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ALUMINUM REDUCTION TECHNOLOGY

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IN DEPTH ANALYSIS OF ENERGY-SAVING AND CURRENT EFFICIENCY IMPROVEMENT OF ALUMINUM REDUCTION CELLS

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Abstract

In view of the existing aluminum overcapacity and lower aluminum price in China, many companies took measures to reduce the production cost and the energy consumption, but there has been no normalized theory and method defined as yet.

To address these issues, this paper puts forward the evident effects of energy-saving and current efficiency improvement in aluminum reduction cells using new thermal insulation pot lining design, application of optimal cathode structure and reduction of horizontal current device. A proper application of new lining materials and combination of relevant process parameters based on the finite element software ANSYS® and thermal field simulation software as the calculation method combining the actual production data are also used. Practice proves that the above-mentioned method combining design, simulation and experiment can become the effective and feasible way to achieve low energy consumption, low cost and high profit.

Introduction

In recent years, the nonferrous metal industry sets off an upsurge of scientific and technological innovation activities on quality and capacity increase, energy-saving, consumption-reduction and environment protection. The key technologies in aluminum reduction area such as low temperature operation, intensifying current, on-line measurement of superheat, "3-variables" control technology, anode slotting technology, irregular cathode technology, improved thermal insulation lining design, cathode design that reduces metal pad horizontal current, application of new lining materials, inert anode etc. have been studied and are in the process of being implemented.

This will soon raises Chinese aluminum reduction technology to the world advanced level. Moreover, the consumption of energy and raw material for aluminum reduction production has been very high in recent years, especially power consumption. With the energy crisis, the aluminum reduction production cost must be reduced without delay. For this, the most efficient method is to reduce the DC consumption by increasing current efficiency (CE) and reducing pot voltage.

Analysis of mechanism and nature of pot work voltage reduction based on energy balance principle

The pot energy balance was summarized by Warren Haupin as shown in Figure 1.

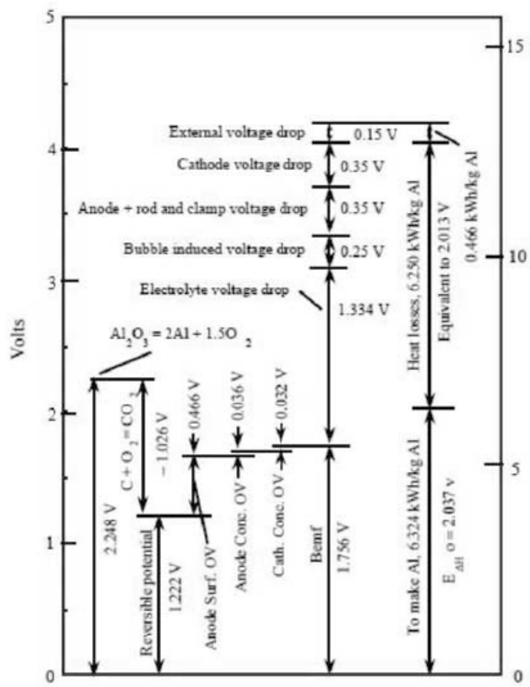

Figure 1. Energy balance relationship[1]

Figure 1 shows that the heat input/output may be divided into the above items based on pot energy balance principle. The object of voltage reduction is the voltage combination in the heat input, the majority of which is voltage drop between anode-cathode.

It should be pointed out that the high-temperature production during aluminum reduction mainly depends on the Joule heat generated in the bath in which the current passes from the anode to the cathode. The normal production shall be kept through the dynamic balance of heat output and heat input during operation. If the Joule heat generated from heat input is not enough to maintain the heat output, the pot shall get cool gradually, and the process system shall be damaged.

Therefore, the energy balance of the pot is maintained by reducing the heat dissipation in heat output combination as well as the voltage in heat input combination so as to reduce the voltage.

