Modeling of Energy Saving by using Cathode Design and Inserts

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Abstract:

The use of modified cathode shape and inserts in the cathode allow drastically redistributing the current density in the aluminium liquid pool. As a result both the cathode voltage drop and the anode to cathode voltage drop can be significantly decreased. Electrical modeling can easily explain the energy savings in the cathode. Magneto-hydrodynamic modeling shows why and how specific energy can be saved in the anode to cathode distance. The energy saving inside the cell depends on the cell initial design but may exceed 1 kWh/kg Al.

I. Introduction

The aluminium industry is continuously working on reducing the specific energy consumption as it is one of the most important contributions to the production cost. To reduce the specific energy consumption one must act on two parameters; the current efficiency and the cell voltage. It is trivial to say that the current efficiency must be increased and the cell voltage decreased. The current efficiency is mainly a result of the cell design, the cell operation and the quality of the raw materials. Today, the best cells achieve 96% current efficiency. Further improving the current efficiency is mostly linked to the materials properties and the operation of the cell. This study is focusing on the cell design and is assuming a constant current efficiency.

II. Specific energy consumption

In order to discuss the different components of the specific energy consumption let us first introduce some notations:

U_{cell}	Cell voltage	[V]
I	Line current	[kA]
η	Cell current efficiency	[1]
t	Time	[hours]
F	Cst. (Faraday's law) 0.3356	[kg/kAh]
P_{rod}	Cell production	[kg]
P_{cell}	Cell power	[kW]
E_{cell}	Cell energy for the period Δt	[kWh]
E	Cell specific energy cons.	[kWh/kg Al]

Basic physics tells us that (K.Grjotheim, H.Kvande [11]):

P_{cell}	$= U_{cell} * I$	Total power	[kW]
E_{cell}	$= U_{cell} * I * \Delta t$	Energy	[kWh]
P_{rod}	$= F * \eta * I * \Delta t$	Production	[kg Al]

And from there the specific energy is found equal to:

$$E = U_{cell} / (F * \eta) \quad [kWh/kg] \qquad (Eq. 1)$$

The cell voltage U_{cell} can be decomposed into the following contributions (K.G. & H.K.[11]) :

$$U_{cell} = U_{ext} + U_{ano} + U_{bath} + U_{cvd} \quad with:$$

U_{cell}	Total cell voltage
U_{ext}	Ext. voltage from collector bars to the anode stubs
U_{ano}	From anode stubs to the bottom of the anodes
U_{bath}	From bottom of anodes to the liquid metal pool
U_{CVD}	Cathode voltage drop (metal pool to coll. bars)

And the bath voltage is:

$$U_{bath} = U_{dec} + U_{aro} + U_{aco} + U_{cco} + U_\Omega + U_{bub} + U_{AE}$$
$$U_{bath} = U_{elec} + U_\Omega + U_{bub} + U_{AE}, \quad with:$$

U_{dec}	Decomposition voltage
U_{aro}	Anode reaction overvoltage
U_{aco}	Anode concentration overvoltage
U_{cco}	Cathode concentration overvoltage
U_Ω	Ohmic voltage drop in ACD
U_{bub}	Bubbles voltage drop
U_{AE}	Average anode effect voltage
U_{elec}	Electrochemical voltage

Each contribution can be determined rather accurately if the bath temperature, the chemical composition and the local current density are known.

Table 1 presents a typical situation for a modern cell:

Table 1: Voltage and related specific energy

Curr. eff.	96%		
Voltage	**[V]**	**Specific Energy**	**[kWh/kg]**
U_{cell}	4.126	E_{cell}	12.807
U_{ext}	0.228	E_{ext}	0.708
U_{ano}	0.348	E_{ano}	1.080
U_{bath}	3.291	E_{bath}	10.215
U_{elec}	1.840	E_{elec}	5.711
U_Ω	1.239	E_Ω	3.846
U_{bub}	0.162	E_{bub}	0.503
U_{AE}	0.050	E_{AE}	0.155
U_{CVD}	0.259	E_{CVD}	0.804

In fact the specific energy consumption has decreased from about 60 kWh/kg at the end of the 19th century to about 12.5 kWh/kg Al in 2010 [10].

Are there more solutions for saving voltage?

The external voltage can only be reduced by changing the busbars electrical resistance. This means for example

increasing the mean busbars cross-sectional area and/or changing the busbars topology and/or using copper. Today modern side by side cells are already rather well optimized in term of external voltage and additional voltage reduction is very often not economical.

