Energy Reduction Technology for Aluminum Electrolysis: Choice of the Cell Voltage

Feng Naixiang[1], Peng Jianping[1], Wang Yaowu[1], Di Yuezhong[1], Liao Xian'an
[1]School of Materials and Metallurgy, Northeastern University, Shenyang, 110819, China

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Abstract

In China, all the aluminum smelters are making efforts to reduce the electrical energy consumption of aluminum reduction by decreasing cell voltage. One measure is decreasing cell voltage without any cell structure change. Another measure of decreasing cell voltage is using novel structure carbon cathode. For the first measure, the current efficiency (CE) would be decreased because the anode-cathode-distance is reduced. For the second measure, if the cell voltage is reduced much more, the CE also can be lost. The best choice to decrease energy consumption is that the CE should be maintained when the cell voltage is reduced. It means that the cell should be operated at a reasonable low cell voltage, so that the CE could not be decreased or could be improved. In this paper, the CE and electrical energy consumption of aluminum smelters with different cell voltage operating are shown and the economic benefits are discussed.

Introduction

Currently, primary aluminum is produced by the Cryolite-Alumina molten salt electrolysis, which is characterized by high-energy consumption. Energy-saving is important for the aluminum electrolysis. China is the biggest electrical energy consumption country of the aluminum production in the world. In 2013, aluminum electrolysis production capacity in China could reach 30 million tons which could account for over half of the world. The electricity energy in China is very expensive, which is RMB 0.5-0.6 / kWh. Therefore, some energy-saving technologies have been the focus of attention.

Theory and Technology on Energy Saving

In aluminum electrolysis industry current efficiency (CE) and direct current (DC) consumption are used to evaluate the technology level of electrolysis process.

The DC power consumption (W) is calculated by Eq.(1):

$$W = 2980 \times \overline{V} / CE \quad \text{(kWh/t-Al)} \qquad (1)$$

Where $\overline{V}$ is an average voltage drop of an aluminum reduction cell.

According to Eq.(1), there are two methods to reduce DC power consumption. One is to decrease the cell voltage and the other is to improve the CE. In China, the cells using the traditional cathode technology are operated at 4.0-4.1V of cell voltage, and CE is 91%-93%. For some cells in good operation, CE could reach 93.5%.

For a cell which works at 4.0 V of cell voltage and 93% of CE, the DC power consumption would be reduced by 320 kWh per ton aluminum if the cell voltage is decreased by 0.1 V, and the DC power consumption of aluminum per ton would be decreased by 136 kWh if the CE is increased by 1%.

If a cell is operated in a certain technical index, cell voltage should be determined by anode-cathode-distance (ACD). In other words, the cell voltage is decreased when the ACD is decreased, which will result in loss of the CE. Figure 1 shows the influence of the ACD on the CE.

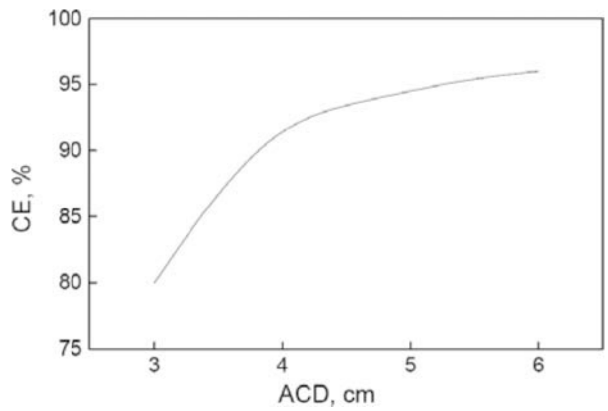

Figure 1: Influence of the ACD on the CE

For an industrial aluminum cell, the ACD should be confirmed when cell voltage is fixed. The cell voltage may be expressed by the following formula.

$$V_{cell} = E_0 + \eta_a + \eta_c + IR_a + IR_c + IR_B \qquad (2)$$

With
E_O— Theoretical decomposition voltage of Al_2O_3 in bath (V)
η_a—Anodic overvoltage (V)
η_c—Canthodic overvoltage (V)
R_a—Anode resistance (Ω)
R_B—Resistance of molten bath (Ω)
R_c—Cathode resistance (Ω)
I—Cell Current intensity (A)

For a cell, the voltage drop in molten bath is mainly determined by resistance of the molten bath itself. And the resistance and voltage drop in the molten bath would be increased due to the anode gas and the carbon particles entering into the bath.

