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INVESTIGATION OF CATHODE & COLLECTOR BAR MODIFICATION ON THERMAL BALANCE OF A LOW AMPERAGE CELL

Amit Gupta[1], Saibal Modak[1], Mahesh Sahoo[2], Jinil Janardhanan[2],
[1]Aditya Birla Science and Technology Company Ltd, Plot No 1 & 1- A/1, MIDC, Taloja, Panvel, Raigad, Maharashtra, 410208, India
[2]Hindalco Industries Ltd, Hirakud, Sambalpur, Orissa, 768016, India

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Abstract

Globally, aluminium smelter's focus has been on the energy reduction and in this context cathode lining is one of the key areas of research. The design and the material modifications of cathode and collector bar have shown potential for reducing the cathode voltage drop, also it results in improved current distribution in the metal region. Such modifications have been reported mostly for the higher amperage cells, where heat dissipation is much sought as compared to the lower amperage heat conservative cells. Hence, these modifications may have detrimental impact on the thermal balance of a low amperage cell and should be carefully evaluated. The present work focuses on the simulation studies, for understanding the effect of various modifications in the design and the material of cathode and collector bar, on voltage drop and thermal balance of an 85 kA cell. Simulations have been performed using a 3D thermo-electric model, validated with the plant measurements. This study depicts that the collector bar modification have substantial impact on the thermal balance of a low amperage cell.

Introduction

In an aluminium smelter there are several electrochemical cells, also known as pots, connected in series to form one or more potlines. Within a cell the current flow vertically downward through the anode, molten electrolyte, molten aluminum, cathode and flow horizontally through the collector bars to the cathode busbar, connected with the risers of next cell. For a particular cell configuration based on the electrical conductivity differences in molten metal, cathode and collector bar, the current density increases towards the exit of the collector bar, which results in generation of the horizontal currents in the molten metal [1]. The force generated due to the interaction of the horizontal current and the vertical magnetic field is prime responsible for the interface deformation, also lead to the magnetohydrodynamic (MHD) instability in the cell. Such instability increases the cell voltage and results in higher energy consumption.

Over the years, the cell busbar arrangement optimization has been an area of research to alter the magnetic field components for improvement in MHD stability of the cell [2]. However, it is rather difficult to modify the busbar arrangement in a running potline. Therefore, the focus is shifted towards finding ways to reduce horizontal current in molten aluminum in order to enhance the MHD stability of a cell. In recent years, most of the emerging methodologies of significant energy reduction are related to the design & the material modification of the cathode and the collector bar [1,3]. These provide reduction in the cathode voltage drop as well as reduction in the inter-electrode voltage. Most of these have been developed for high amperage cells (>200kA) where heat dissipation is preferred because of low ratio of surface area for heat loss to the internal heat generation. However for low amperage cells (<100kA) this ratio is comparatively high, which makes the low amperage cells to operate in heat conservative mode. Since such modifications would increase the heat loss from the cell, therefore for low amperage cells, these methodologies of voltage reduction require meticulous consideration of the thermal balance.

The objective of this paper is to evaluate the modifications in design and material of the cathode and the collector bar for energy reduction, while considering electrical and thermal aspects of the cell. In this study, a computational model developed in ANSYS for a 85 kA cell, has been utilized to analyze the design and the material modification. The thermo-electric model has also been validated with the plant measurements.

Modeling Approach

In recent years, computational modeling has played a pivotal role in the area of aluminium cell development and performance improvement. In present study, electrical simulation has been performed for analyzing the effect of change in electrical resistivity and the dimension of the collector bar on the cathode voltage drop and the horizontal current in molten metal. Subsequently, thermo-electric simulations have been performed to analyze the impact of some of these modifications on the thermal balance of an 85 kA end-to-end cell.

Electrical Simulation

The current distribution can be calculated by application of Ohm's Law as shown in equation (1).

$$J = - \ \nabla V \tag{1}$$

Since current is conserved within the cell therefore:

$$\nabla . J = 0 \tag{2}$$

Equations (1) and (2) yields to,

$$\nabla . (\sigma \nabla V) = 0 \tag{3}$$

Which is the Laplace equation in electric potential 'V' and this can be solved with appropriate boundary conditions. In Equations (1) and (2),   is the electrical conductivity (S/m) and J is the current density vector (A/m^2). Representative amperage value at current entering location and reference potential at current exit location is used as the boundary conditions.

