# Impact of copper insert on low amperage aluminium reduction cell

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## Abstract

Copper insert in collector bars have been one of the recent research areas for energy reduction in aluminium smelters worldwide. Most of the research on copper inserts has been focused on high amperage cells, which are heat dissipative cells. Use of copper inserts in the collector bars significantly reduces horizontal currents, thus improving cell stability which facilitates energy reduction. However, use of copper inserts also enhances heat loss through collector bars, which could have an adverse impact on thermal balance of low amperage cell, since these cells are designed to be heat conservative in nature. Hence the use of copper insert in low amperage cells requires careful evaluation of thermal balance. In the present study, different designs of copper insert in the collector bar have been analyzed to see their impact on the horizontal current, cathode voltage drop and thermal balance. Simulations have been performed using a validated 3D thermo-electric model. Structural analysis has also been performed for these designs to check the deformation under the thermal stress. Simulation results show that use of copper inserts has potential of energy reduction in low amperage cell, provided that thermal balance of the cell is maintained.

**Keywords:** Collector bar copper insert; cathode lining; aluminium reduction cell; cell thermal balance.

## 1 Introduction

Aluminium smelting is an energy intensive process where energy cost is around 40 % of the total cost of aluminium production. Ever increasing energy price and lower London Metal Exchange (LME) price of aluminium have put significant pressure on worldwide smelters to take measures on energy reduction. The typical cell voltage distribution for aluminium reduction cell, given by Haupin [1], is shown in Table 1, which shows the potential areas for reducing the energy consumption.

**Table 1. Typical voltage breakup of an electrolytic cell**

| Cell Component | Voltage (V) |
|---|---|
| Anode voltage | 0.235 |
| Cathode voltage | 0.300 |
| External conductors | 0.160 |
| Bubble voltage | 0.259 |
| Electrolytic bath | 1.640 |
| Reaction voltage | 1.779 |
| **Total pot voltage** | **4.373** |

Flow of high current through the external busbar generates strong magnetic field in and around the cell. The electric current flowing through the molten metal and electrolyte, interact with the magnetic field and give rise to volumetric forces, known as Lorentz or electromagnetic forces. These forces are responsible for movement of the metal and the bath as well as for deformation of the metal-bath interface, which limits the reduction of inter-electrode gap also known as anode-to-cathode distance (ACD). Cryolite bath is a poor conductor of electricity, which result in maximum voltage drop in the ACD region of the cell. It is desirable to maintain ACD as low as possible while satisfying the heat balance requirement of the cell. The busbar configuration can also be changed to improve magnetic field and achieve better cell stability, however it is capital intensive [2]. Besides optimizing the magnetic field, reduction in the horizontal current is another way to improve the stability of cells and thus reduce ACD [3].

Worldwide many smelters have been evaluating the benefit of using copper inserts in the collector bar. Cu-insert collector bar is known to reduce generation of horizontal currents in the metal region thus improving the cell stability; it also decreases cathode voltage drop [4]. Most of the literature on copper inserts highlights its use in high amperage cells which have high heat loss. Use of copper insert in low amperage cell might adversely affect overall heat balance of low amperage cell, hence need proper evaluation before its use. This paper evaluates the use of copper inserts in low amperage cell with respect to electrical, thermal and structural aspect of the cell by performing simulation studies.

Since copper has much higher electrical conductivity than steel, it alters the electrical resistance path in the cathode assembly. This results in more uniform current distribution in the cathode block and in reduction of horizontal currents in the metal. Copper also reduces cathode voltage drop, and consequently, it reduces the heat generation and thus disturbs the thermal balance of the cell. Since these cells are low heat loss cells due to higher insulation in cell lining, any reduction in ACD enabled by improved cell stability further deteriorates the thermal balance. To compensate this,eventually, extra voltage would be required for stable cell operation. Therefore, the use of copper in the low amperage cell needs to be carefully analyzed before its use and thermal balance needs to adapt to modified conditions by optimizing cell design and process parameters accordingly. The increase in stress in cathode block generated from thermal expansion of copper needs to be evaluated for the structural integrity.
Figure **1** shows two designs of rectangular and cylindrical copper insert in the collector bar. In Case-1 copper insert is rectangular and placed near the top surface of the collector bar, whereas in Case-2 it is cylindrical and placed at the center of the steel collector bar. Along with these two, one unconventional design of copper insert, referred as Case-3 in subsequent sections, has also been analyzed. In each case the volume of copper was kept same and analyzed for electrical, thermal and structural stability of the cell.

