THE IMPACT OF CATHODE AND COLLECTOR BAR DESIGNS ON CELL PERFORMANCE

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Abstract

Recently novel cathode and modified collector bar designs have been tested by the aluminum industry. Interesting achievements in terms of specific energy consumption have been shown. The designs weaknesses and strengths are discussed on the basis of three dimensional thermal, electrical and magneto-hydrodynamic modeling work. Some of the model predictions are validated by in-situ measurements in test cells. A good cathode design helps decrease the CVD and make the current density uniform in the liquid metal. Conversely highly structured cathodes may be critical for the operation and have short life even more so if the cell productivity is high. If some basic concepts are valid for all smelters, the optimum solution depends on the local cost structure.

Keywords: cathode design, copper inserts, collector bars, energy consumption, magneto-hydrodynamic

1. Introduction

Cathode design remains an interesting field of investigation to achieve lower anode to cathode distance (ACD) and hence lower specific energy consumption. The current density field in the liquid metal is strongly dependent on the cathode material, shape and collector bar design. A number of shapes have been presented and it is certainly of interest to analyze the impact from a thermo-electric and magneto-hydrodynamic point of view. Cathode designs and studies presented lately can be found in the literature [1-15]. Fig 1.1 shows two examples patented in 1994 by Prof. Vittorio de Nora.

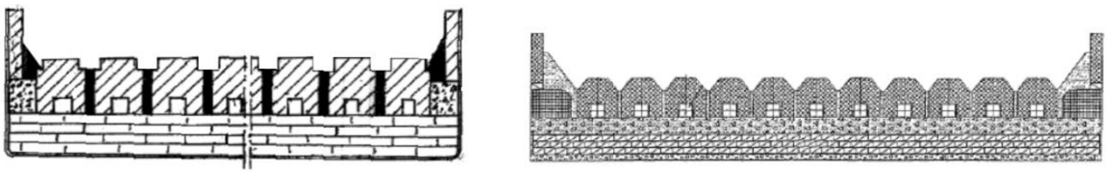


Fig 1.1: Shaped cathode surface "Vittorio de Nora" 1994

Fig 1.2 shows two examples of Novel Structural Cathodes (NSC) in use in China. Others can be found in reference [9]. The most important statements found in the literature concerning shaped cathodes can be summarized as follows:

- Smaller electromagnetic forces
- Smaller bath/metal deformation
- Lower cathode voltage drop (CVD)
- Horizontal current reduction
- Little impact on gas bubbles
- More uniform cathode current density
- Lower velocity field

- Increase of cell life
- Difficulty in operating cathode with grooves

Fig 1.2: NSC cells, 350 kA Qingtongxia smelter [7]

From a quantitative point of view, the most comprehensive results for NSC are summarized in Table 1.1:

Table 1.1: NSC cells [9]

	Amperage [kA]	Cell average voltage [V]	CE [%]	DC Power [kWh/t]
Qingtongxia "Traditional cathode"	350	4.05	91.5	13190
Huadong "Traditional cathode"	200	3.90	90.0	12913
Huadong NSC cells "First generation"	200	3.76	92.2	12146
Jiaozuo NSC cells "First generation"	280	3.73	90.4	12300
Qingtongxia NSC cells "First generation"	350	3.91	93.7	12435
Qingtongxia NSC cells "New generation"	350	3.88	96.0	12044

CSU (Central South University) together with Sichuan Qiya Aluminum Group published the results of two studies including industrial cells in [8] and mention 400 kA and 3.8 V during the period 2008-2010 and 400 kA, 3.72-3.8 V during 2009-2011. This means 12,200 kWh/t at 92% current efficiency.

Finally let us mention that the goal of the Chinese aluminum industry is to achieve 11,500 – 11,700 kWh/t. Other important aluminum producers even target 10,000 kWh/t. Remarkable progress has been achieved but significant steps remain before getting close to the last vision. Does it mean that the world aluminum industry will very soon move to "structured" cathodes? If so, which shape should be considered?

2. The Ideal Cathode

Each smelter certainly dreams of operating at 11,500 kWh/t or lower. However the aluminum industry is not only driven by the specific energy but obviously by the production cost. It is therefore with this objective in mind that one should analyze the implementation of a new cathode.

