1’000’000 amperes dream cell

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Abstract

The aluminum industry is constantly looking at reducing the production cost. During the last three decades it has mainly been achieved by the economy of scale consisting in increasing the cell dimensions allowing for higher current and therefore increasing the plant production and productivity. This paper presents under which conditions a step change can be achieved without increasing the shell dimensions. The design of a cell of the future is discussed in term of voltage distribution, heat loss, energy saving, productivity and environmental consequences.

Introduction

During the last three decades, the line current in aluminium reduction plants has increased considerably and has reached 600 kA. During the same period all smelters have been active at increasing the productivity in their existing shell by increasing the anode size and the anode current density. This was achieved by better cathode and collector bars designs sometimes combined with busbars modifications to improve the cell magneto-hydrodynamic stability. A better magneto-hydrodynamic cell state allows decreasing the anode to cathode distance (ACD) needed for achieving the right thermal balance. If the cell productivity is expressed as tons produced per year and square meter inside a given shell, the increase have proven to be in the range of 10 to 30%. In the best case it has reached 80% depending on the initial state of the cell technology and level of optimization. During the same period the current efficiency has also improved and the best technologies achieve results close to 96%. When analyzing the evolution of the specific energy consumption (E), a decrease from above 14 kWh/kg to 13 kWh and lower was achieved in many smelters. The theoretical energy consumption can be expressed as:

$$E = 1.431 / \eta + 4.915 \text{ kWh/kg}$$

where η is the current efficiency. The energy efficiency is the ratio of the needed energy to the used energy. The energy efficiency of the Hall-Héroult process is low as shown in table 1. It was increased from about 43% to 48% over 30 years and has hardly reached 50% in the best cases.

Table 1: Hall-Héroult process current efficiency

Current efficiency	Specific energy	Energy efficiency
%	kWh/kg	%
94	6.26	100
94	15.00	41.7
94	14.00	44.7
94	13.00	48.2
94	12.00	52.2
94	11.00	56.9
94	10.00	62.6

It is reasonable to ask ourselves what can be done to further improve the plant productivity. Should we double the length of the cell to double the current? Would it help at increasing the energy efficiency and current efficiency? Knowing that today high amperage cells are in the range of 20 meters in length, doubling the length does not seem to be reasonable. Increasing the width appears also as a challenge for the magneto-hydrodynamic cell stability and for the

anode length and weight. Not to be forgotten, for every kilo of aluminum produced more than one kilo carbon-dioxide and about hundred grams of carbon monoxide are produced. With sixty millions tons of aluminum produced every years it is not negligible.

So what can be done?

The cell of the future

The cell of the future should satisfy our dreams, however realistic dream, such as:

- High productivity — More than double than today
- Low specific energy consumption — Lower than 12 kWh/kg
- High current efficiency — Higher than 95%
- High volume of bath/kA — Higher chemical stability
- Low bath temperature — Higher current efficiency, lower energy

Is it a dream or does it make sense?

How can we achieve these performances?

The authors see no possibilities to achieve such a dream with the existing carbon anodes, but, when using metallic anodes (Ref 1,2), many possibilities of redesigning the cell are coming up. As this paper is part of a dream session, the authors have analyzed what looks very promising to their point of view. Table 2 challenges the parameters of a dreaming cell to an existing cell technology.

Table 2: Comparison between an existing technology and "A dream cell"

How to make a dream come true 1'000'000 A cell			
		REFERENCE	**VISION**
		Modern Hall-Héroult technology	**Future Hall-Héroult technology**
	Unit		
Operating parameters			
Productivity	%	100%	278%
Amperage	kA	360.0	1000.0
Specific energy consumption	kWh / kgAl	12.84	11.73
Gross volt	V	4.05	3.78
Current Efficiency	%	94.0	96.0
Production	kg Al /pot-day	2726	7732
Geometry			
Cell length	m	15	15
Cell width	m	4.4	4.4
Cell cavity	m	1.3	1.3
Anode Width	mm	650	650
Anode Length	mm	1600	1600
Nbr of anodes		40	112
Anodic current density (geometry)	A/cm2	0.865	0.859

The table speaks by itself but let us comment the important parameters. The productivity is increased by a factor of 2.8. This was never achieved before. The specific energy consumption is lower than 12 kWh/kg. This is remarkable and contradicts many believes stating that the “inert anode” has to pay one extra volt and therefore will produce with about 3 kWh/kg increase of specific energy. The result is of course linked to the design shown after. The current efficiency is shown as 96%. This cannot be calculated with accuracy but is more an assumption linked to the fact that the anode to cathode distance is constant in the dream cell and the amount of bath is more than ten times bigger for every kA in the cell. The bath chemistry and bath temperature that are strongly correlated must therefore remain much more stable than today for the benefit of the current efficiency. Last but not least, the operating temperature of the dream cell is 900 °C in our model which is also in favor for higher current efficiency. Each point will be further highlighted. The cell dimensions are kept fully unchanged and so are the anode dimensions. Only the number of anodes is increased from 40 to 112. How is that possible?