Thermo-Electric Simulation

For the thermo-electric analysis, a 3D quarter cell model has been used, where electrical and thermal equations are coupled through

Joule heating term. Joule heating term $\dot{Q}$ can be calculated from equation (4) as follows.

$$\dot{Q} = \frac{|J^2|}{\sigma} \quad (4)$$

For obtaining the temperature profile in the simulated domain, general heat transfer equation has been solved with joule heat as source term. Since, this is a solid model therefore the equation was simplified by considering effective thermal conductivity k_{eff} (W/m.K) to account for convection in the molten liquids [4]. Also, aluminium reduction cell operates at thermal equilibrium, therefore transient term can be eliminated, which lead to following equation [5]:

$$0 = \nabla(k_{eff}.(\nabla T)) + \dot{Q} \quad (5)$$

Where, T is the temperature (^{0}C). Convection and Radiation boundary condition has been applied to the sidewall, top and bottom surfaces. Adiabatic boundary condition has been provided on symmetry faces. Commercial software ANSYS Multiphysics has been utilized for solving equation (1) to (5). Figure 1 shows the finite element mesh of 3D quarter section of the cell considered for the thermo-electric simulations.

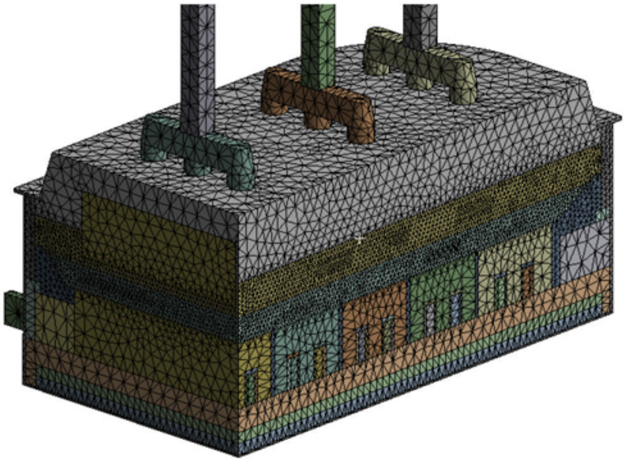

Figure 1: Finite element mesh of thermo-electric model

Base case model has been developed for a 85kA cell of Hindalco Hirakud. The inter-electrode gap was computed based on the plant voltage break down measurements. Electrical resistivity of the joining material between the cathode and the collector bar has been calibrated to account for contact drop based on the plant measured value of cathode voltage drop. Similarly electrical resistivity of the joining material between yoke and anode has also been calibrated.

Origin has been considered at the center and bottom of the cell in the thermo-electric model. X-axis, Y-axis and Z-axis have been considered along the short side, the long side and the height of the aluminium reduction cell respectively.

Results & Discussion

Thermo-electric model for base case was developed and validated with the measurement on a representative cell. Figure 2 shows the electric potential distribution in half section of cathode and collector bar assembly obtained from electrical simulations.

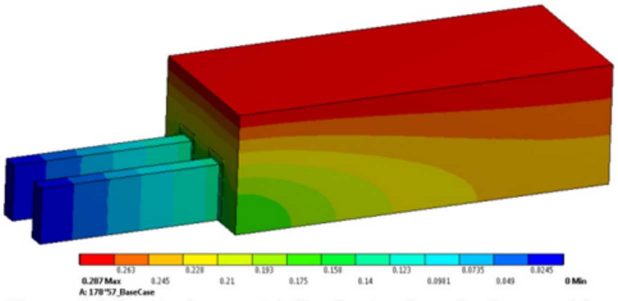

Figure 2: Electrical potential distribution in cathode assembly

Figure 3 shows the typical current distribution in the simulated molten metal region of the cell. It is evident that current density increases towards the exit of collector bar for base case, which increases the horizontal current component in the molten metal.