As mentioned, it is the cost of aluminum produced that is the most important parameter. One relevant parameter for the cell productivity is the tonnes of aluminum produced per square meter of cathode. Obviously the productivity will increase if the current is increased. This means that the current density in all conductive elements of the cell will increase and the same goes for the voltage. As a result the specific energy consumption will increase. In other words it is rather easy to achieve very low specific energy consumption given a very low current density in the cell and hence a low cathode productivity. Table 2.1 highlights the point by looking at each voltage component assuming the same electrical design for two levels of current in the cell. For the sake of simplicity, the resistance of each component is assumed to be constant. In fact, due to temperature effects, the resistance is slightly increasing with the current increase. The global trend remains however unchanged.

Table 2.1: High productivity versus low energy

Same technology, only thermal insulation differs Cell parameters	Unit	HIGH PRODUCTIVITY CELL	LOW ENERGY CELL
Amperage	kA	360.0	300.0
Gross volt	V	4.15	3.75
Current Efficiency	%	95.0	95.0
Busbars	mV	230	192
Anodes	mV	260	216
Cathode	mV	250	209
Anodic current density (geometry	A/cm2	0.88	0.74
Anodic reaction overvoltage	V	0.503	0.485
Anodic concentration overvoltage	V	0.052	0.039
Cathodic overvoltage	V	0.088	0.074
Gas bubbles / Thonstad-Vogt	V	0.186	0.156
Bath	V	1.330	1.129
ACD	cm	4.1	4.1
Production	kg/day	2755	2296
Specific energy consumption	kWh/kg	13.02	11.76
Internal heat generation	KW	674	453
Cathode productivity	kg/m2day	62.6	52.2

Table 2.1 shows that by operating at the same ACD, the specific energy can be decreased from 13,020 kWh/t to 11,760 kWh/t only due to the impact of the current density on the different voltage components. Operation at low specific energy leads to low heat loss (busbars not considered). In the presented case it is a decrease of 674 - 453= 221 kW. This may be a challenge by itself as a strong thermal insulation of the cell sides cannot be used as it is not compatible with side ledge protection.

Let us comment on further aspects of the cathode. Fig 2.1 shows important characteristics that any cathode design should demonstrate and some driving parameters to achieve them. The CVD should be low as it contributes to the cell voltage and to the energy consumption. The first trivial parameter for the CVD is the height of the cathode, the lower the better for the CVD but maybe not for the cathode life. A low CVD can be achieved with highly conductive materials and this speaks for graphite. A large collector bars cross-section can also help decrease the CVD and even better, the use of copper inserts will further decrease the cathode resistance. The second very important characteristic is the impact of the cathode design on the current density inside the liquid metal. The cathode can significantly contribute to optimizing the magneto-hydrodynamic state of the cell due to the interaction of the current density with the existing magnetic field. The ideal cathode would lead the current vertically from the anodes to the cathode avoiding any horizontal current inside the liquid metal. This can be partially achieved by using the same parameters as for decreasing the specific energy but can be improved by insulating the collector bars which will be detrimental to the CVD. A uniform current density in the liquid metal will give the potential of decreasing the ACD while keeping a stable bath-metal interface. The current will be increased to realize a constant heat production in the cell and to enhance the cell productivity. If the energy is the driving parameter, then the thermal insulation of the cell must be revisited and a lower specific energy can be achieved. Finally the cathode must demonstrate a “good” cell life. In other words, the lining cost including all spent pot lining treatments must be competitive. The good news is that the homogeneous current density in the metal also improves the current density at the cathode surface. As the electro-erosion is strongly influenced by the current density this helps the cathode life. On the opposite, graphitic material is weaker to electro-erosion [16] and obviously a sufficient cathode height will help increase the cathode life. Therefore a compromise must be found between all parameters with the aim of minimizing the metal cost and not the cathode cost.

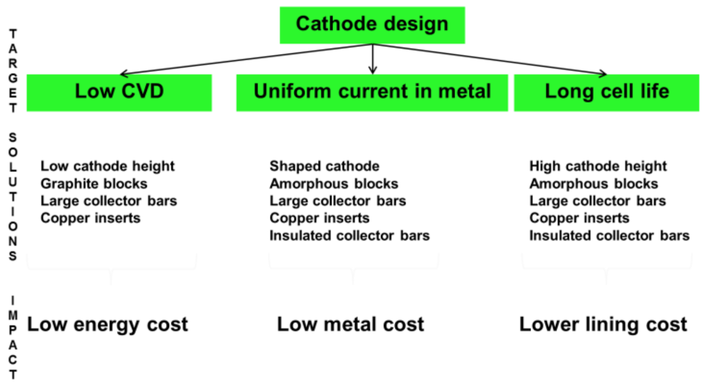


Fig 2.1: Cathode design objectives and parameters

The metal cost is also impacted by the current efficiency which depends on the cell design and operating practices. In particular, the anode quality and anode demand must be reviewed when increasing the current [17]. Also the choice of bath composition may change the ACD and heat balance for the same technology.