As we know, for an aluminum cell the value of E_O, η_a and η_c should be given, so the cell voltage is dependent on the voltage drops of bath, anodes and cathodes.

If the voltage drops of anodes and cathodes are decreased, the voltage drop of the bath must be increased as the same cell voltage drop is kept, so the cell could be operated at bigger ACD and higher CE could be achieved, shown in figure 1. The DC power consumption of aluminum per ton would be thus reduced.

The voltage drops of anodes and cathodes could be decreased by the following measures:

- To decrease the electrical resistivity of anode
- To reducing contact resistance between anode steel stud and carbon anode
- To use graphitized cathode blocks
- To reduce properly current density of the cathode steel rod
- To improve the connection between cathode steel rod and cathode carbon blocks.

Feng proposes to improve the CE and reduce the cell voltage by using the novel structure cathodes (NSC) and the novel structure anodes (NSA). The principle of the NSC is by reducing the flow velocity and the wave amplitude of molten aluminum, while that of the NSA is by reducing bath turbulence resulted from anode gas emissions.

In addition to the above-mentioned technical methods, the DC power consumption can also be decreased by optimizing electrolyte composition and technology conditions. Conductivity of the electrolyte can be improved by adding lithium salt which would decrease liquidus temperature. However, the conductivity of the electrolyte at low electrolysis temperatures is lowered, so the effect of lithium salt on the conductivity of the bath in industrial cells would be limited.

However, as to a cell ($\overline{V} \approx 4.0$V) with relatively good CE, if the cell voltage is reduced forcibly without any measures of reducing voltage of anode, cathode or electrolyte as mentioned above, the results would be cutting down the ACD and losing the CE.

The Selection on Cell Voltage and the Structures of Cathode

The NSC cells have been widely used in China. The cathode carbon block of the first generation NSC cells has two longitudinal ridges. For the new generation NSC cells, there are many cylinder ridges on the cathode carbon block. The two different structure cells are shown in Figure 2 and Figure 3, respectively.

Figure 2: The first generation NSC cells
(350kA, in East Hope Group)

Figure 3: The new generation NSC cells
(350kA, in Qingtongxia Smelter)

The first generation NSC cells are successfully used in many smelters in China. A typical example of the application is in Zhejiang Huadong Aluminum Corporation Ltd. Ninety-four 200 kA NSC cells have been employed since June 2009. The cell working voltage is being kept at 3.72V (about 3.76V of the average cell voltage) with about 92% of the CE in the past three years. Now there are still about 70 mm high of the ridges, and the abrasion degree of the ridges is approximate 1.0 cm per year. The technical performance mentioned above is very typical in most smelters using the first generation NSC cells.

There are some smelters in the application of the first generation NSC cells with different technical conditions. For example, in Qingtongxia Smelter 350kA NSC cells have been operated at 3.87V of working voltage (3.9V of the average cell voltage), 2.5 of cryolite ratio, 960-965℃ of electrolysis temperature and 94% of CE.

The new generation NSC cell technology has been tested firstly in Qingtongxia Smelter and has been applied already by several smelters at present. In Qingtongxia Smelter, the new generation NSC cells have been operated at 3.85 V (3.88V of the average cell voltage) and a high CE, ~96%, and a low DC power consumption, 12,044 kWh per ton, have been achieved in the past ten months.

However other traditional structure cathode cells in Qingtongxia Smelter have worked at 4.0V (4.05V of the average cell voltage) with 2.45-2.5 of cryolite ratio, 960℃ of electrolysis temperature and 91.5% of CE are achieved.

Based on the above discussion, the technical condition of different structure aluminum electrolysis cells are shown in Table 1.