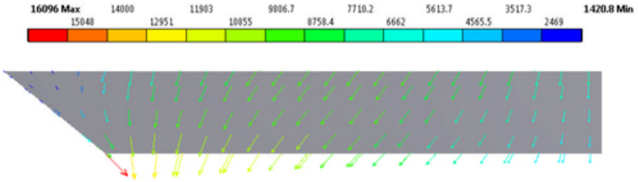

Figure 3: Typical current distribution in molten metal region

Figure 4 shows the cross-sectional view of cell for base case, highlighting the temperature contour in various lining element of the cell. Ledge profile is predicted from the model by tracking of the liquidus isotherm in the molten liquid region.

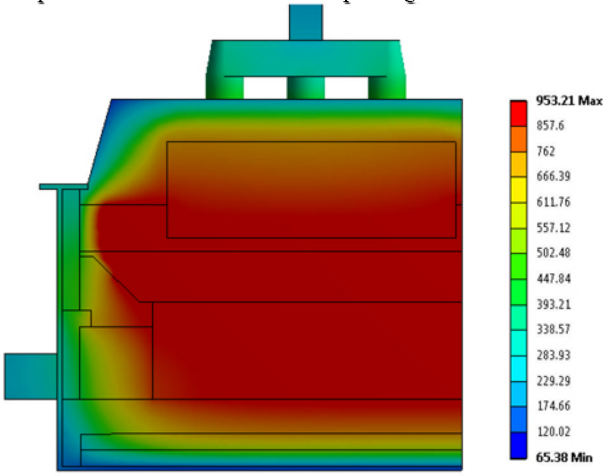

Figure 4: Temperature isotherms from thermo-electric model

Thermo-Electric Model Validation

Thermo-electric model has been validated with the thermal measurement conducted on a representative cell in Hirakud potline. Model validation for the ledge profile, molten electrolyte temperature and the outer steel shell wall temperature has been presented here.

a) Ledge/Freeze Profile

Figure 5 shows the comparison between the model predicted ledge profile and the plant measured ledge profile in a representative pot. The model predicted ledge profile is presented as continuous solid line and the plant measured ledge profile as dotted line. The model predicted ledge profile shows good agreement with the measured ledge profile.

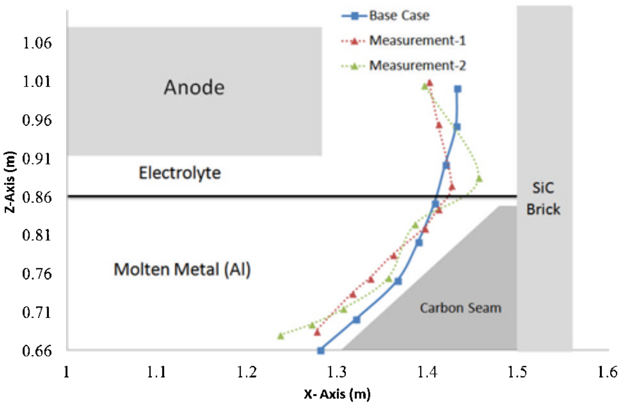

Figure 5: Comparison of simulated ledge profile with measured ledge profile

b) Electrolyte / Bath Temperature

The measured electrolyte temperature in the center of the running cell was about 955^{0}C, which found to show a close match with the model prediction of ~953^{0}C with a superheat of ~10 degree.

c) Steel Shell Temperature

Model results have been further validated with the temperature measured at various locations on the steel shell of a representative cell. The temperature values were found to be in close conformance with the model predicted temperature values.

Electric Analysis

Electrical simulations have been performed for a 85kA cell to analyze the impact of the modifications in design and material properties for reduction in cathode voltage drop and horizontal current. These modifications have been focused on reducing the electrical resistance R (ohm) defined by equation (6) as follows.

$$R = \rho \frac{l}{A} \tag{6}$$

ρ is the electrical resistivity (Ω.m), l is the electrical path length (m) and A is the cross-sectional area (m^2) for current flow. For present cell design, i.e. base case, the height 'H' and the width 'W' of collector bar in a cathode block has been shown in Figure 6. For calculation of percentage change in horizontal current, average value of current component J_x for different cases has been compared with base case.