In order to quantify the impact of the cathode design on the current density at the surface of the cathode, a number of cases are considered. All cases assume the same graphite quality and the variation of the heat flux through the collector bar with respect to the reference case is maximum 10%. Fig 2.2 shows typical collector bars with its cast iron around the bar. The corresponding CVD is 325 mV and will represent our reference.

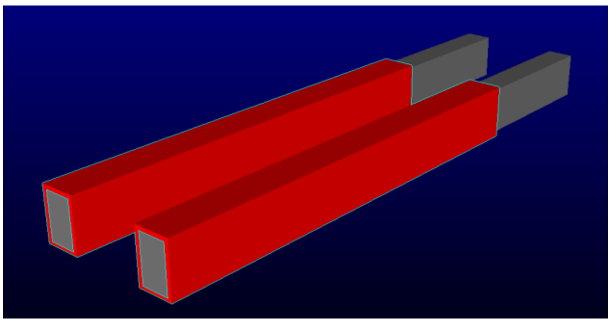
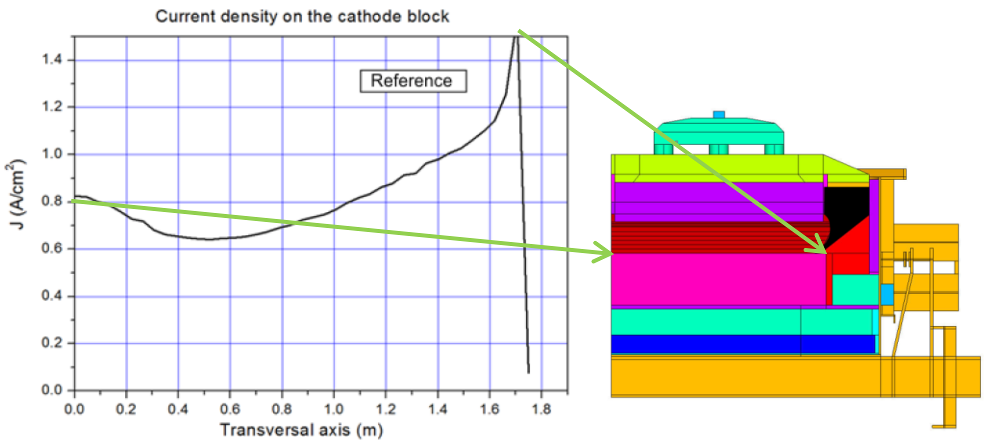


Fig 2.2: Collector bars with standard cast iron (reference)

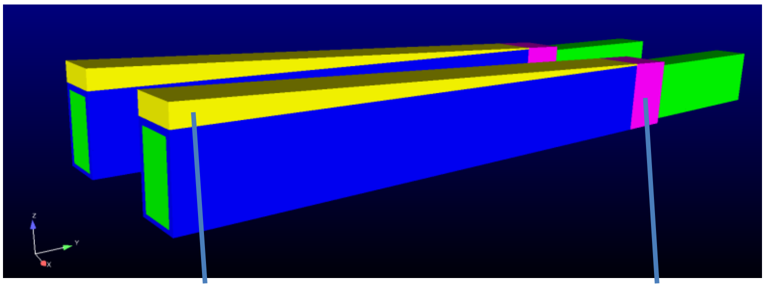
This particular cell would operate with a current density at the cathode surface as shown in Fig 2.3. The current density is about 0.8 A/cm^2 at the center, it is going down close to 0.6 A/cm^2 before increasing to 1.5 A/cm^2 at the edge of the cathode. This typical current density profile leads to the known “W shape” of the cathode surface at autopsy time. The electro-erosion is the strongest where the current density is the highest.