Analysis of potentialities and approaches on voltage reduction by voltage composition of heat input

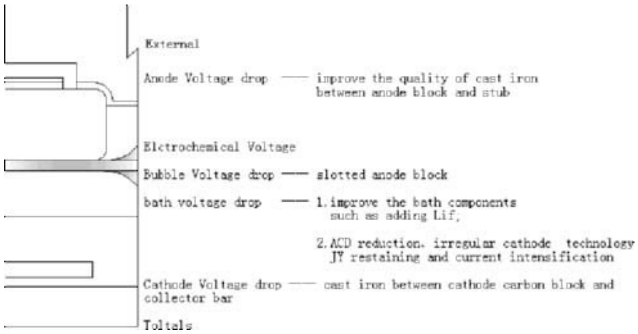

Figure 2. Heat input structure and approaches of voltage reduction

The total pot voltage is just the sum of the parts as follows[2,3]:

$$V_{pot} = V_{anode} + |E_e| + \eta_{sa} + \eta_{ca} + V_{bub} + V_{ACD} + \eta_{cc} + V_{cath} + V_{ext} \quad (1)$$

Where:

- V_{pot} is the Pot Voltage (V);
- V_{anode} is the Anode Voltage (V);
- $|E_e|$ is the Equilibrium Potential (V);
- η_{sa} is the Anode Surface Overvoltage (V);
- η_{ca} is the Anode Concentration Overvoltage (V);
- V_{bub} is the Bubble Voltage (V);
- V_{ACD} is the Voltage Across the ACD (V);
- η_{cc} is the Cathode Concentration Overvoltage (V);
- V_{cath} is the Cathode Voltage (V);
- V_{ext} is the External Voltage (V).

Figure 2 shows that if the design dimensions of the pot are determined, the object of pot voltage reduction is mainly the voltage drop reduction between the anode and the cathode (industry term: active voltage). If the CE is fixed, the object of voltage reduction is mainly the voltage drop of bubble (V_{bub}) and in the bath across the ACD (V_{ACD}).

Bubble voltage drop[3]

$$V_{bub} = \frac{i_a}{\chi}\left[\frac{(\delta - t_a)}{(1-\varepsilon)^{1.5}} \cdot \frac{t_a}{(1-1.26 f_c)}\right] \quad (2)$$

$$f_c = \frac{1}{(1 + 0.75\% Al_2O_3)} \quad (3)$$

Where:

- i_a is the Anodic Current Density (A/cm^2);
- χ is the Electrical Conductivity of the Bath ($1/\Omega cm$);
- δ is the Bubble Layer Thickness (cm);
- t_a is the Adhering Bubble Thickness (cm);
- ε is the Gas Fraction in the Bath ($0.02 \cdot \%Al_2O_3$);
- f_c is the Fraction of the Anode Covered with Gas ().

From Equations 2 and 3, we can see that the mechanism of bubble voltage drop reduction lies on improving the bubble release capacity, hence reducing the bubble coverage fraction and reducing the bubble thickness.

Until now, the measures taken by the industry mainly include the slotting of anodes, the control the length-width ratio of anode, the improvement of bath composition, etc.

The slotted anode can make the bubble release from the anode bottom more efficient to reduce the bubble coverage fraction and the bubble thickness, so as to reduce the bubble voltage drop of anode, thus reducing the pot voltage.

There is deeper research on the slotted anode technology abroad, including slotting location, slotting width, slotting depth, slotting process, etc. At present, the more mature slotted anode structure in China consists of 2 slots (at trisection location), slot width around 1~1.5 cm, slot depth or height of half of anode consumed in anode change cycle as per the anode height generally. The slotting process is generally vibrating forming plus slot cleaning. As per a lot of on site tests in China, using slotted anode can reduce the pot voltage by 30~60 mV.

Bath voltage drop[3]

$$V_{ACD} = \frac{i_a}{\chi}(ACD - \delta) \quad (4)$$

Where:

- ACD is the Anode to Cathode Distance (cm).

Equation 4 shows that the mechanism of ACD voltage drop reduction lies on changing the bath composition and reducing the ACD itself.

Perspective of changing the bath composition

Up to now, the measures taken in industry are as follows: the bath conductivity is increased by adding the additive, in which the most effective method is to add the LiF, and there will be significant effect combining with low bath ratio technology.

From the present calculation and statistical data, it is seen that for every increase of LiF by 1%, the voltage drop of unit ACD (cm) will be reduced by about 3~5 mV. For a pot with an ACD of 5 cm for example, every 1% LiF addition can reduce the voltage by 15~25 mV, and every 3% LiF addition can reduce it by 45~75 mV, which is a considerable effect.

Perspective of ACD reduction

The ACD reduction is theoretically divided into: (1) effective ACD reduction; (2) non effective ACD reduction (see Figure 3).