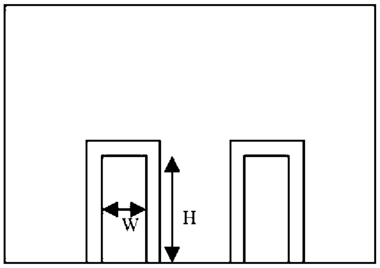

Figure 6: Cathode and collector bar configuration

Effect of Design Modification

a) H/W Ratio of Collector Bar

Simulation has been performed for various changes in the H/W ratio of collector bar. Simulation results show that for increase in H/W ratio from 3.12 (for base case) to 4.88, while keeping same cross-sectional area, resulted in reduction in cathode voltage drop, however the horizontal current were found to be increased. On contrary when H/W ratio of collector bar is decreased to 2.0 and 1.0 from 3.12, it resulted in increase in the cathode voltage drop and however helped in reducing the horizontal current. Table 1 provides a summary of cases studied for change in the H/W ratio while keeping the same cross-sectional area.

Table 1: Effect of change in H/W ratio of collector bar

Configuration	H/W ratio	Cathode voltage drop (volt)	Change in horizontal current
Base Case	3.12	0.287	
Increase in H/W ratio	4.88	0.273	+9.2%
Decrease in H/W ratio	2.00	0.299	-5.3%
Decrease in H/W ratio	1.00	0.313	-10.4%

b) Cross-sectional Area of Collector Bar

In this section, simulation has been performed for increase in cross-sectional area for various H/W ratios as shown in Table 2. Increase in cross-sectional area, reduces the electrical resistance as illustrated in equation (6), and thus decreases the cathode voltage drop. Simulation results show that for the same increase in the cross-sectional area, reduction in cathode voltage drop is more for higher H/W ratio of the collector bar. On contrary, for the same increase in cross-sectional area, reduction in horizontal current is more for lower H/W ratio of the collector bar.

Table 2: Effect of increase in cross-sectional area of the collector bar for various H/W ratios

Configuration	H/W ratio	Cathode voltage drop (volt)	Change in horizontal current
Base Case	3.12	0.287	
Increased area by 20%	3.12	0.250	-1.8%
Increased area by 10%	2.00	0.279	-6.7%
Increased area by 20%	2.00	0.262	-7.8%
Increased area by 50%	2.00	0.223	-10.5%
Increased area by 20%	1.00	0.278	-12.6%

It is evident that the increase in the cross-sectional area of the collector bar is advantageous for reduction in the cathode voltage drop. However, any increase in the cross-sectional area would also increase the heat loss. Therefore some of these cases would be analyzed in later part of this paper for understanding the impact on thermal balance of cell.

Effects of Change in Material Properties

a) Cathode Material Property

Cathode blocks are available in the form of anthracitic, semi-graphitic, 100% graphitic or fully graphitized, with improved thermal and electrical properties. Table 3 illustrate that increased degree of graphitization, increases the electrical conductivity, thus resulting in the lower cathode voltage drop, however it increase the horizontal current generation in the molten metal. Also higher graphite content increase the thermal conductivity of cathode, which result in increased heat loss and may affect the thermal balance of the cell.

Table 3: Simulation results for change in cathode material

Configuration	Electrical resistivity of cathode (x10^{-6})	Cathode voltage drop (volt)	Change in horizontal current
Base Case	35.0	0.287	
50% Graphitic	22.5	0.263	+8.02%
100% Graphitic	12.0	0.234	+22.35%

b) Collector Bar Material Property

The modification in collector bar material properties has been analyzed through simulations. Result shows that decrease in the electrical resistivity of the collector bar material, decreases the cathode voltage drop moreover it also reduce the horizontal current in the molten metal significantly. Table 4 shows that modifying electrical resistivity of the collector bar can yield to substantial saving in the cathode voltage drop. Also by reducing the horizontal current some voltage reduction is expected in the inter-electrode gap. However, the material change of the collector bar is associated with the change in the thermal properties and may adversely affect the thermal balance of the cell and should be analyzed.