CVD = 325 mV

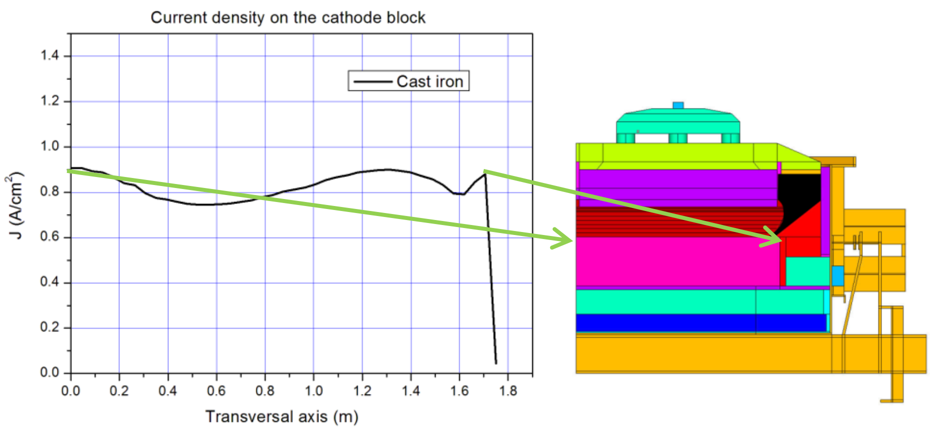
Fig 2.3: Reference, current density at the cathode surface (from cell center to the ledge)

A solution has been proposed suggesting the increase of the cast iron level above the collector bar when moving towards the cathode center. If combined with the right electrical insulation at the start of the collector bar this leads to an interesting result (Fig 2.4). The current density is always lower than 1 A/cm^2 which is a good target (Fig 2.5). However, this solution increases the CVD by 33 mV to 358 mV. The increase in voltage is related to the electrical insulation around the collector bar pushing the current towards the center. If the insulation is not used, the amount of current flowing in the cathode close to the ledge remains too important. The global cell voltage could be equal or lower than the reference due to the improved magneto-hydrodynamic state of the cell since the cell could be operated at lower ACD.



Cast iron 50 mm Electrical insulation

Fig 2.4: Variable cast iron above collector bar



CVD = 358 mV (+33 mV)

Fig 2.5: Variable cast iron, current density at the cathode surface

The next solution consists in using a copper insert combined with an insulating area (Fig 2.6). Fig 2.7 shows that the current density remains always under 1 A/cm^2 and is rather equivalent to the previous design. However the CVD is 301 mV which is 57 mV lower than for the cast iron solution. The copper insert solution can be therefore qualified as better from a technical point of view.

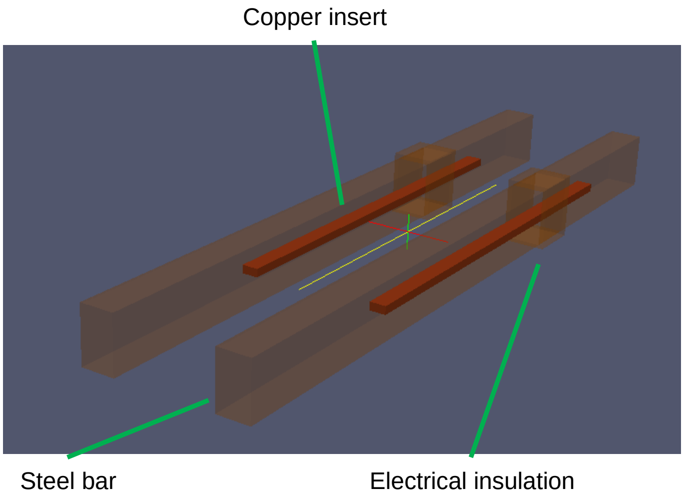
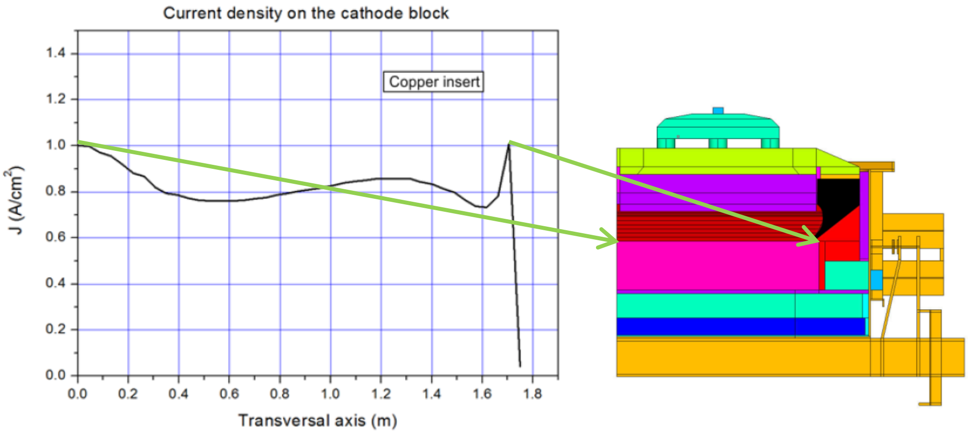


Fig 2.6: Copper insert inside collector bar



CVD = 301 mV (- 24 mV)

Fig 2.7: Copper insert, current density at the cathode surface

The next option consists in using a variable copper cross-section. Fig 2.8 shows the copper cross-section variation over the bar length. This solution is technically more difficult to implement and the resulting CVD (312 mV) is 10 mV higher when compared to the constant copper insert. The reason for the larger CVD is the high current density at the thinner end of the copper insert. The cathode current distribution looks good but it is comparable to the one of the other copper insert solution (Fig 2.9).