Case-1

Case-2

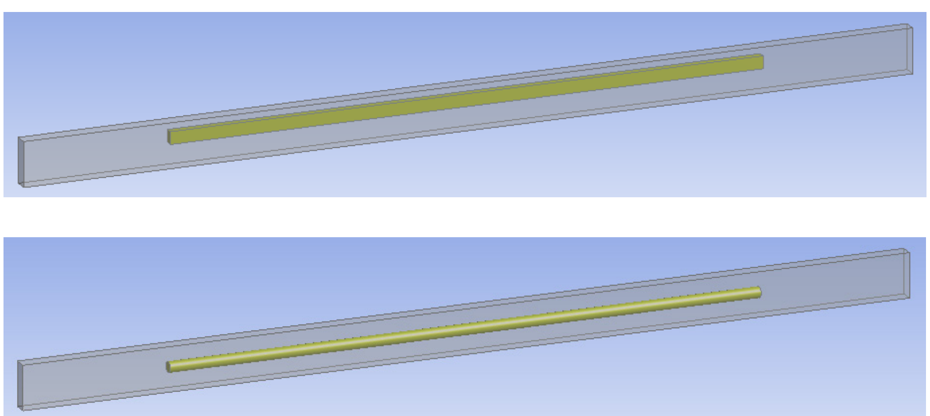

**Figure 1. Conventional design of copper insert collector bar.**

## Modeling approach

In recent years, computational modeling has played a pivotal role in the area of aluminium reduction cell development and performance improvement. In the present study electrical, thermal and structural simulations were performed for analyzing the three different designs of copper inserts in collector bars. For model development and simulations commercial software ANSYS was used. Figure 2 shows the geometry considered for thermo-electric and thermal-structural model. The origin of the co-ordinate system is at the center and bottom of the cell in the thermo-electric and thermal-structural model. X-axis, Y-axis and Z-axis are along the short side, the long side and the height of the aluminium reduction cell, respectively.

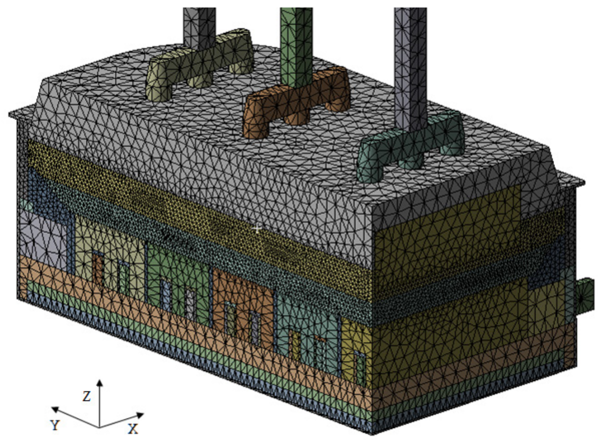


**Figure 2. Geometry and finite element mesh of the model.**

### 1.1 Thermal electrical model

In this study, 3D quarter cell, thermo-electric model developed for low amperage cell was used for analysis of these designs of copper insert. Thermo-electric model solves electrical and thermal equations simultaneously which are coupled through Joule heating term. More details regarding the governing equations, model development and its validation with the measurements, have been reported earlier by present authors [5]. Base case represents the validated model of present cell with steel collector bar.

### 1.2 Thermal structural model

A finite element 3D quarter cell model was developed for calculation of structural deformation of the cell lining material. Material non-linearity and temperature dependence were accounted for in the model. Temperatures obtained from the thermo-electric model were used as initial condition for structural model. To account for cathode swelling effect, equivalent pressure was applied on lower sidewall. Model provides information on deformation of various parts such as cell lining deformation, stress in cathode block due to collector bar thermal expansion, etc. Model prediction of cell lining deformation was validated with plant data.

## 2 Results and discussions

In this study, different designs of copper insert in collector bar were analyzed to understand their impact on the current distribution, the cathode voltage drop, the thermal balance and the structural integrity of the cell.