Table 4: Simulation results for change in collector bar material

Configuration	Electrical resistivity of collector bar (x10^{-6})	Cathode voltage drop (volt)	Change in horizontal current
Base Case	1.00	0.287	
Material-1	0.325	0.141	-73.98%
Material-2	0.076	0.089	-92.41%

Modifications in the design and the material have potential for reducing the cathode voltage as well as voltage in the inter-electrode gap. Most promising case for voltage reduction from electric analysis may not be suitable from the thermal balance point of view. Therefore, some of the potential cases for voltage reduction have been analyzed for thermal balance of the cell, which have been discussed in following section.

Thermo-Electric Analysis

From the electrical analysis, some potential cases have been identified for energy reduction. From these potential cases, following have been considered for thermal analysis with respect to ledge profile, superheat in the cell, cathode temperature gradient and temperature at exit of collector bar. For all the simulations, the geometry/design, the material properties and the boundary conditions have been kept same unless stated in relevant cases.

- Base Case: Present cathode assembly with collector bar H/W ratio 3.12
- Case-1: Reduced H/W ratio of collector bar to 2.0 with same cross-sectional area
- Case-2: Reduced H/W ratio of collector bar to 2.0 with 20% increase in cross-sectional area
- Case-3: Reduced H/W ratio of collector bar to 2.0 with 50% increase in cross-sectional area
- Case-4: Base case with cathode material changed to 50% graphitic
- Case-5: Base case with cathode material changed to 100% graphitic
- Case-6: Base case with collector bar material change to material-1
- Case-7: Base case with collector bar material change to material-2

Effect of Design Modification

a) Decrease in H/W Ratio of Collector Bar

Simulation was performed to analyze the effect of reduction in H/W ratio on thermal balance of cell. Results shows that decrease in H/W ratio from 3.12 to 2.0 resulted in very little increase in the ledge thickness as shown in Figure 7. This depicts that changing the H/W ratio, while keeping the same cross-sectional area has diminutive affect on the thermal balance of the cell.

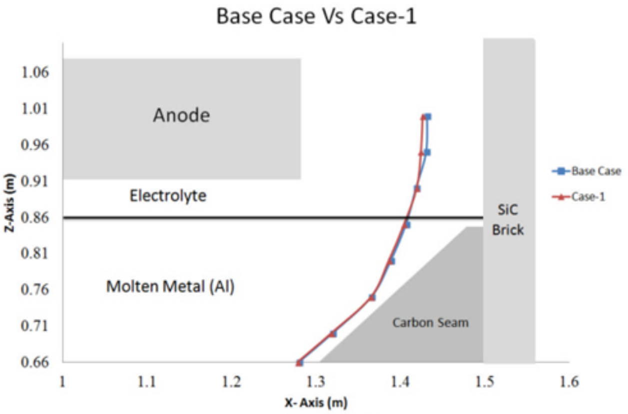

Figure 7: Ledge profile for change in H/W ratio of collector bar

b) Increase in Cross-sectional Area of Collector Bar

The cross-sectional area of the collector bar has been increased by 20% and 50% for H/W ratio of 2.0 in case-2 and case-3 respectively. Figure 8 show that increasing the cross-sectional area, enhances the ledge thickness near to metal-electrolyte interface by 1cm and 2.8cm for case-2 and case-3 respectively.

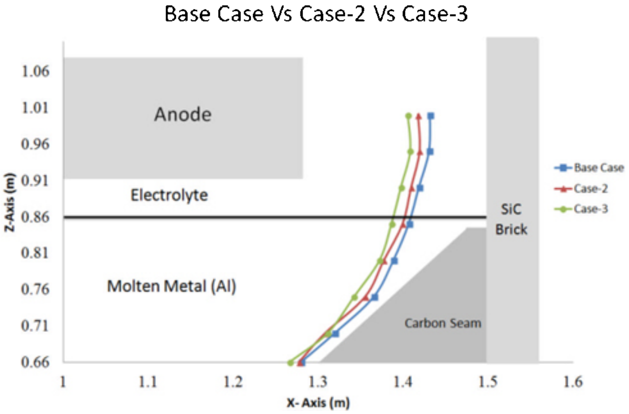

Figure 8: Ledge profile for increase in cross-sectional area of collector bar

Increase in the cross-sectional area also raise the heat loss from the collector bar, which provide cooling effect to the cathode block as shown in Table 5. For case-1, there was no change in the cathode temperature gradient, however slight increase in the temperature at the exit of collector bar has been observed. This increase is due to reduction in total exposed area of the collector bar for the heat loss to the surrounding, compared with the base case.