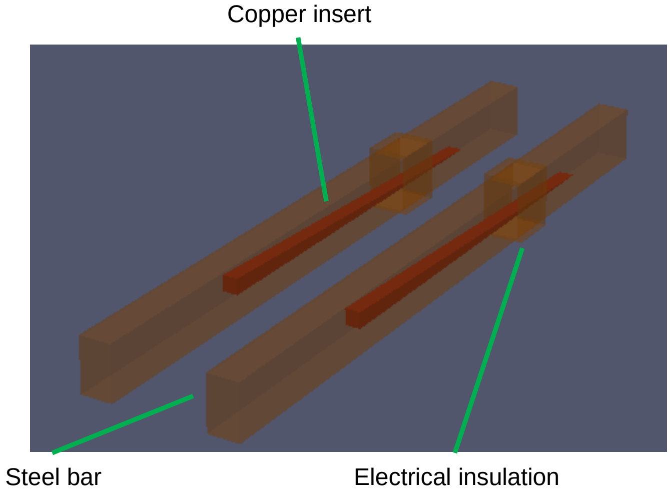
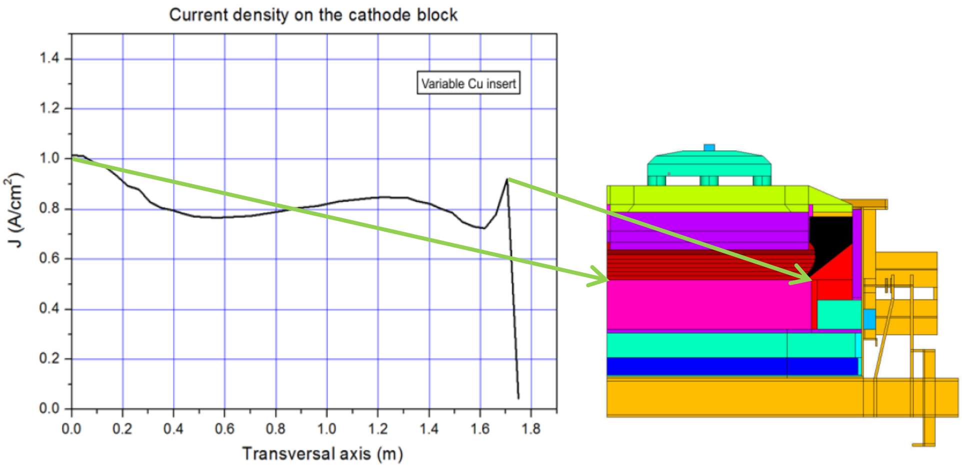


Fig 2.8: Variable copper insert inside collector bar



CVD = 312 mV (-13 mV)

Fig 2.9: Variable copper insert, current density at the cathode surface

One further option consists of modifying the cathode shape. Fig 2.10 illustrates the concept [12]. The collector bars are insulated electrically at the edge of the cathode. The resulting CVD is 356 mV. The solution can be considered equivalent from the electrical point of view to the variable cast iron solution. However, due the higher metal pad at the center of the cell, the magneto-hydrodynamic cell stability is improved. Assuming the same total mass of liquid metal, the side metal level would be lower helping at saving heat losses. This solution is therefore preferable. This is due to the fact that the heat flux between liquid metal and ledge is higher than between bath and ledge.

