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ENERGY SAVINGS IN ALUMINUM ELECTROLYSIS CELLS: EFFECT OF THE CATHODE DESIGN

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Abstract

Non uniform current distribution inside aluminum electrolysis cells is responsible for energy losses, a phenomena impacting on both the economy and the environment. Indeed, non uniform distribution induces premature wear of the cathode surface and triggers magneto-hydro-dynamic instabilities in the molten aluminum of the cell. The present study addresses this problem by examining the effect of the cathode shape and design on the current distribution. A computational methodology based on a finite element method is developed. It is then employed to determine the optimal cathode design, i.e., the design that minimizes the energy losses and maximizes the lifetime of the cell. The effect of various design parameters on the current distribution is highlighted. Their economic impacts on the operation of the cell are also assessed.

Introduction

Non uniform current densities inside electrolysis cells contribute to the reduction of their lifetime. Not only are these currents responsible for the presence of undesirable wavelets at the electrolyte/aluminum interface, but they also accelerate the electrochemical erosion of the cathode.

The present paper examines this erosion problem from the design point of view of the cathode block. A three dimensional finite element model for the cathode of an AP-30 cell is first developed. The model is then used to investigate the effect of the current density inside the cathode on its erosion rate (Fig.1). These findings will lead to a predictive model for the lifetime of the cathode. Design modifications for the collector bar/cathode block assembly are then proposed and their economic impacts on the operation of the cell are assessed.

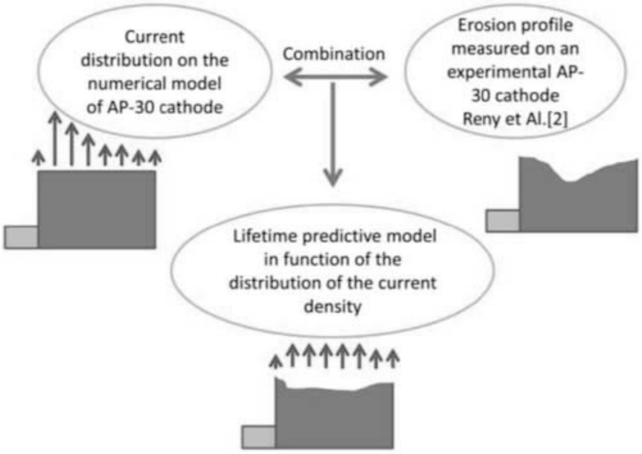

Figure 1- Schematic representation of the method used to investigate the effect of the current density on the lifetime of a block

Litterature review

The main factors responsible for the premature erosion of cathode blocks inside electrolysis cells are thoroughly discussed in Sorlie [1]. According to Reny et al. [2], the erosion of the cathode is dictated by the electric current flowing at its surface. On the other hand, the magneto-hydrodynamics studies conducted by Das et al. [3] and Li et al. [4] have shown that the non uniform current density inside the molten metal also play a role on the magneto-hydro-dynamic (MHD) instabilities of the cell. Von Kaenel et Antille [5] have examined the effect of the shape of the cathode on the electric stability of the metal and have proposed a design that makes the current density more uniform throughout the entire cell. None of these studies however have been able to clearly establish the relation between the current density and the erosion rate of the cathode.

Dupuis [6] has tackled this problem and came up with a correlation for the lifetime of a cathode block in terms of the current density. This correlation, which rests on the overall current density, predicts the maximum erosion rate. It ignores however the erosion profile along the cathode length. The intent of the present paper is to remedy this shortcoming by proposing a full thermo-mechanical model for the erosion of the cathode and to use it to assess the economical potential of various designs aiming at uniformizing the current density at the cathode surface.

Numerical Model

A schematic of the block assembly for an AP-30 cell is depicted in Fig. 2. The numerical grid comprises 270 000 parallelepipedic finite elements of 2 cm edge. The collector bar is made of carbon steel sealed with cast iron. The cathode block is made of graphitized carbon. The liquid at the cathode surface, which is a mixture of liquid aluminum and ledge, is represented by a layer of what we call a pseudo-material. The thermal as well as the electric properties of the pseudo-material are the temperature dependent properties, reflecting the properties of molten aluminum at higher temperatures and that of the ledge at lower temperatures.