Table 5: Thermal results for design modification

Cases	Calculated superheat in pot (^{0}C)	Cathode temperature (^{0}C)			Temperature at exit of collector bar (^{0}C)
		Max	Min	$\Delta_{max-min}$	
Base	10.14	953	833	120	208
Case-1	10.06	953	833	120	214
Case-2	9.59	952	813	139	211
Case-3	8.52	951	788	163	209

For case-2 and case-3 temperature gradient in the cathode block has increased. This is evident, as the heat transfer through the collector bar has increased because of the increased cross-sectional area. Such increase in the heat loss may result in freeze formation on the cathode surface during cell operation. Therefore, it may require more side wall insulation near to the cathode block to compensate this effect.

Effect of Change in Material Properties

The modification in cathode and collector bar material has been simulated for the thermal balance. The thermal and electrical properties considered for the cathode and the collector bar are illustrated in Table 6.

Table 6: Material properties of the cathode and the collector bar

Material	Electrical Resistivity (x10^{-6})	Thermal Conductivity
Cathode (Base Case)	35.0	14
Cathode (50% graphitic)	22.5	24
Cathode (100% graphitic)	12.0	50
Collector bar (Base Case)	1.0	32
Collector bar material-1	0.325	60
Collector bar material-2	0.076	120

a) Cathode Material Property

Simulation has been performed for change in the material property of cathode from 30% graphitic (base case) to 50 % and 100% graphitic. Increasing graphitic content increases the thermal conductivity, which results in higher heat transfer to the surrounding thus increases the ledge thickness. Figure 9 shows that for case-4 and case-5, the ledge thickness increased by 0.8cm and 2.5cm respectively near to metal-electrolyte interface.

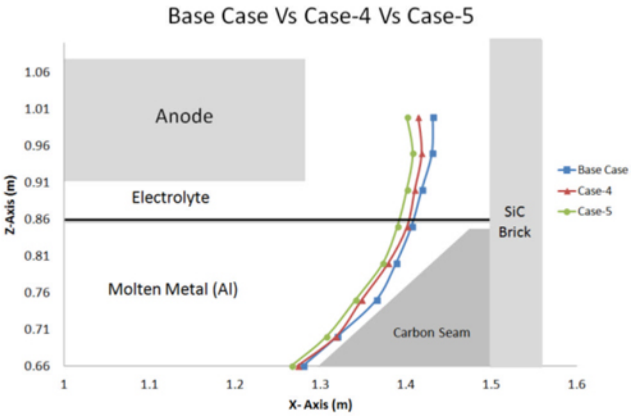

Figure 9: Ledge profile for material change of cathode block

a) Collector Bar Material Property

The collector bar material property has been changed to material-1 and material-2 for case-6 and case-7 respectively. These material properties have been described in Table 6. The ledge profile comparison for case-6 and case-7 with base case has been presented in Figure 10. Increase in the thermal conductivity of the collector bar results in higher heat transfer through the collector bar. Due to such increase in heat transfer, the ledge thickness, near to the metal-electrolyte interface, has increased by 2.1 cm and 5.4 cm for case-6 and case-7 respectively. For case-7, the lower ledge has grown significantly on the cathode surface extending into the anode shadow, which would reduce the cathode surface area for current flow.

The material modification of the collector bar has shown the worst impact on the thermal balance of pot in comparison to all other cases, whereas from the electrical analysis it was found to be most promising case for the energy reduction. Therefore, modifying the collector bar material property may require an optimal thermal conductivity value along with revamping of cathode lining material for increasing the thermal insulation of a low amperage cell.