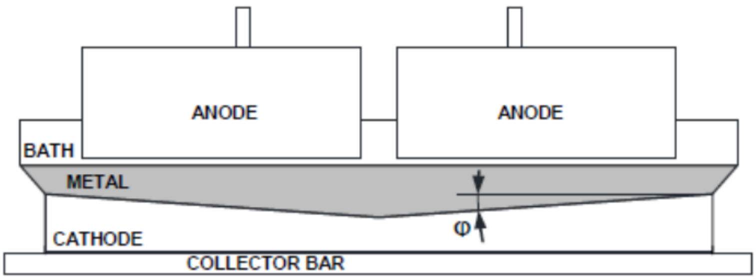
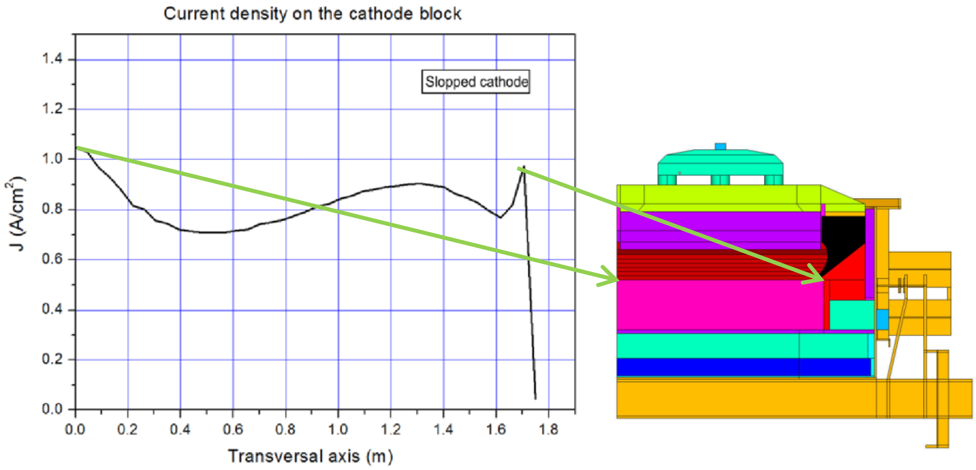


Fig 2.10: Slope of the cathode surface



CVD = 356 mV (+31 mV)

Fig 2.11: Slope of the cathode surface, current density at the cathode surface

Fig 2.12 summarizes the impact on the cathode current density for the five cases. The solutions are rather equivalent but the use of copper shows the best result in term of CVD as shown in Table 2.2.

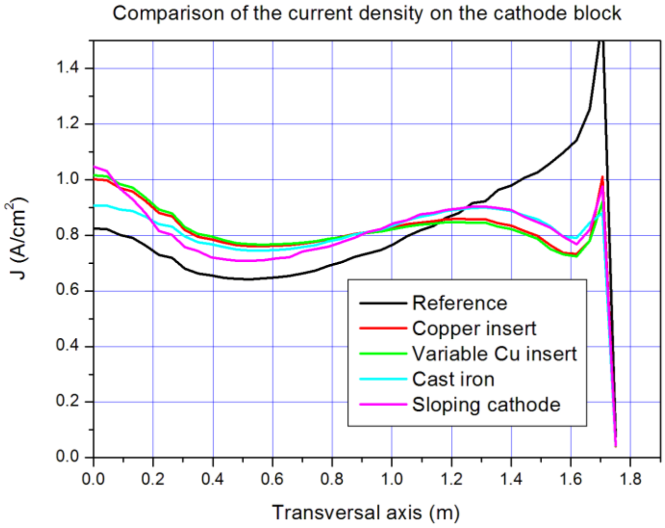


Fig 2.12: Comparison of the current density on the cathode block for the five cases.

Table 2.2: Comparison of the CVD for the five cases

Case	CVD [mV]
Reference	325
Copper insert	301
Variable Cu insert	312
Cast iron	358
Slope of the cathode surface	356

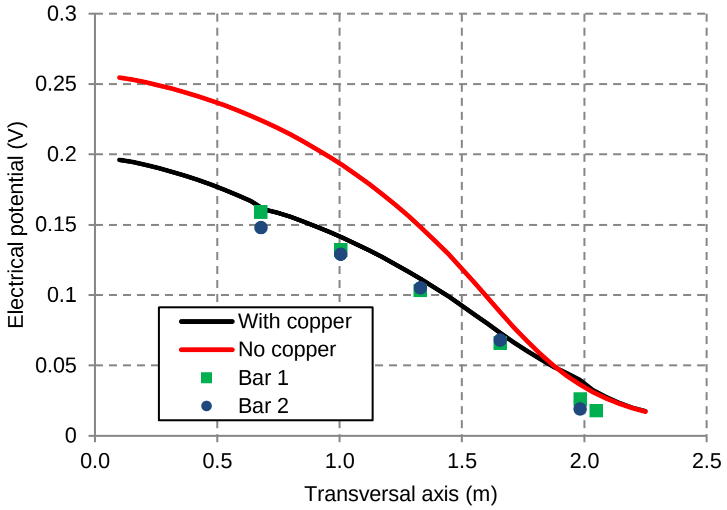


Fig 2.13: Calculated electrical potential along the collector bar with and without copper insert together with measured electrical potentials in two collector bars.