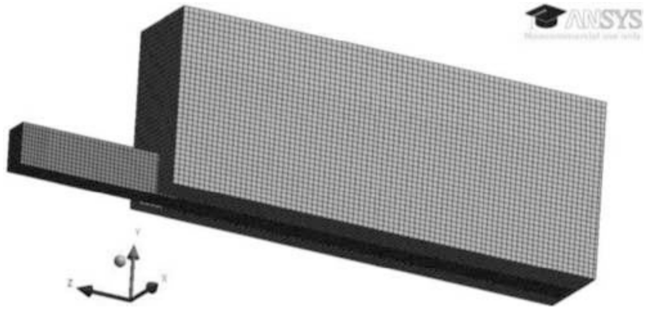

Figure 2 – Schematic representation of the cathode for an AP-30 cell

Based on the aforementioned observations, the governing equations for the conservation of energy and of the electric charge may be stated as:

$$\rho c\left(\frac{\partial T}{\partial t}+\{V\}^{T}+\{L\}T\right)+\{L\}^{T}\{q\}=\ddot{q} \qquad (1)$$

$$\nabla\left[\{J\}+\left\{\frac{\partial D}{\partial t}\right\}\right]=0 \qquad (2)$$

Where ρ is the density; c is the specific heat; T is the temperature; t is the time; V is the velocity vector; L is a vector operator for partial derivate; q is the heat flux vector; $\ddot{q}$ is the heat generation rate per unit volume representing the Joule effect; J is the total current density vector and D is the electric flux density vector.

The above equations are subjected to the boundary conditions identified in Fig. 3 and summarized in Table 1.

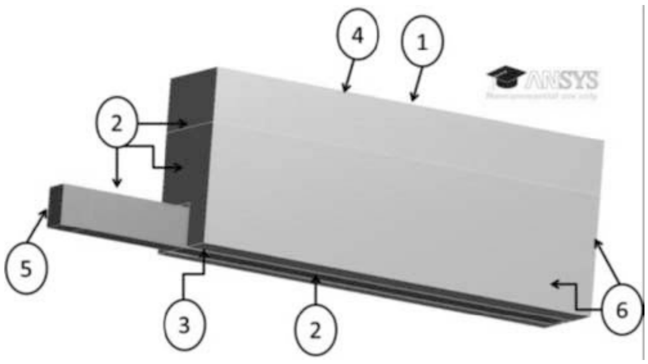

Fig. 3 – Identification of the boundaries

Table 1 – Boundary conditions

1	Fixed temperature.
2	Convection heat transfer.
3	Fixed electric contact resistance at the sealed joint.
4	Fixed voltage.
5	Fixed current.
6	Symmetry for heat transfer and electric current.

Once the temperature and the electric current distributions have been predicted from the numerical solution of Eqs. (1-2), the erosion profile of the cathode (and therefore its lifetime) may be determined from the current density versus erosion profile measured at Alouette Aluminum Co. by Reny et al. [2] (Fig. 4).

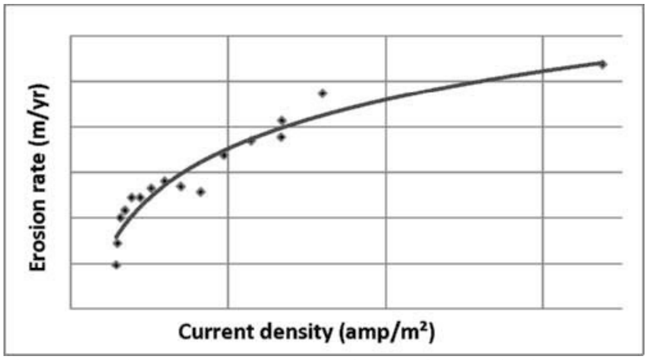

Fig. 4 – Erosion rate versus current density for a cathode

For the sake of the present analysis, it is assumed that the erosion rate and the CVD remain constant for the entire lifetime of the cathode. Additional analysis considering variable erosion rate showed minor differences and almost no impact on the prediction of the cell life.