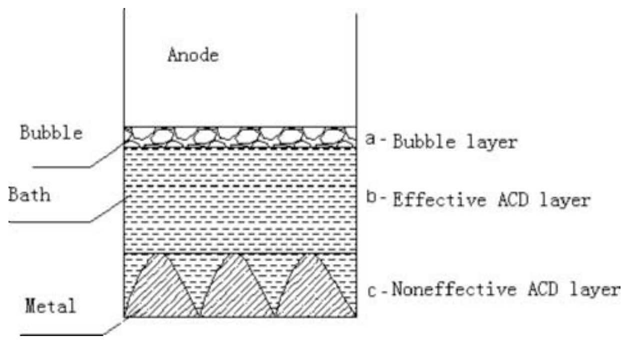

Figure 3. 3-layers structure model of ACD[4]

As shown in Figure 3, the ACD consists of 3 parts including a- a bubble layer, b- an effective ACD layer and c- a non effective ACD layer. Zone a depends on the width of the anode, the specific gravity and viscosity of liquid bath, the surface tension of bath to carbon dioxide gas, the alumina concentration, etc.; zone b is a heating area for maintaining the high temperature production of the pot, as well as an isolation layer for making the wave crest of metal away from the lower edge of bubble to avoid the back reaction; zone c depends on the MHD cell stability.

For the conventional pot, if the ACD is 5 cm, as per the calculation and averaged measurement, generally zone a (bubble layer) is about 0.5cm, zone c (non effective ACD) is 1.5~4 cm (it has relationship with the pot stability), hence, zone b (effective ACD) is 0.5~3 cm. The irregular cathode technology and the horizontal current reduction technology are decreasing the height of zone c (non effective ACD) to reduce the pot voltage; and the current intensification technology is decreasing the height of zone b (effective ACD) to reduce the pot voltage, i.e. the lowest voltage of current intensification selected in order to satisfy the heat balance, thus obtaining the lowest height of zone b assuming no CE loss. Therefore, if the pot with bad stability has current intensification to reduce the voltage, it is highly possible that it will reduce the height of zone c and bring about more back reaction, thus the pot will experience CE loss and overheating.

We can divide the type of applications used to reduce the ACD in three categories: (1) irregular cathode technology; (2) horizontal current reduction technology; (3) current intensification.

Irregular cathode technology

In 1994, Vittorio de Nora put forward the thinking of the irregular cathode structure. The irregular cathode structure is adopted to change the metal and bath flow state and reduce the melt flow velocity and the interface wave range of metal surface (reduce the non effective ACD), thus improving the pot stability in order to gain the option to reduce the ACD. Such technology is a kind of method to reduce the non effective ACD.

The main designs tried in the aluminium industry in China have been a stepped surface cathode, a sloped surface cathode and a flow resistance block.