In Figure 2.13, in-situ electrical potential measurements in collector bars confirm the model predictions in terms of CVD for the copper inserts case. From the electrical potential data, the current density along the collector bar can be inferred validating the more uniform current density in the cathode obtained numerically.

Coming back to the NSC solutions, one should not forget that the current is flowing in between the elevated cathode since the liquid metal is by far more conductive than the cathode itself. As a result, the cathode current density is strongly increased when compared to the one of planar cathodes. The current density at the surface of the cathode may range from 1.2 A/cm^2 to 2.6 A/cm^2 depending on the length and number of channels. This is about twice the value found on a smooth surface. Should we conclude that the electro-erosion will be twice as fast? In addition the height of NSC is lower. What can we conclude on the cathode life? The high current density at the edge of the cathode (close to the ledge profile) appears very clearly on the reference cell. The three NSC designs show high current densities (> 1.5 A/cm^2) in some locations. A high electro-erosion should be expected in these locations and these designs may be critical in our point of view.

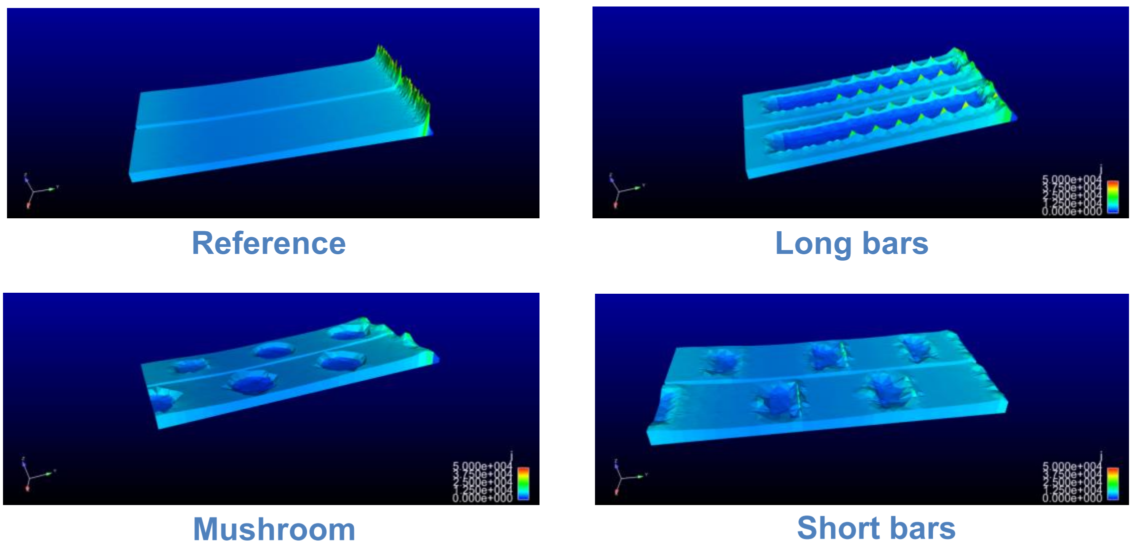


Fig 2.14: NSC cathodes, current density at the cathode surface

The current density in the liquid metal and at the cathode surface is a very important parameter but it should be considered together with the global cell magneto-hydrodynamic (MHD) state. Indeed, the operating point of the cell depends also on the external busbars which define the basic structure of the induction magnetic field in the cell. Figure 2.15 reminds the importance of the external busbars using a “standard” cathode on the magneto-hydrodynamic stability for a side by side cell. It demonstrates the potential of increasing the current at constant internal heat production. The use of copper inserts in the collector bars further helps improve the cell magneto-hydrodynamic stability. The impact of the copper inserts is clear although not as important as the busbars effect.