Optimization model

The aim of the optimization analysis is to find the design for the collector bar/cathode block assembly which yields the most uniform current density, i.e., the current density that maximizes the lifetime of the cathode (Fig. 4). Moreover, the analysis takes into account the economic aspects by maximizing the following cost function.

$$AE_{economy}=AE_{AP-30\ Ref\ Model}-AE_{modified\ model} \qquad (3)$$

The cost function accounts for the construction and the start up of the electrolysis cell, the additional machining, the cost of the materials and the marginal electricity consumption. For comparison purposes, the annual equivalent cash flow (AE) is estimated for each design. As a result, the cost function represents the annual savings produced by the optimum design with respect to the actual AP-30 reference cell.

The optimization analysis was conducted for the ten geometric parameters shown in Fig. 5. Over 300 full numerical simulations per case study were carried out, each simulation requiring no less than 20 minutes of CPU time on four 3,2 GHz parallel processors.

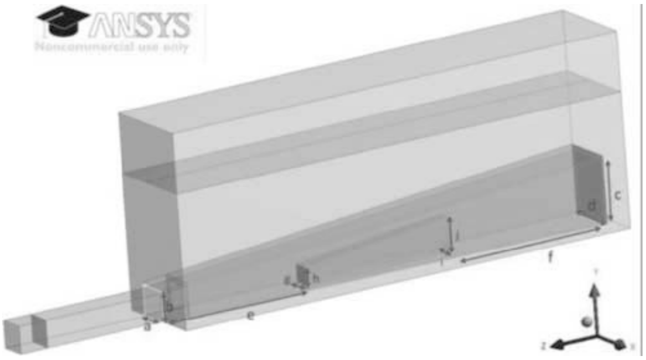

Fig. 5 – Geometric parameters examined.

Once all the numerical simulations for a given case are completed, a second order polynomial function is generated to approximate the behavior of the various parameters on the magnitude of the cost function. Through the Workbench platform, different optimization techniques are then employed to determine the optimal design: the screening approach, the MOGA approach (genetic algorithm) and the NLPQL approach (gradient based). The two first methods are better to locate the global optimum and the third one is more suitable for the refinement.

Results and discussion

The main results of the optimization study have been gathered and summarized in the following four cases:

Case no. 1: Rectangular Collector Bar and Copper Insert

In case no. 1, the shape of the collector bar and that of the copper insert remains rectangular. The predicted optimum geometric parameters are reported in Table 2. The corresponding operating characteristics of the cell are summarized in Table 3. Fig. 6 provides an example of the current density inside the cathode block with a copper insert (good electric conductor).

Table 2 – Optimum dimensions of the cathode block (Case no. 1)

Parameter	With a copper insert **(m)**	Without a copper insert **(m)**
Height of the bar (a,c)	0.07	0.13
Width of the bar (b,d)	0.20	0.20
Length of the insert	0.90	
Height of the insert (h,j)	0.05	
Width of the insert (g,i)	0.05	

Table 3- Operating characteristics (Case no. 1)

Model Output	Copper insert **(predictions)**	No copper insert **(predictions)**
CVD difference from AP-30 ref model	-39 mV	-68 mV
Lifetime (% comparison with AP-30 Ref Model)	7.75 yrs (+ 50%)	6.25 yrs (+ 20%)
Copper volume	0.0025 m³	---
AE economy	+ 19177 $	+ 16859 $

(% comparison with AP-30 Ref Model)	+17%	+15%

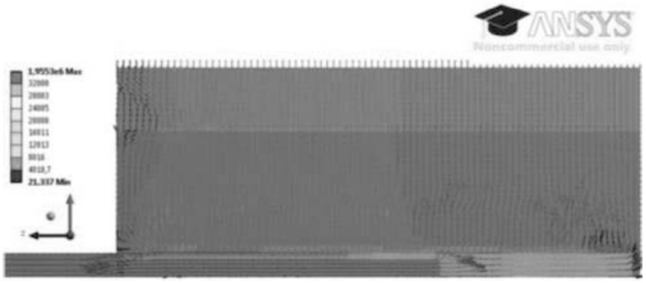

Fig. 6 – Current density through the cathode with an embedded copper bar (Case no. 1).