<u>Stepped surface cathode metal flow model</u>

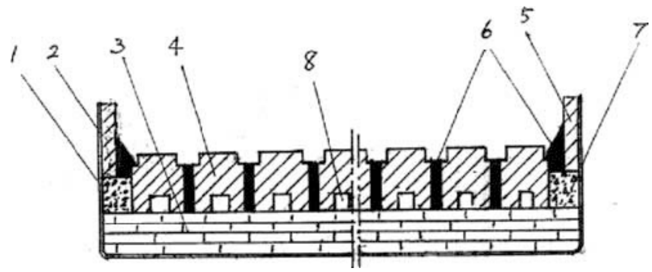

Figure 4. Stepped surface cathode design

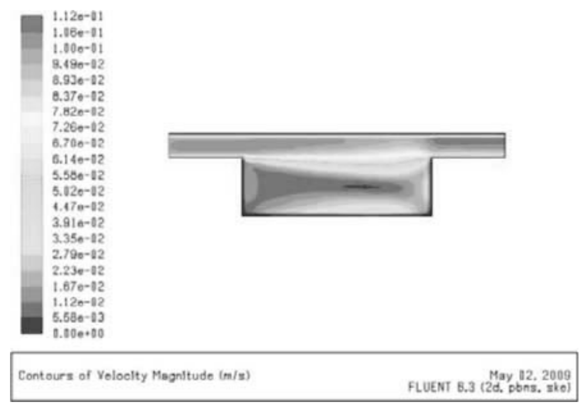

Figure 5. Model of metal flow velocity of stepped surface cathode

<u>Sloped surface cathode metal flow model</u>

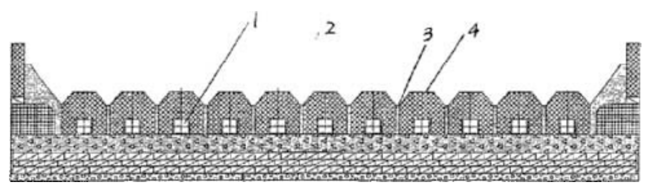

Figure 6. Sloped surface cathode design

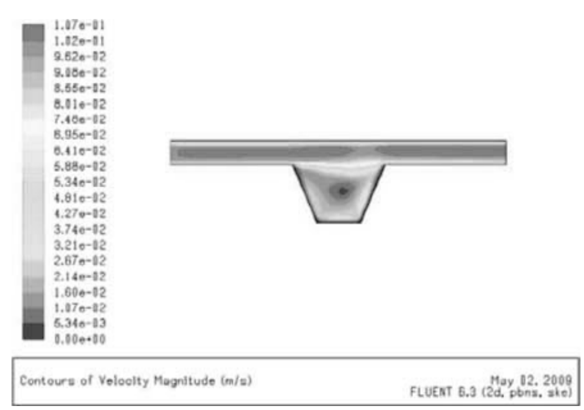

Figure 7. Model of metal flow velocity of sloped surface cathode

Comparison of results obtained

Table 1 is the comparison of calculation and measurement between irregular cathode and standard cathode in a plant in China.

	Max. flow velocity (cm/s)		Max deformation of metal surface (cm)	
	Calculation	Measurement	Calculation	Measurement
Standard pot	15.73	14.99	1.82	1.97
Irregular cathode	7.47	8.24	0.65	0.51
Variation percentage	52.50%	45%	64.30%	74.10%

Table 1. Comparison of calculation and measurement between irregular cathode and standard cathode in a plant

Compared to the standard cathode, for the irregular cathode the flow velocity is reduced by about 50%, the maximum deformation of metal surface by 65~75% and noise by 10~15%. At present, the voltage of the most of irregular cathode pots in China is about 3.7~3.9 V, based on the calculation of 2~3% of CE loss. The power consumption can be reduced by 560 kWh/T Al compared to the standard cathode pots.

Horizontal current reduction technology

It has been proved by the long-term practice that the fluctuation of metal liquid layer and bath liquid layer has close relationship with the horizontal current and the vertical magnetic field, which combined brings about the pot voltage fluctuation. So for a given vertical magnetic field, a reduction of the horizontal current in the metal can make possible a significant reduction of the height in the metal pad, reducing the cell heat loss and so provide an opportunity for pot voltage reduction, while maintaining the pot production and increasing the CE, all for the purpose of reducing the specific energy consumption.

The horizontal current has relationship with the following factors:

1) Geometric dimensions, such as width and length of cathode, width and height of collector bars;
2) Material of cathode, such as material of cathode carbon block, connection method between the cathode carbon block and the collector bar;
3) Geometric dimensions of the pot, such as dimension of thermally insulating pier, hence the position of the ledge toe;
4) The location of the collector bars exit out of the pot (side wall or otherwise).

The up to date prototype tests were designed to:

1) Increase the electrical insulation between cathode carbon block and collector bar;
2) Try a cathode design with bottom exit collector bar.

Special insulation[5] between cathode carbon block and collector bar

This new kind of design is a cathode assembly which reduces the horizontal current by adding an electrically insulated region between the cathode carbon block and the collector bar, as shown in Figure 8.

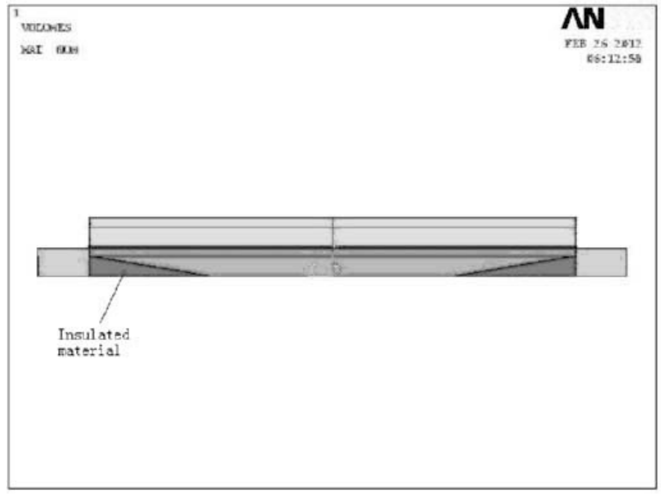

Figure 8. Cathode assembly for restraining the horizontal current (JY)

This design has been modeled using a 3D generic parametric whole pot model, based on ANSYS® 13.0, as shown in Figure 9.

