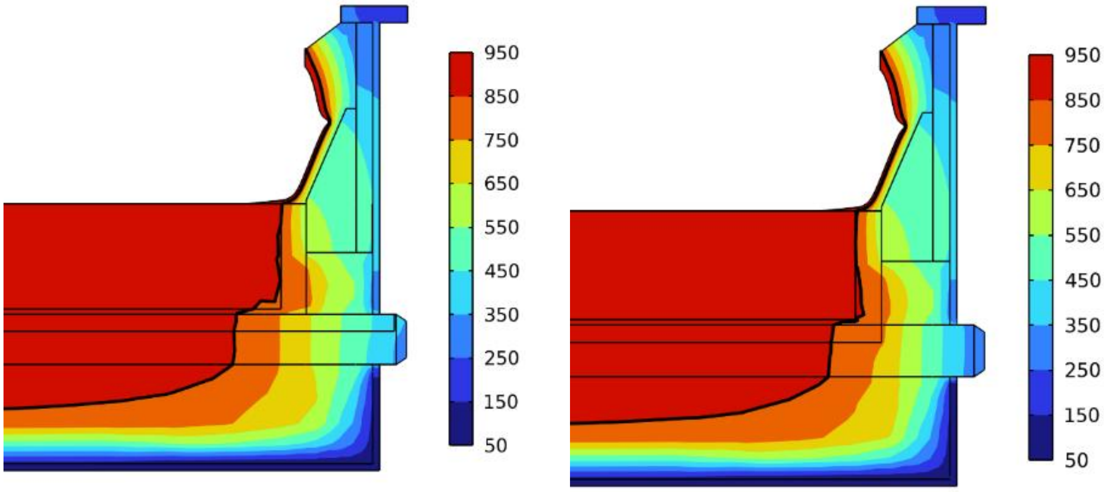

Figure 13. Impact of the copper insert length on solidus isotherm and end of collector bar temperature (°C).Left: copper starts 50 mm outside the potshell; Right: copper starts 200 mm inside the potshell.

6. Sloped Copper Insert

One of the widely-discussed ideas for redistribution of the current density in the metal pad and cathode block is the introduction of a copper insert with a non-constant cross-section. It is hypothesized that enlarging the copper area closer to the center of the cell could redistribute more current to the middle of the cell. To evaluate this, four models were compared: a model with a conventional copper insert (case 3.6), a full-length insert (case 3.7), a full-length insert with increasing area towards the center (case 3.8), and a model with a large copper block in the center (case 3.9). Copper inserts in options 3.7 and 3.8 have the same volume, to study the effect of the copper distribution within the collector bar.

As discussed in Section 4, the increase in copper length between cases 3.6 and 3.7 yields only marginal gains in CVD and current distribution, while leaving the thermal balance largely unchanged. Contrary to expectations, the introduction of the sloped copper insert resulted in a 6 % increase in horizontal currents within the metal pad and a 3 % decrease in maximum cathode surface current density (Figure 14). Sloped copper insert is predicted to have only a minor impact on collector bar temperature and heat losses while increasing CVD by 4 %. However, the addition of a large copper block (case 3.9) leads to a 15 % reduction in horizontal currents and a 2 % reduction in cathode currents. Despite these improvements, this option results in a twofold increase in copper insert mass, rendering it impractical (Table 4).

Table 4. Summary of copper insert shape variation results.

Parameter	Unit	Case			
Data:		3.6	3.7	3.8	3.9
Cu insert area	mm^2	2500	2500	variable	variable
Cu length	mm	1500	2185	2185	2185
Cu length inside the block	%	61	97	97	97
Copper mass per bar	kg	33.4	48.6	48.6	115.4
Heat loss:					
Total cathode heat loss	kW	511	511	509	511
Including:					
Potshell	kW	332	332	332	332
Underneath shell	kW	60	60	60	60
Collector bar	kW	119	119	117	118
Temperature:					
Collector bar temperature	°C	343	343	341	343
Max potshell temperature	°C	443	443	443	443
Electrical:					
Total CVD	mV	194	192	203	190
Volume average of J_y in the metal	kA/m^2	3.8	3.3	3.5	2.8
Max current per slice	%	100	98.3	101.3	96.5