The presence of the ledge is highlighted by a zone of high electric resistivity. It is expected that the increased mass of carbon and the relatively uniformed current density at the surface of the cathode will prolong the lifetime of the cathode.

The two optimums found here are better than the reference model, based on the cost function. The copper design has a better lifetime, thanks to its larger aspect ratio (large bar of small height). On the other side, the non-copper design operates at a lower CVD due to a taller bar with its lower contact resistance on the sides. The copper insert helps to get uniform current density through the block (Fig. 6), which also leads to a lifetime improvement. However, the limited size of the copper insert (which is a good electric conductor) doesn't compensate for the difference of height with the non-copper design on the CVD.

Case no. 2 : Collector Bar from the Reference Model (same dimensions) with a Copper Insert

In this case, a copper insert is added to the collector bar of an AP-30 electrolysis cell (Fig. 7). The predicted optimum geometric parameters are reported in Table 4. The corresponding operating characteristics of the cell are summarized in Table 5.

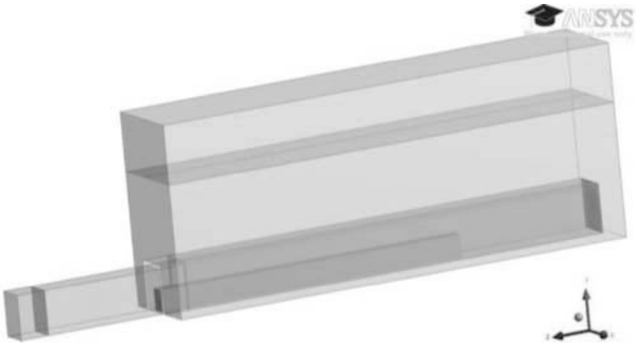

Fig. 7 – Cathode block for case no. 2

Table 4 - Optimum dimensions of the cathode block (Case no. 2)

Parameters	Dimensions (m)
Length insert	1.1
Width insert (h)	0,05
Height insert (g)	0,075
Height insert (i)	0.075

Width insert (j)	0,05

Table 5 - Operating characteristics (Case no. 2)

Model Output	Predictions
CVD difference from AP-30 ref model	-59 mV
Lifetime (% comparison with AP-30 Ref Model	6.25 yrs (+ 20%)
Copper volume	0.0041 m³
AE economy (% comparison with AP-30 Ref Model)	+ 9860 \$ + 9%

In spite of the fact that the AE economy is less than that for Case no.1, the benefits of adding a copper insert to the collector bar are unquestionable.

Case no. 3 : Uniformity of the Current Density on the Lifetime

This case focuses on the effect of the uniformity of the current density on the lifetime of the AP-30 cathode. The main results are gathered in Table 6. It is found that (1) by increasing the contact resistance by 50%, (2) by extending the sealed joint 0,23 m towards the center of the cell and (3) by adding copper to the collector bar, the lifetime of the cathode may be substantially prolonged.

Table 6 – Predicted operating characteristics (Case no. 3)

Model Output	Predictions
CVD difference from AP-30 ref model	+33 mV
Lifetime (% comparison with AP-30 Ref Model)	8.125 ans (+ 57%)
Copper volume	0.0210 m³
AE economy (% comparison with AP-30 Ref Model)	-11 771 \$ - 10%

The uniform current density depicted in Fig. 8 is at the origin of a 57% lifetime improvement for the AP-30 cathode. It shows that such an improvement is possible while keeping the same bar dimensions. The CVD has however increased, having an important impact on the operating costs of the cell. Overall, the cost function shows that the AP-30 reference model is better, because of much important impact of higher CVD and construction costs on the cost function. It might however be interesting to wonder what the cost function would become if the benefits of uniform current density on the cell stability would have been accounted for.