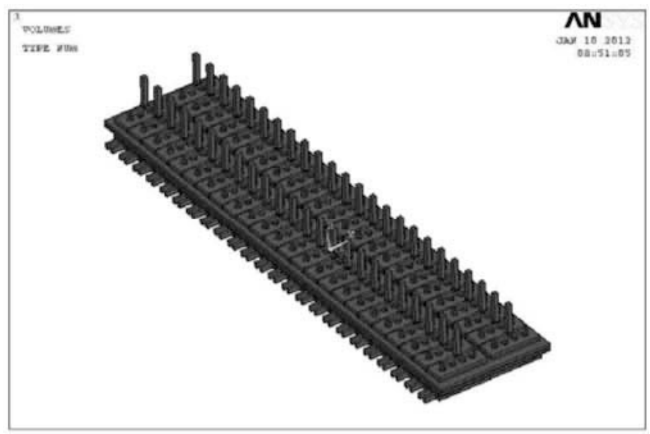

Figure 9. Geometry of the ANSYS® based 3D generic parametric whole pot model

The comparisons of simulation results between the cathode assembly without restraining horizontal current and that with restraining horizontal current are shown in Figures 10 and 11 respectively.

From the above analysis and comparisons it shows that the cathode assembly with insulation has a good effect on the reduction of the horizontal current; from the curve distribution, it shows that the curve of no sloping pasting presents the raised parabola (Figure 10) with a maximum value of 0.26 A/cm^2. However, the curve of the anode bottom middle of sloping pasting presents a leveled curve (Figure 11) at a value of 0-0.04 A/cm^2.

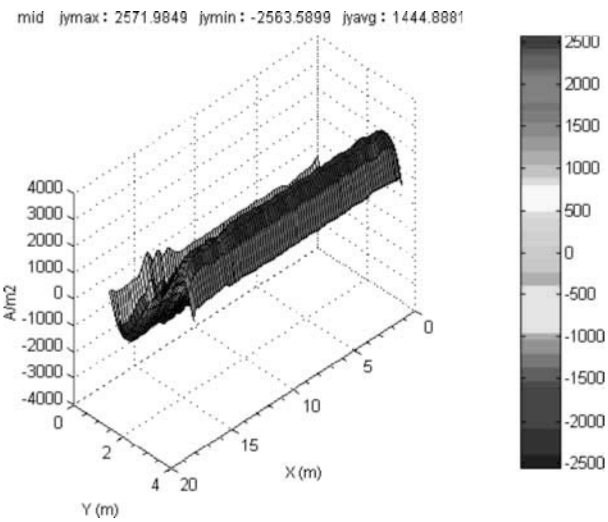

Figure 10. Cathode assembly without restraining horizontal current (JY)

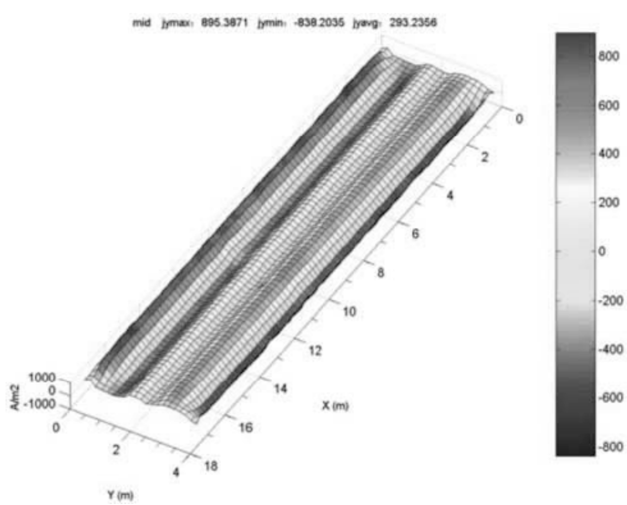

Figure 11. Cathode assembly with restraining horizontal current (JY)

From the curve distribution and values it shows that the sloping pasting technology has obvious effect for restraining the JY. At the moment in China, the different insulated materials for this technology are adopted for test and engineering applications.

Cathode design with bottom exit collector bar

This kind of design is the cathode assembly which reduces the horizontal current by changing the collector bar design and cell exit location. Figures 12 and 13 show that the cathode voltage drop is 194 mV (anode current density is 0.73 A/cm^2) which is a reduction of 70~100 mV compared to that of traditional cathode based on the same anode current density. From the horizontal current reduction analysis, it shows that the vertical current density in the cathode carbon block increases by about 0.2 A/cm^2 due to bottom exit. This technology is currently only in test phase, and the potential of voltage reduction needs to be proven.