The anode voltage drop has a number of components [3] but depends mostly on the anode electrical resistivity and the anode height. Since long, the anodes have been analyzed and optimized in term of baked density and carbon recipes (Sheralyn Marie Hume[2]). Only small improvements to the anode voltage drop are possible today, unless using different materials such as metallic anodes which are out of the scope of discussion of this paper.

The electrochemical voltage components can be slightly modified by the current density in the cell and by the bath composition and temperature. These components cover the minimum theoretical energy needed to convert alumina into aluminium ($1.43/\eta$ +4.91 kWh/kg Al) and there is not much to do at that level.

The bubbles voltage drop can be reduced by minimizing its thickness layer. The use of slots in the anodes for helping the gas to escape is one solution [4]. However, today the trend is to increase the anode current density and this means most of the time increasing the bubble voltage drop.

The average anode effect voltage drop is low and all efforts to reduce the number of anode effects further reduce its value. There is no big challenge left when considering only the energy.

The only two remaining voltage contributions that were not discussed so far, are the ohmic voltage drop in the anode to cathode distance (U_a) and the cathode voltage drop (U_{CVD}). Both together they still represent about 1.5 V or 4.7 kWh/kg Al.

III. Cathode voltage drop minimization

Many efforts have been taken to minimize the cathode voltage drop (CVD) [5,6]. On one hand the carbon properties of the carbon blocks are strongly modified by changing from amorphous blocks to graphitized, graphitic, impregnated or even using variable resistivity properties blocks. On the other hand the current collector bars design has been upgraded both from a geometrical and material point of view. A number of patents cover different aspects [7,8,9]. The use of copper inserts has allowed an interesting step in the CVD minimization.

IV. ACD ohmic voltage drop minimization

At first glance the minimization of the ohmic voltage drop in the anode to cathode distance (ACD) looks very simple as it is only necessary to reduce the ACD. This is without considering the thermal balance and the magneto-hydrodynamic effects. In fact, for some cell designs, one should consider increasing the CVD for minimizing the total cell voltage. This can be understood when analyzing the whole thermal and magneto-hydrodynamic effects.

More recently, new cathode designs have shown real improvement in the cell voltage, leading to a specific energy consumption in the range of 12.2-12.5 kWh/kg Al [10]. New cathode shapes allow decreasing the ACD without reaching the magneto-hydrodynamic instabilities [11,12].

The electrical conductivity of molten cryolite is very low, typically 220 $\Omega^{-1}m^{-1}$ and the ACD cannot be decreased too much due to the formation of magneto-hydrodynamic instabilities leading to waves at the metal-bath interface. The existence of waves leads to a loss of the current efficiency of the process and does not allow decreasing the energy consumption under a critical value. In average in the aluminium industry, the current density is such that the voltage drop in the ACD is minimum 0.3 V/cm. As the ACD is 3 to 5 cm, the voltage drop in the ACD is typically 1.0 V to 1.5 V. A thorough study of cell magneto-hydrodynamic instabilities led to the conclusion that there is still a large possibility of improving the interaction of the magnetic field with the local current density in the liquid metal by modifying the local current density. The magnetic field inside the liquid metal is the result of the currents flowing in the external busbars and the internal currents. The internal local current density inside the liquid metal is mostly defined by the cathode geometry and its local electrical conductivity. In other words, changing the cathode geometry and conductivity will lead to new current distribution inside the liquid metal. The magnetic field and current density produce the Lorentz force field,

$$f = j \, X \, b \, [N/m3] \qquad \qquad (Eq. \, 2)$$

j Current density vector field.
b Induction magnetic vector field generated by
   internal + external currents.
f Lorentz force vector field.

That itself generates the metal surface contour, the metal velocity field and defines the basic environment for the magneto-hydrodynamic cell stability. The cell stability can be expressed as the ability of lowering the ACD without generating unstable waves at the surface of the metal pad. The level of stability depends on the current density and induction magnetic fields but also of the shape of the liquid metal pool. The shape of the pool depends on the surface of the cathode and the ledge shape. In order to eliminate potential sludge problems this study was restricted to smooth cathode surfaces.