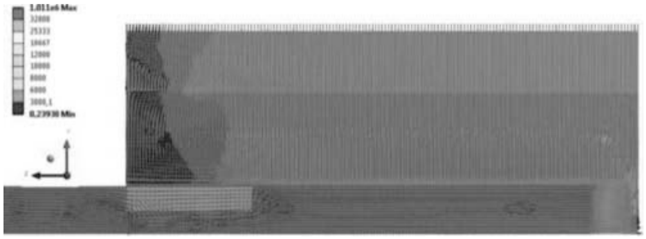

Fig. 8 – Optimum current density for an AP-30 cathode (Case no. 3).

Case no. 4 : Optimum Lifetime with a Constant CVD

Case no. 4 considers the possibility of prolonging the lifetime of the cathode while keeping a fixed CVD. The dimensions of the collector bar and those of the copper insert may however vary. The predicted optimum cathode block is shown in Fig. 9. The related geometric parameters are reported in Table 7. Its main characteristics are summarized in Table 8. Results have revealed that the lifetime of the optimum cathode may be prolonged by 75% with respect to that of the reference cathode. This is due to the fact that the shape of the optimum cathode tends to move the current distribution towards the center of the cell. Moreover, the copper insert reduces the electric resistance in the horizontal direction thereby promoting a more uniform current distribution (Fig.10).

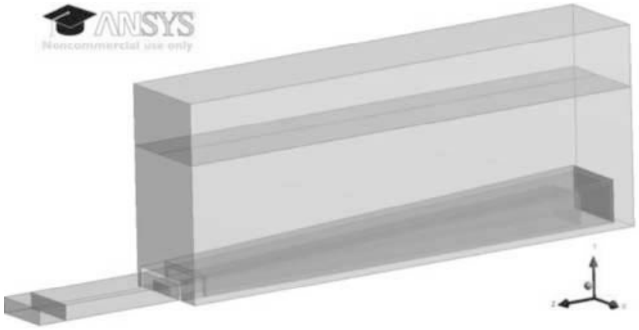

Figure 9 – Optimum shape of the cathode block. The CVD is fixed.

Table 7 - Optimum dimensions of the cathode block (Case no.4)

Parameter	Dimensions (m)
Height bar (a)	0,05
Height bar (c)	0,125
Width bar (b)	0,2
Width bar (d)	0,2
Length insert	1,5
Height insert (h)	0,035
Hauteur insert (j)	0,1
Largeur insert (g)	0,1
Largeur insert (i)	0,15

Tableau 8 - – Predicted operating characteristics (Case no. 4)

Model Output	Valeurs calculées
CVD difference from	+ 0 mV

AP-30 ref model	
Lifetime (% comparison with AP-30 Ref Model)	9,2 ans (+ 77%)
Copper volume	0.0131 m³
AE economy (% comparison with AP-30 Ref Model)	+ 9980 $ + 9%

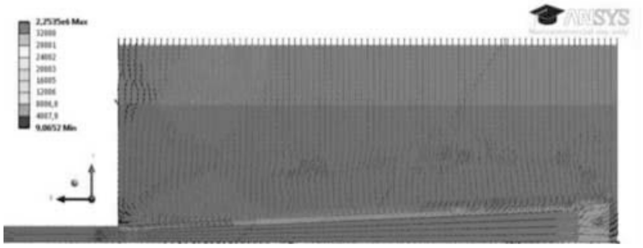

Fig. 10 – Current density through the cathode with an embedded copper bar (Case no. 4).

These results show that it is possible to design a cathode block operating at a uniform current density to optimize its lifetime and at the same time reduce its annual operating cost.

CONCLUDING REMARKS

This study has examined the effect of non uniform current distribution on the lifetime of cathodes inside electrolysis cells. The shape and the materials of the cathode block/collector bar assembly have been investigated. It was found that for minimum design modifications, it is possible to save up to 20000$ on the annual operating cost of a AP-30 cell.

Case 3 and 4 have revealed that it also possible to prolong the lifetime of the cell by up to 75%. Can the costs related to the additional machining, the materials and the CVD be offset by a better stability of the cell? This question remains to be answered in a future study.

ACKNOWLEDGEMENTS

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