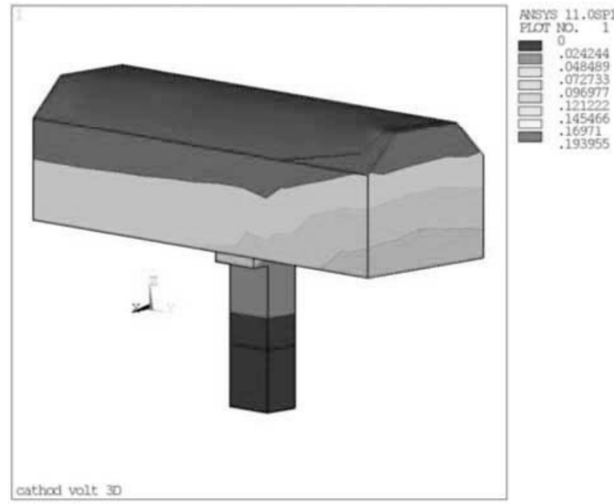

Figure 12. Voltage results for the cathode with bottom exit collector bar

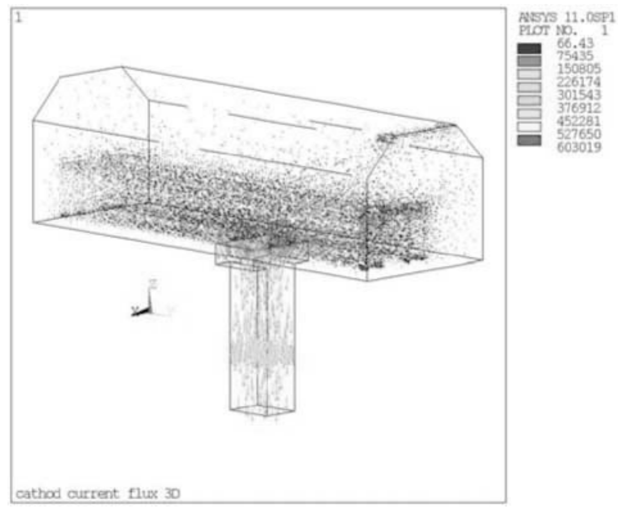

Figure 13. Current density results for the cathode with bottom exit collector bar

Current intensification

This technology reduces the voltage and maintains the relative constant heat input by the current intensification, thus obtaining a way to maintain the stable thermal balance. Such way is a method to reduce the effective ACD, the premise of which is that the pot has good MHD stability.

The development trend of current intensification for advanced cell technology outside of China at present is as follows:

1) Rio Tinto Alcan (Pechiney): pot capacity: 300 kA → 400 kA, anode current density: >0.98 A/cm^2 , pot voltage: <4.02 V, CE: 95%-96%, DC consumption: 12800 kWh/T Al;

2) Hydro Aluminium: pot capacity: 300 kA → 420 kA, anode current density: > 0.99 A/cm^2, pot voltage: 4.08 V, CE: 94%-95%, DC consumption: 12800kWh/T Al;

3) Dubal: DX type pot capacity: 340 kA → 370 kA, anode current density: >0.99 A/cm^2, pot voltage: 4.15 V, CE: 95%-96%, DC consumption: < 13000 kWh/T Al.

Today, the development condition of advance representative pot type in China is: an anode current density of current intensification for pots operating from 200 kA to 400 kA already that reaches 0.8~0.83 A/cm^2, and a voltage of 3.85~4.05 V.

Conclusions

In summary, through lots of prototype tests, mathematical modeling and comparison, the main effective approaches for reducing the pot voltage are as follows at present in China:

- Change of bath composition
- Sloped surface cathode
- Cathode assembly technology for restraining JY
- Current intensification
- Optimization of anode design
- Cast iron rodding for cathode

For the pot with the above technologies, for example in a plant in China the voltage is 3.75~3.85 V and the CE is above 94% [6][7]. Compared to the traditional pot with voltage being 4.1~4.2 V and CE being 93%, the energy consumption can be reduced to about 1250 kWh/T Al, and reduced by about 62.5*10^7 kWh per year based on an annual production capacity of 500 thousand tons. The operation cost savings are about 312 million Yuan per year based on power price being at 0.5 Yuan per kWh.

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