V. Cathode design and inserts

Different geometries have been described [12], using both a change in the surface shape and the use of conductive inserts. Figure 1 shows a possibility of using a deeper pool ("A") machined out of the standard cathode ("B").
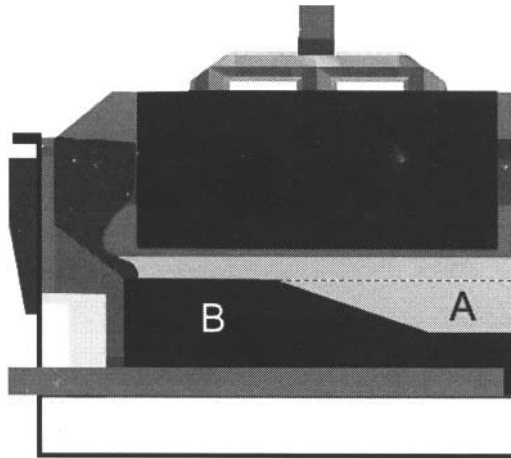
Figure 1: Modified metal pool

The impact of the busbars on the cell magneto-hydrodynamic stability is well known. As an example, reference [13] analyses an end-to-end cell technology using three different busbars topologies. In this study, the cell stability was determined by using sophisticated models that were published earlier [14,15,...,25]. The impact of the cathode shape and the use of inserts are analyzed. Instead of changing the magnetic field generated by the external currents of the cell, the internal current density in the liquid metal is modified by changing the cathode geometry and conductivity. Obviously due to the Lorentz force equation (2) the change of current density in the cell will have a strong impact on the cell magneto-hydrodynamic state.

Three cases are compared:

Case 1: Reference cell with a standard cathode block (Figure 3).

Case 2: Modified cathode surface but using the same collector bars (Figure 4).

Case 3: Addition of a conductive inserts above the collector bars while using the same collector bars (Figure 5).

Stationary quantities are analyzed for all three cases such as metal upheaval, metal velocity field and electrical field. The stationary state is further analyzed to determine the cell magneto-hydrodynamic stability.

The followings parameters are considered for the cell:

I	170 kA	Line current
j_A	0.9 A/cm2	Mean anode current density
h_m	19.0 cm	Mean metal height
h_b	22.0 cm	Mean bath height
Q_{int}	310 kW	Internal heat

The ACD has been kept constant under each anode, i.e., the anode surface is deformed in order to follow the metal surface. The total volume of metal has been kept constant when modifying the cathode surface.

For the cell magneto-hydrodynamic stability calculations, the anode to cathode distance is decreased while the current is increased. The decrease is such that the total internal heat is kept constant.

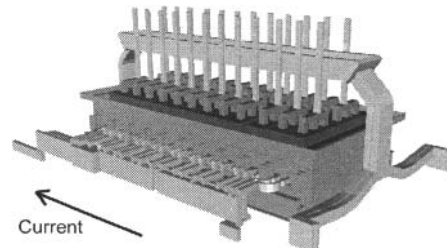Figures 2 and 3 show the reference cell.

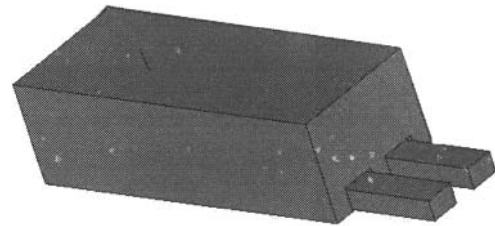*Figure 2: Case - Reference cell design (end to end)*

Figure 3: Case 1- Cathode block of the reference cell

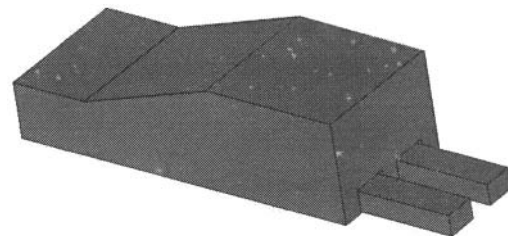Figure 4 shows the modified cathode block surface.

Figure 4: Case 2 - Modified cathode block surface

In order to further improve the cell stability (magneto-hydrodynamic cell state) one can use conductive metallic inserts in the cathode to drive the current through a different path. Figure 5 shows the inserts on top of the current collector bars. The cathode is not visible but the metal pool is shown.
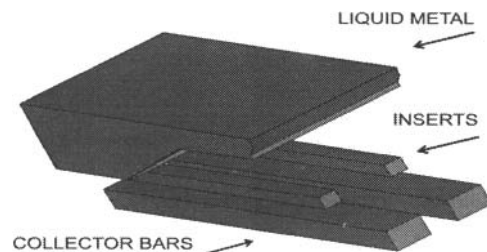