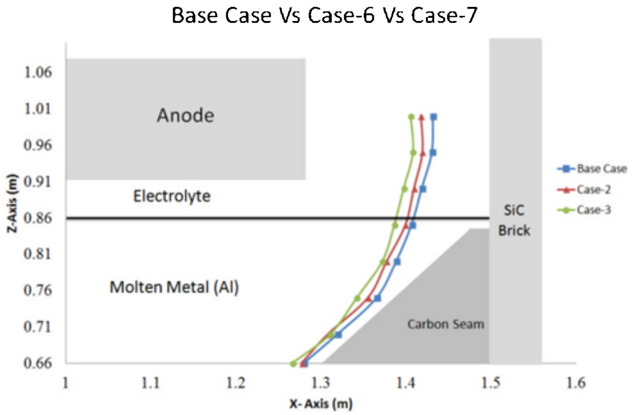

Figure 10: Ledge profile for material change of collector bar

Table 7 shows that for case 4 and 5, the cathode temperature gradient is decreased because of the increased thermal conductivity of the cathode material. However, a slight increase in the temperature at exit of collector bar results in little increase in heat loss to the surrounding through the collector bar. For case 6 and 7, the temperature gradients in cathode have increased significantly also the temperature at the exit of the collector bar has increased. This would lead to higher heat loss to the surrounding through the collector bar, and may increase the risk of formation of freeze on the cathode surface. For case-7, the superheat has decreased to significantly low value of 5.8^{0}C, which may adversely affect the cell performance.

Table 7: Thermal results for material modification

Cases	Calculated superheat in pot (^{0}C)	Cathode temperature (^{0}C)			Temperature at exit of Collector bar (^{0}C)
		Max	Min	$\Delta_{max-min}$	
Base	10.14	953	833	120	208
Case-4	9.99	953	859	94	209
Case-5	9.53	952	890	62	211
Case-6	8.31	951	757	194	225
Case-7	5.8	948	708	240	278

It is evident that increase in the cross-sectional area of the collector bar and increase in thermal conductivity of the collector bar enhances the chance of freeze formation on the cathode surface. In case of power interruption or power outage, higher thermal conductivity of collector bar may adversely affect the sustainability of pot for long duration.

Table 8 shows the summary of the cases considered for thermo-electric analysis. This describes the effect of the modifications with respect to the design and the material of cathode and collector bar, on electrical and thermal aspects of an 85kA cell.

Table 8: Summary of electrical and thermal analysis

Cases	Cathode voltage drop (volt)	Change in horizontal current (%)	Change in ledge thickness (cm)	Super heat in pot (^{0}C)	Cathode temp. $\Delta_{max-min}$ (^{0}C)	Temp. at exit of collector bar (^{0}C)
Base	0.287			10.14	120	208
1	0.299	-5.3%	+0.3	10.06	120	214
2	0.262	-7.8%	+1.0	9.59	139	211
3	0.223	-10.5%	+2.8	8.52	163	209
4	0.263	+8.0%	+0.8	9.99	94	209
5	0.234	+22.3%	+2.3	9.53	62	211
6	0.141	-74.0%	+2.1	8.31	194	225
7	0.089	-92.4%	+5.4	5.8	240	278

In future, the electromagnetic and MHD aspect for some of these cases would be carried out. This would be followed by the implementation in some trial pots for the proposed modification in cathode and collector bar.

Conclusions

In this study, the effect of change in the design and the material of the cathode and the collector bar of an 85 kA cell were analyzed for the cathode voltage drop, horizontal current in molten metal and the thermal balance of cell. Simulation results shows that horizontal currents reduces with decrease in height to width (H/W) ratio and with decrease in the electrical resistivity of the collector bar. Also it shows that reduction in the cathode voltage can be achieved by increased cross sectional area of collector bar and with lower electrical resistivity materials of cathode and collector bar.

Based on the thermal simulation studies, decrease in height to width ratio, while keeping same cross-sectional area, has diminutive effect on thermal balance. Further simulation studies shows that change in the cathode and collector bar material properties along with higher thermal conductivity increases the ledge thickness at the metal-bath interface, however it also extend the ledge toe under the shadow of anode. The cathode temperature gradient decreases with the increase in % graphitic content of the cathode material. The temperature gradient in cathode widen up with the increase in the cross-sectional area and with the increase in thermal conductivity of collector bar.

This simulation study provides an insight to energy reduction by design and material modification of cathode and collector bar, while considering the electrical and the thermal aspect of the cell.

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