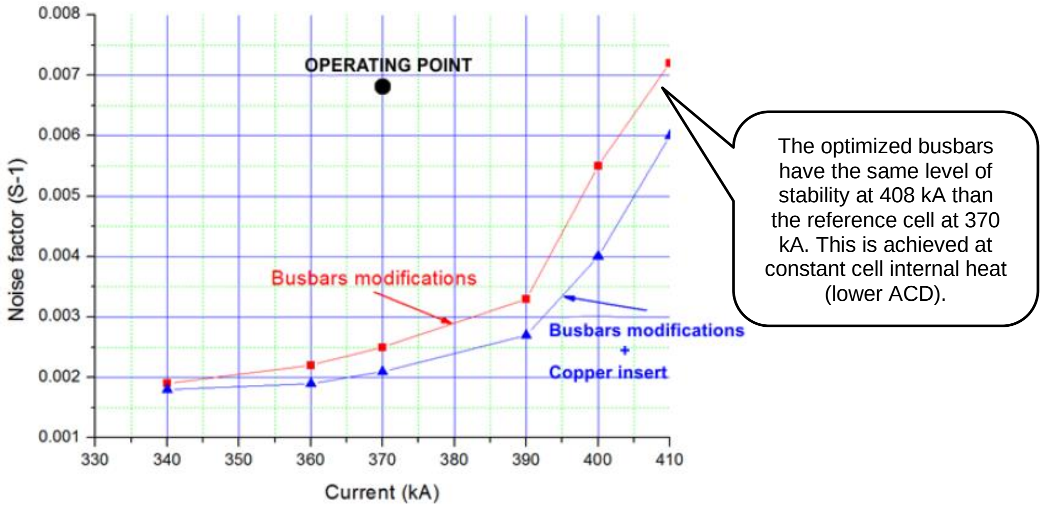


Fig 2.15: Impact of copper insert in the collector bar on the cell MHD stability

In this example, the specific energy is decreased by 500 kWh/t when moving from 370 kA to 400 kA. The combined use of optimized busbars, optimized collector bars and the adequate NSC cathode can easily lead to a decrease of the specific energy above 1,000 kWh/t. Figure 2.16 shows that the metal velocity field is strongly affected by copper inserts in the collector bars (maximum in the cell decreases from 25 cm/s to 6 cm/s). It also decreases the metal upheaval from 8.6 cm to 3.1 cm.

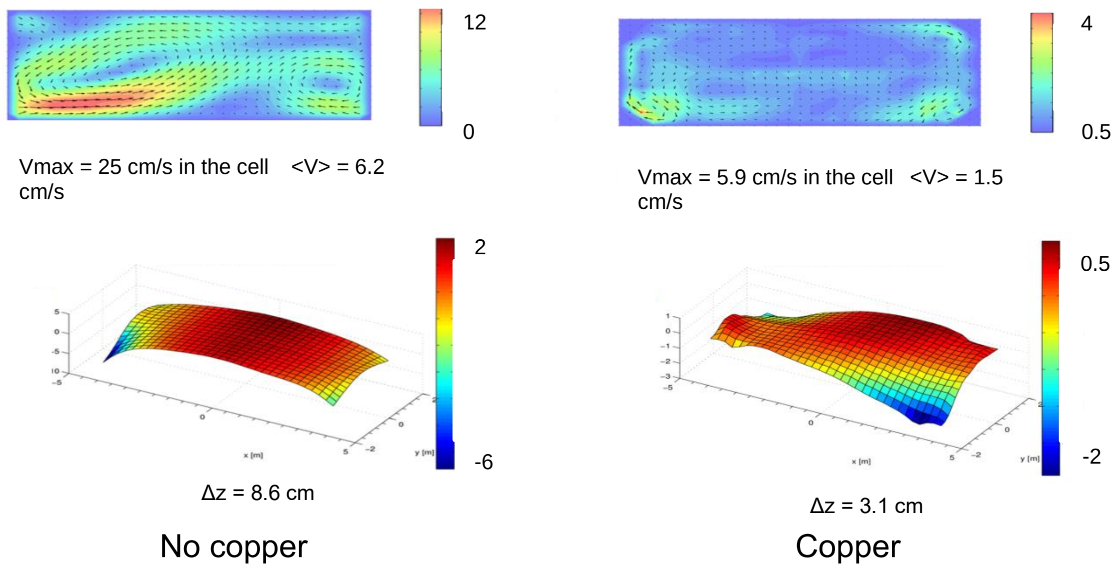


Fig 2.16: Impact of copper insert in the collector bar on the metal velocity field and metal upheaval

3. Conclusions

There are many ways to optimize the cell productivity of any given technology. The cathode design gives clearly a good potential. However, one should not forget to consider the basic busbars system which defines the ground on which the technology is working.

A good cathode design may help decreasing the CVD and the bath voltage significantly. The combination of both may represent more than 1,000 kWh/t specific energy saving together with an increase of the cell productivity. The lowest voltage or lowest specific energy consumption might not represent the highest benefit for the cell. Each smelter must define its own route depending on the local material and energy cost. Highly structured cathodes might be very critical for the operation and might have very short life even more so if the cell productivity is high. Last but not least, the anodes quality needs to follow the current increase.

4. References

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