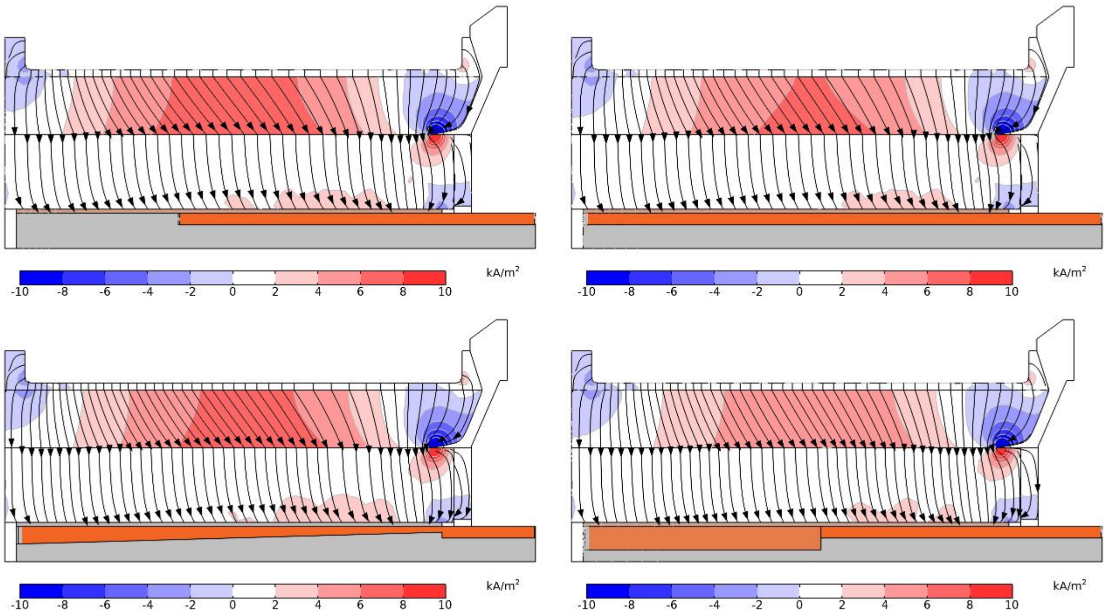

Figure 14. Impact of the copper insert shape on horizontal current in the metal (kA/m^2). Left Top: case 3.6; Right Top: case 3.7; Left Bottom: case 3.8; Right Bottom: case 3.9.

7. Conclusions

Copper inserts play a substantial role in the modern aluminum industry. As excellent conductors of both electricity and heat, they serve dual purposes: CVD reduction and thermal balance control, thus improving reduction cell key performance indicators (KPIs).

The copper insert cross-section is a crucial parameter affecting CVD, heat loss, cathode surface current density, horizontal current in the metal, etc. Its size can be increased provided that compensatory measures, like enhanced thermal insulation through lining or anode cover material (ACRM) are taken to offset the accompanying heat losses and reduction of internal heat generation. Failure to do so can lead to operational issues related to low bath temperature, such as slower alumina dissolution, and formation of anode spikes.

The copper insert length and shape inside the cathode block primarily affect the cathode surface current density and horizontal current in the metal, and to a smaller extent, the CVD. These parameters do not have a significant impact on heat loss and collector bar temperature. On the other hand, the copper insert length and shape outside the cathode block do affect CVD, heat loss, and collector bar temperature.

For the cell design, essentially two approaches can be considered. The first approach is tailored for high-productivity cells and involves maximizing the copper cross-section provided the solidus isotherm remains outside the cathode block. The second approach is used for low specific energy or “cold” cells and involves careful selection of the copper insert cross-section, length, and position to achieve the highest operational efficiency. However, the copper insert has to be utilized with care, because modification of the cell thermal balance might cause an increase in collector bar temperature which could be associated with accelerated corrosion by sodium ooze.

While copper inserts offer a range of benefits in optimizing cathode performance, their design and placement must be carefully considered to maximize advantages. The complexity and interconnection of thermal and electrical effects in such design studies make them difficult to carry out without a comprehensive 3D finite element modelling. Copper inserts also affect cell magnetohydrodynamics (MHD), which was part of this sudy but is not presented in this paper for the lack of space.

8. References

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