Figure 1 shows the reference carbon anode. Figure 2 shows how the metallic anode has a surface of 2.8 times the surface of the carbon anode. Figure 3 shows the metallic anode. This is where the miracle takes place. Due to the dimension stability of the anodes and the high conductivity of metallic anodes, the geometry can be fully revisited. The average current density is almost kept constant but the electrical circuit is fully revisited.

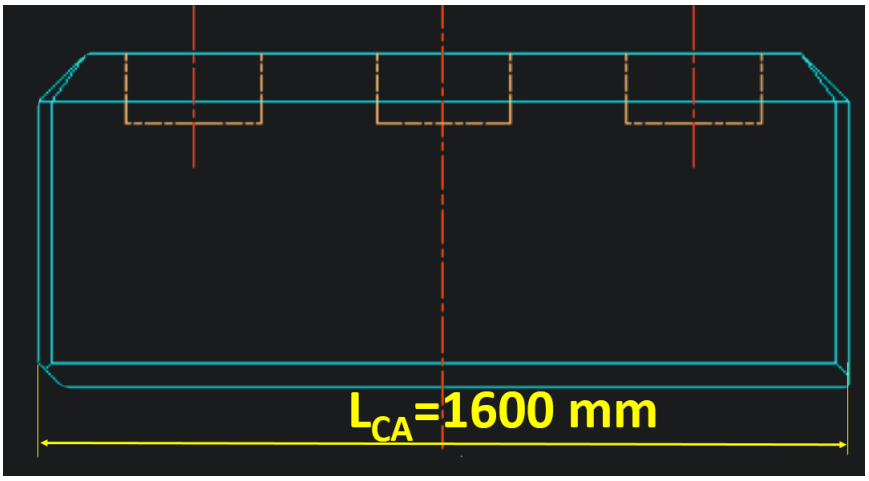

Figure 1: Carbon anode

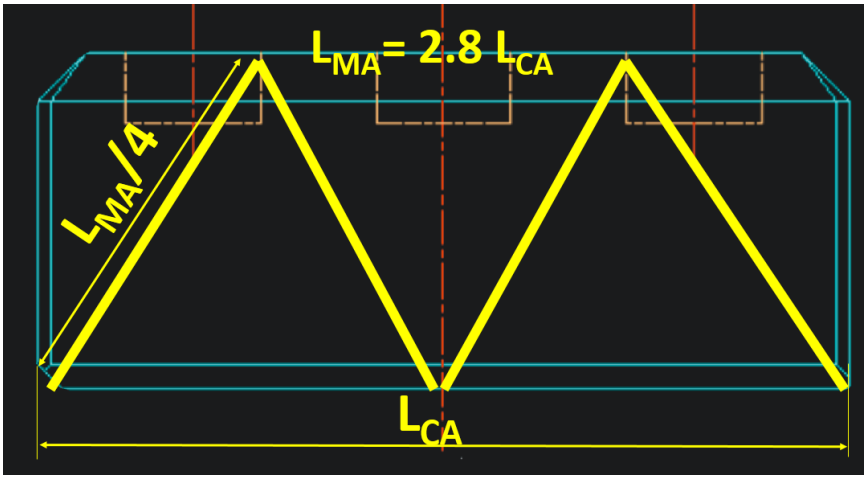

Figure 2: Concept for the surface for the metallic anode

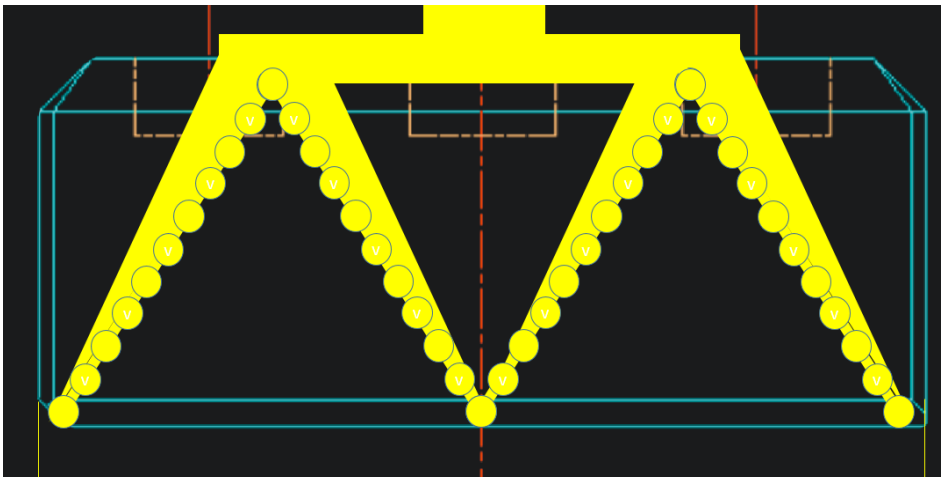

Figure 3: Example of Metallic anode geometry

Cell thermal-electrical model

Table 3 summarizes the voltage breakdown of both technologies. The external voltage is assumed to be the same for both. This can be achieved by using adequate busbars sections. The anode voltage drop is 160 mV lower for the metallic anode due to the higher conductivity of the assumed Ni-Fe metallic structure compared to the carbon anode. No anode effects are expected to take place with the metallic anode and the bubbles voltage is considered as negligible due to the anode geometry. The decomposition voltage of the metallic anode is about 1 V higher. This is the cost of producing oxygen instead of carbon dioxide. The energy needed to produce the metallic anode will also be lower than for the carbon anode and this is not considered in our energy balance. The fixed anode geometry will allow to operate at lower anode to cathode distance (ACD). In this example a distance of 2 cm was calculated in order to produce a reasonable heat loss for the cell that is compatible with a good ledge thickness.

Table 3: Voltage breakdown

How to make a dream come true 1'000'000 A cell			
		REFERENCE	**VISION**
		Modern Hall-Héroult technology	**Future Hall-Héroult technology**
Voltage breakdown			
External			
Busbars + Beam to anode	V	0.230	0.230
Internal			
Anode voltage	V	0.260	0.100
Anode Effects + Anode Change	V	0.005	0.000
Gas bubbles /Thonstad-Vogt	V	0.197	0.000
Decomposition voltage	V	1.248	2.250
Anodic reaction overvoltage	V	0.512	0.000
Anodic concentration overvoltage	V	0.060	0.063
Cathodic overvoltage	V	0.095	0.090
Cathode Voltage Drop (CVD)	V	0.252	0.200
Ubath	V	1.191	0.847
ACD with bubbles	cm	3.47	2.03
Bath volume per kA	dm3/kA	6.4	39.6
Gross volt	V	4.05	3.78