Figure 5: Case 3- Conductive inserts on top of the current collector bars

Figures 6, 7 and 8 show the metal upheaval for the three cathode designs.
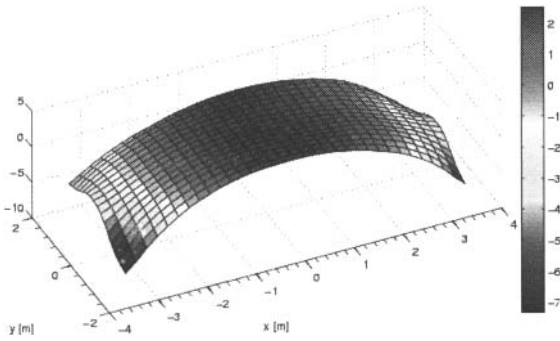
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Figure 6: Metal upheaval of the reference cell
(Min = -7.3 cm, Max = 2.5 cm)

The use of a modified cathode surface leads to a much lower metal upheaval which is favorable for the anode setting.
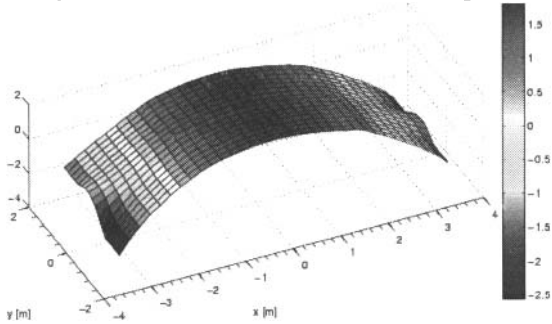

Figure 7: Metal upheaval of the modified cathode surface
(Min = -2.6 cm, Max = 1.8 cm)

The additional inserts do not further help to reduce the metal upheaval, which remains almost unchanged when compared to the modified surface cathode.
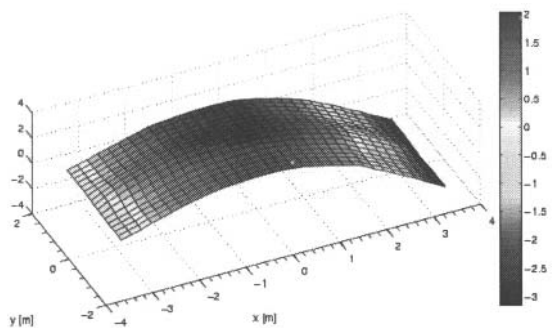

Figure 8: Metal upheaval of the cathode using inserts above collector bars
(Min = -3.1 cm, Max = 2.0 cm)

Figure 9 shows the horizontal components of the velocity field 8 cm above the surface of the cathode for the reference cell. The maximum value is 0.13 m/s.
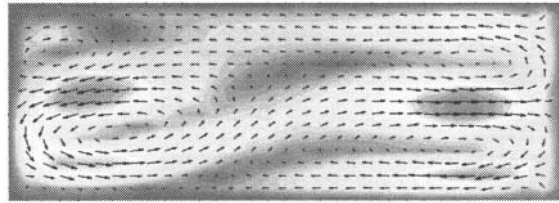

Figure9: Velocity field of the reference cell
(Maximum velocity = 0.13 m/s)

Figure 10 shows the impact of modifying the cathode surface. The global pattern flow is kept similar but the maximum velocity is slightly higher at one position. This is most likely due to the lower level of metal above the cathode on the long sides of the cell.
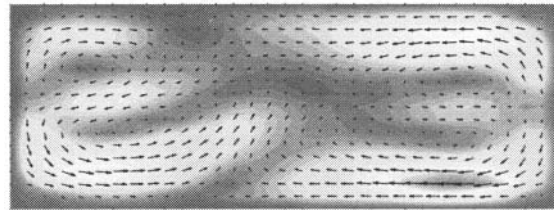

Figure 10: Velocity field of the modified cathode surface
(Maximum velocity = 0.15 m/s)

Figure 11 shows the impact of the inserts. The change is drastic, the flow has changed its sign at one end of the cell, and the maximum value of the velocity field is less than half of the previous cases.
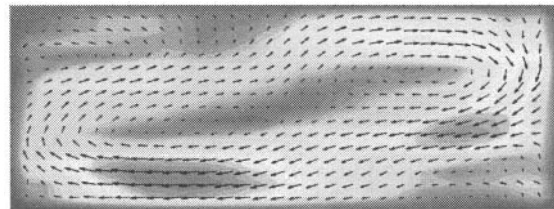

Figure 11: Velocity field of the cathode using inserts above the current collector bars
(Maximum velocity = 0.06 m/s)