### 2.1 Electrical analysis

All cases of copper insert collector bar show reduction in horizontal current as well as in the cathode voltage drop, however there are some variations for different designs of copper inserts, which are explained in subsequent sections.

#### 2.1.1 Current distribution

Copper insert in collector bar provides reduction in horizontal current density. Such reduction in horizontal current also reduces the variation in vertical current density, making it more uniform in the cathode block. Figure 3 shows vertical current density variation over the half length of cathode block for different cases considered. For the base case with no copper insert, vertical current density varies significantly from the center of the cathode to the end of the cathode. Presence of copper insert in collector bar effectively reduces this variation and makes it more uniform.

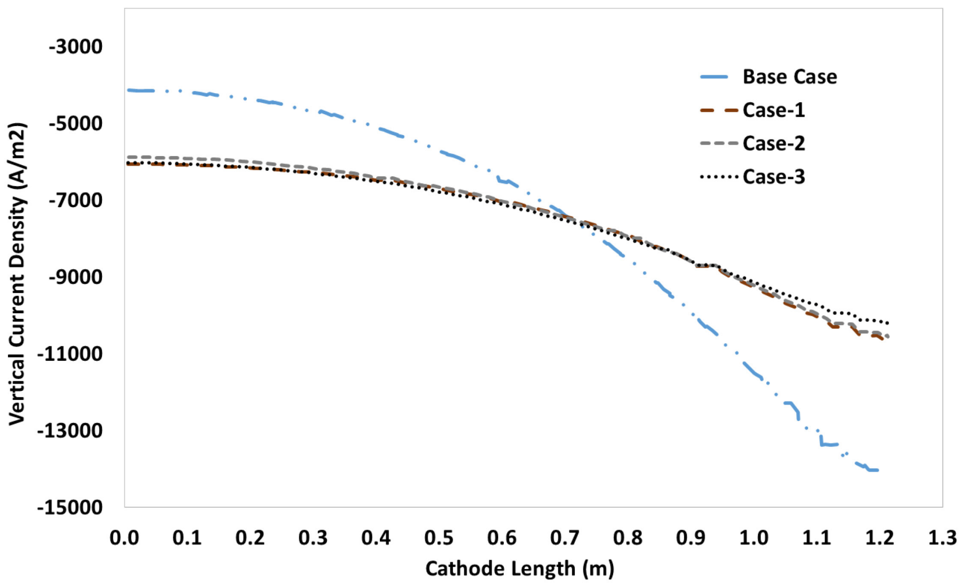


**Figure 3. Effect of copper insert collector bar on vertical current density.**

Table 2 shows the impact of copper insert designs on the vertical as well as horizontal current density in the metal region near to cathode surface. It shows that vertical current density increases at the center of cathode block and decreases near the ends of cathode block resulting in reduced variation in the vertical current density as well as reduction in the horizontal current density. Case-1 provides slightly higher reduction than Case-2 due to location of copper insert bar in the steel collector bar. The unconventional design of copper insert offers further improvement, in vertical and horizontal current density, with respect to Case-1 and Case-2.

**Table 2. Vertical current density variation in the metal region ($A/m^2$).**

| | Base case | Case-1 | Case-2 | Case-3 |
|---|---|---|---|---|
| Reduction in $\Delta_{max\text{-}min}$ of vertical current density (%) | - | 55.6 | 53.3 | 57.3 |
| Reduction in horizontal current (%) | - | 26.1 | 23.6 | 27.8 |

#### 2.1.2 Cathode voltage drop

Table 3 shows that there is reduction of cathode voltage drop in all the cases of copper insert collector bar. For Case-1 and Case-2 the voltage reduction is almost the same, however for unconventional design Case-3 voltage reduction is found to be comparatively lower than Case-1 and Case-2.

**Table 3. Cathode voltage drop variation for different design of copper insert**

| | Base case | Case-1 | Case-2 | Case-3 |
|---|---|---|---|---|
| Cathode Voltage Drop (mV) | 287 | 243 | 249 | 257 |

### 2.2 Thermal analysis

Thermo-electric simulations were performed for mentioned cases of copper insert collector bar along with base case. The results are discussed in the next section with respect to cathode temperature gradient, collector bar exit temperature, ledge profile and its thickness.