In Table I, for the aluminum cells with traditional structure cathode the better technical conditions are cell voltage at 4.0~4.1V, 91.5% of CE and 12,880~13,200 kWh/t-Al of DC power consumption in China. While the first generation NSC technology is used, the DC power consumption of aluminum per ton is 12,150~12,450 kWh and 600~1,000 kWh of energy per ton is saved.

Table I: Technical Conditions and Economic Indexes of Several Aluminum Smelters

	Amperage (kA)	Cell Working Voltage (V)	Cell Average Voltage (V)	CE (%)	DC Power Consumption (kWh/t-Al)
Traditional structure cathode cells, Qingtongxia Smelter	350	4.0	4.05	~91.5	13,190
Traditional structure cathode cells, Huadong Smelter	200	3.85	3.90	~90	12,913
The first generation NSC cells, Huadong Smelter	200	3.72	3.76	92	12,146
The first generation NSC cell, Jiaozuo Smelter	280	3.70	3.73	90.5	12,300
The first generation NSC cells, Qingtongxia Smelter	350	3.88	3.91	93.7	12,435
The new generation NSC cells, Qingtongxia Smelter	350	3.85	3.88	~96	12,044

CE would be lost with the decrease of cell voltage for both traditional cathode cells and NSC cells. For the first generation NSC cells, the cell voltage shouldn't be decreased to less than 3.80V, otherwise high CE will be difficult to maintain.

The interface of electrolyte and molten metal in the new generation NSC cells is more stable than that in the first generation NSC cells. For the new generation NSC cells operating at 3.85V (3.88V of the cell average voltage), current efficiency can be more than 95.5%. So the new generation NSC technology will be widely applied in the future.

For industrial aluminum cells CE is the most important technological and economic index. The higher the CE is, the higher the yields of aluminum are without any other investments. Generally, it is inadvisable to reduce the cell voltage merely for energy saving if that results in the decrease of the CE.

It takes the first generation NSC cells for examples. For 350 kA NSC cells of Qingtongxia Smelter, the working voltage is 3.88V (3.91V of the average cell voltage) with 93.7% of the CE and the DC power consumption is 12,435 kWh/t. For 280 kA NSC cells of Jiaozuo Smelter operating at 3.70V of cell voltage (3.73V of the average cell voltage) the DC power consumption is 12,300 kWh/t and the CE is only 90.5%. The cell voltage of the former (Qingtongxia) is 0.18V higher than that of the latter (Jiaozuo), and the DC power consumption of the former is 135 kWh/t higher than that of the latter. However, the CE of the former is 3.2% higher than that of the latter. In other words, the yield of the former is 3.2% higher than that of the latter.

Assuming that the aluminum yield is 500,000 ton per year and that the price of electricity is RMB 0.5 /kWh, for NSC cells using the former technology, operated at higher cell voltage drop with higher CE as in Qingtongxia Smelter, 3,108.75 million Yuan of energy will be cost. For NSC cells used the latter technology as in Jiaozuo Smelter, the 16,000 ton per year of aluminum yield will be decreased due to loss of the CE, so it is needed 2976.60 million Yuan of energy to produce 484,000 ton per year of aluminum with 12,300 kWh/t of DC power consumption. Comparing with the energy cost of the former, 132.15 million Yuan will be saved.

However, 16,000 ton per year of the yields would be decreased since the CE is reduced by 3.2%. If the market price of aluminum is 15,500 Yuan per ton in China and the income is about 10,000 Yuan per ton excluding the cost of raw material, the loss on economic benefit would reach 160 million Yuan per year due to the loss of the CE.

In summary, although the latter can save 132.15 million Yuan per year from the cost of the energy consumption, the economic benefit is 27.85 million Yuan per year less than that of the former.

Conclusions

The power consumption of aluminum electrolysis depends on both cell voltage and CE. Although, for traditional cells, the power consumption can be decreased by reducing cell voltage without any measures, the CE of cell would be lost. It is a disadvantage to decrease overly cell voltage for getting the maximum economic benefit.

For the first generation NSC cells, the DC power consumption of aluminum per ton is 12,150~12,450 kWh, which is 600~1,000 kWh per ton lower than the traditional cathode cells. For the new generation NSC cells operating at proper cell voltage, the higher CE is easily achieved since the interface of electrolyte and molten metals is more stable.

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