Figure 12 shows the electrical potential in the liquid metal for the reference cell. The current is flowing perpendicular to the iso-potential lines (see vectors). It can clearly be seen and it is well known that the current density has a horizontal component leading current from the center of the cell towards the sides inside the liquid metal.
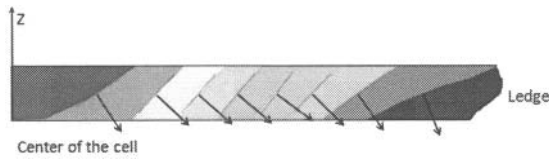
Figure 12: Electrical potential in the liquid metal of the reference cell (CVD = 0.34 V)

Figure 13 shows the electrical potential in the liquid metal for the modified cathode surface. The impact on the CVD is not very important but the current density is more vertical in the liquid metal.
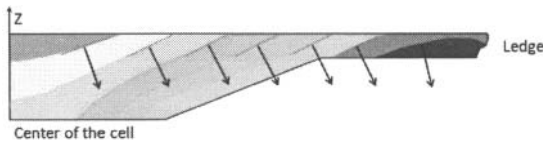

Figure 13: Electrical potential in the liquid metal of the modified cathode surface. (CVD = 0.32 V)

Figure 14 shows the impact of the inserts. The CVD shows a small change but the current density is strongly modified. This is of prime importance for the cell stability and also explains the change of metal velocity field.
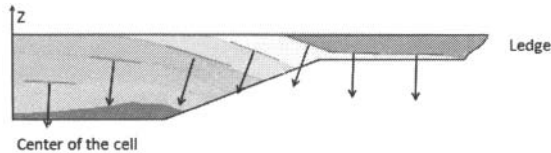

Figure 14: Electrical potential in the liquid metal of the cathode using inserts above the current collector bars (CVD = 0.32 V)

For any given design, the cell stability decreases when the current is increased. In order to keep the same thermal state and save energy using the new cell designs, the current is increased while keeping the same internal heat production. In fact the ACD is lowered while increasing the current. Figure 15 shows the relative change of cell stability for the reference cell and for the modified cathode surface cell to the cell stability of the reference cell. As expected, the instability increases with the current for both cases. However, the current can be increased by more than 15% in the modified cathode cell to reach the same level of stability as for the reference cell.
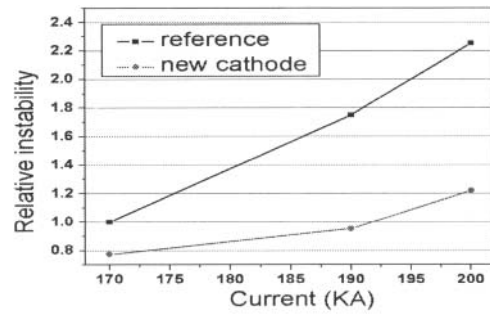

Figure 15: Relative change of cell stability for the modified cell compared to the reference cell

Finally the most important results are summarized in table 2. By increasing the current, the specific energy consumption is decreased and this is possible due to the new cell stability. There are other constraints to current increase that were not discussed in this paper such as the minimum ACD and the maximum current density in the anodes and busbars. Each technology must be analyzed in order to determine the global specific energy saving which is in the range 0.4 - 1 kWh/kg Al while the productivity increases are 10% to 20%.

Table 2: Summary of results

	Unit	Reference	Cathode surface	Insert
Current	kA	170.00	187.00	200.00
Internal heat	kW	307.5	307.1	291.4
Anode Cur. Dens.	A/cm2	0.90	1.00	1.06
CVD	mV	340	353	374
Specific energy saving in ACD & CVD	kWh/kg	0.00	-0.63	-1.29
Total energy saving	kWh/kg	0.00	-0.38	-0.85
Productivity increase	%	0	10	18

In this study the current efficiency was assumed to be constant. In fact, an improved cell magneto-hydrodynamic state may contribute to increase the current efficiency and therefore further decrease the specific energy consumption.

Many more cathode shapes and positions of inserts can be considered to improve the cell stability and the solutions can be applied for end-to-end or side-by-side cell topologies.

VI. Conclusions

New designs of cathode blocks allow for an important reduction of the specific energy consumption and offer great opportunities for production increase. The energy saving is marginally due to the direct energy saving in the cathode but is mostly realized through the possible current increase due to a better cell magneto-hydrodynamic state. The current efficiency might also be increased by the improved cell stability but this must be quantified by operating the cells.

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