Table 4 shows the energy aspects of both technologies. It can be observed that the global energy efficiency is better, the internal heat of both technologies is very similar. This means that a similar thermal equilibrium can be found leading to a similar ledge shape. The specific energy of the metallic anode technology is 11.73 kWh/kg which is lower than any standard Hall-Héroult existing cell. This shows that metallic anodes can be competitive to the carbon anodes when used with the Hall-Héroult process if the cell design is adequate.

Table 4: Energy aspects

How to make a dream come true 1'000'000 A cell			
		REFERENCE	**VISION**
		Modern Hall-Héroult technology	**Future Hall-Héroult technology**
Specific energy Hall-Héroult process			
External heat	kWh/kg	0.73	0.71
Internal heat	kWh/kg	5.67	1.76
Energy to produce metal	kWh/kg	6.44	9.26
Total	kWh/kg	12.84	11.73
Energy efficiency (theoretical/used energy/)	%	48.8	53.6
Power Hall-Héroult process			
External heat	KW	82.8	230.0
Internal heat	KW	644.2	566.3
Energy to produce metal	KW	731	2984
Total	KW	1458	3780

Table 5 shows an example of bath that could be used for both technologies. The use of Lithium is important to decrease the bath resistivity to compensate for the addition of Potassium fluoride needed to decrease the operating temperature. As a result both technologies have about the same bath electrical conductivities.

Table 5: Bath properties

How to make a dream come true 1'000'000 A cell			
		REFERENCE	**VISION**
		Modern Hall-Héroult technology	**Future Hall-Héroult technology**
Bath chemistry	% AlF3 excess	11.5	11.5
	% CaF2	5.0	6.0
	% Al2O3	2.5	4.0
	% LiF	0.0	4.5
	%MgF2	0.3	0.5
	%KaF	0.0	5.0
	Ratio	1.106	1.057
	Bain T	965	900
	AL2O3_SAT	8.33	4.52
	Liquidus T	959	893
	Superheat	5.7	7
	Bath resist.	0.463	0.485

To demonstrate the feasibility a full three dimensional model was realized. The coupled thermal-electrical problem was solved. Figure 4 shows the cell geometry of 3D model.

Figure 4: 3D model of 1'000'000 A cell

The temperature field is shown in a vertical section of the cell in figure 5. The maximum temperature is close to 900 °C and the ledge protection is assured.

Figure 5: Temperature field in a vertical section of the cell

The electrical potential (without the electrochemical voltage) is shown in a vertical section of the cell in figure 6. The voltage distribution given in table 3 were taken from this model.

Figure 5: Electrical potential in a vertical section of the cell

Conclusions

Under the assumptions that:

- A metallic anode is available with an economical life
- A wettable cathode is available for draining the metal

a cell can be designed with:

- More than double productivity than today
- Lower than 12 kWh/kg
- Higher than 95% current efficiency

In other words, the dream is not unrealistic.

References

1) A
2) B
3) Etc..
4)