#### 2.2.1 Cathode temperature

Copper insert collector bar has effectively lower electrical resistivity which results in improvement in current distribution and reduced joule heat generation in the cathode. Also, due to presence of copper, effective thermal conductivity of copper insert collector bar increases. These changes contribute towards shifting the temperature isotherm location in the cathode block, resulting in reduced temperature gradient in the cathode block.

Table 4 shows the temperature gradient for the center cathode block of the cell. In Case-1 and Case-2 the temperature gradient in the cathode block decreases by approximately 4 °C, whereas for Case-3, by 7 °C. In case-1 and Case-2, collector bar end temperature increases by approximately 2 °C, which would increase the heat loss from collector bar. For Case-3, collector bar exit temperature is almost same as base case.

**Table 4. Impact of copper insert on cathode and collector bar temperature.**

| | Base case | Case-1 | Case-2 | Case-3 |
|---|---|---|---|---|
| Center cathode temperature $\Delta_{max-min}$ (°C) | 171.8 | 167.7 | 168.3 | 164.9 |
| Temperature at the end of collector bar (°C) | 202.3 | 204 | 203.7 | 202.5 |

#### 2.2.2 Ledge thickness

Reduced heat generation, shift of isotherm location and change in heat loss distribution, affect the ledge profile and its thickness. Figure 4 shows that for Case-1 and Case-2 lower ledge thickness increases, extending under the anode shadow, due to increased heat loss through the collector bar. This could potentially increase the MHD instability of the cell, unless it is corrected by modifying the cell lining insulation. Low amperage cell usually has higher insulation compared with high amperage cell; hence it might be difficult to further increase the insulation to correct the ledge profile. In Case-3, ledge profile shows improvement with only slight increase in ledge thickness compared with base case.

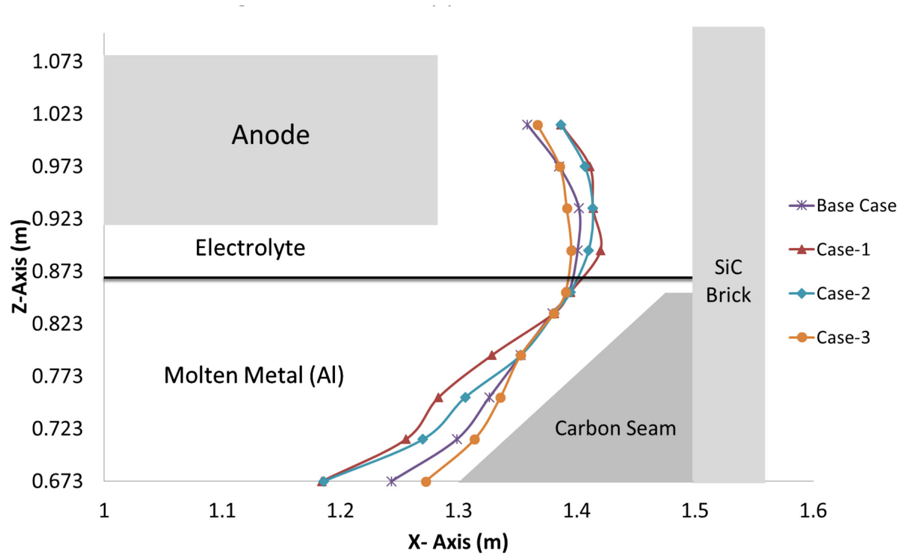


**Figure 4. Impact of different copper insert design on ledge profile.**

### 2.3 Structural analysis

Structural simulations were performed for these cases using 3D quarter cell thermal-structural model. Temperature values obtained from thermo-electric model are input for the calculation of thermal stress. Results were analyzed with respect to increase in stress level in the cathode block and change in deformation of cell lining including the steel shell.

#### 2.3.1 Cathode stress distribution

Figure 5 shows typical stress level in cathode block for base case. For different designs of copper insert, stress values in the cathode block was found to increase and maximum stress is observed in the cathode slot for collector bar.

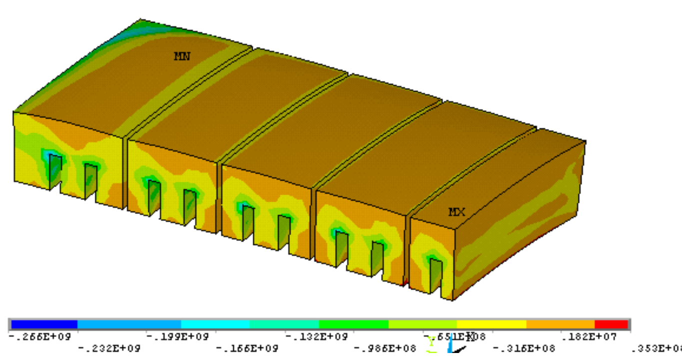


**Figure 5. Typical stress distribution in cathode block for base case.**

Table 5 shows the percentage increase in stress of cathode block due to various copper insert configurations. For Case-1 stress level increase is found to be higher compared with other cases due to rectangular shape and location of copper insert in steel collector bar. For Case-2 it is found to be comparatively lower than Case-1 due to cylindrical shape of copper-insert. For unconventional design of copper insert stress value is found to be lower than Case-1 and Case-2.

**Table 5. Increase in stress of cathode block due to different design of copper insert.**

| | Base Case | Case-1 | Case-2 | Case-3 |
|---|---|---|---|---|
| Increase in principle stress (%) | - | 10.4 | 8.1 | 1.7 |

### 2.3.2 Cell lining deformation

Figure 6 shows the cell lining deformation due to thermal stress and pressure generated from diffusion of various materials in the cathode lining. Maximum deformation is found to be approximately 25 mm and located at the center of long side wall. Similar deformation was observed in the representative running pot in the plant.

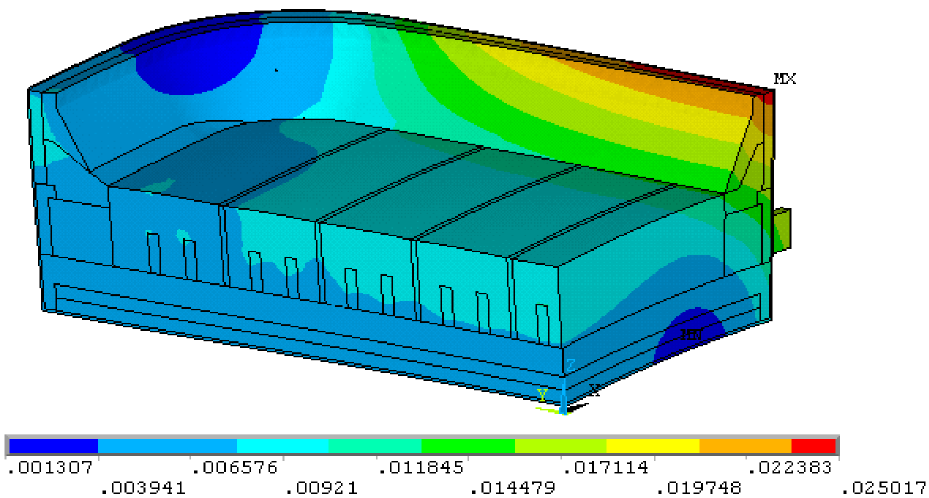


**Figure 6. Cell lining deformation for base case.**

Table 6 shows the simulated value of maximum deformation for various cases. It is found that different designs of copper insert have negligible impact on the maximum deformation of cell lining.

**Table 6. Cell lining deformation for different designs of copper inserts.**

| | Base Case | Case-1 | Case-2 | Case-3 |
|---|---|---|---|---|
| Maximum Deformation (mm) | 25.0 | 24.6 | 24.4 | 24.9 |

## 3 Conclusions

In this study, the effects of different designs of copper insert collector bars were analyzed to identify the potential of energy reduction in low amperage cell. Copper insert can provide energy saving in low amperage cell, if the thermal balance is maintained. Conventional designs of copper insert show slightly higher saving in cathode voltage drop compared with unconventional design. However, these designs have adverse impact on freeze profile with extension of freeze toe under the shadow of the anode, whereas unconventional copper insert design gives better freeze profile and thickness. Furthermore, any reduction in inter-electrode distance due to improvement in current distribution would require additional insulation to maintain the thermal balance and appropriate ledge profile and thickness. Thermal stress in the cathode block also increases due to presence of the copper insert, which could be optimized by modifying the copper insert design.

## Acknowledgement

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