# Overview of High-Efficiency Energy Saving for Aluminium Reduction Cell

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**Abstract:** The paper indicates the potentiality of energy saving for aluminium reduction cell and comprehensive factors involved in execution of energy saving. Based on the application of recent developed high efficiency technologies, the major features and differences are exposed. Furthermore, the paper also indicates the world advanced level of Chinese energy saving techonology in aluminium reduction.

**Key words**: aluminium reduction cell, power cost, energy saving at all levels, material balance, electroheating balance, stability, current effciency

## 1 Preface

Chinese aluminium industry suffers 3 restrictions of energy shortage, power hike, and environmental protection & emission reduction currently. In 2008, reserve of bauxite in China was about 3.223 billion ton, of which provides 0.529 billion ton mining, taking up 1.96% of the world. On May 2010, NDRC, SERC and State Bureau of Energy jointly issued "Notification about favourable power price and other issues governing on high energy consumption enterprises", which prescribed differential prices of power in 8 industries, and a price markup separately to the confined enterprises and rejected enterprises by 0.10 Yuan and 0.30 Yuan. Further, Kyoto Protocal stipulates the validated age of $CO_2$ emission reduction by year of 2012 to 39 industrial developed countries. And, this the protocal may also be called for $CO_2$ emission imposition all-round to developing countries.However, the aluminium smelter produces $CO_2$ by 6750—7500kg per ton. In case of postulation that the sale price in Europe of certified volume of $CO_2$ emission reduction is €8.35 per ton and Chinese aluminium industry yields 20.62 million ton aluminium accepted, the $CO_2$ emission reduction fee will charge €1.162~1.291 billion.

Aluminium industry, called "Electricity Guzzler" became the major object of state micro-contro since 2008 because its power consumption took up 5.51% of China. Although the average DC consumption of aluminium industry decreased from 14085kWh in 2001 to 13258kWh in 2008, the increasing power price made the average cost of power in aluminium industry reaching 44.7%, which exceeded the defined 25% warming line of power cost by 20% in developed countries(See table 1-1)

**Table 1-1 Calculated average production cost in 2008 of China**

| Project | Alumina | Anode Carbon | Cryolite | Al-fluoride | Comprehensive power consumption | Manpower and depreciation | Total cost |
|---|---|---|---|---|---|---|---|
| Cost price,Yuan/t | 2650 | 2750 | 5300 | 5600 | 0.43kWh | — | — |
| Indication of nsumption, kg/t | 1950 | 500 | 5 | 27 | 14323kWh | — | — |
| Cost of primary aluminium,Yuan/t | 5168 | 1375 | 27 | 151 | 6159 | 800 | 13780 |
| Percentage | 37.50 % | 9.98% | 0.02% | 1.10% | 44.70% | 5.81% | 100% |

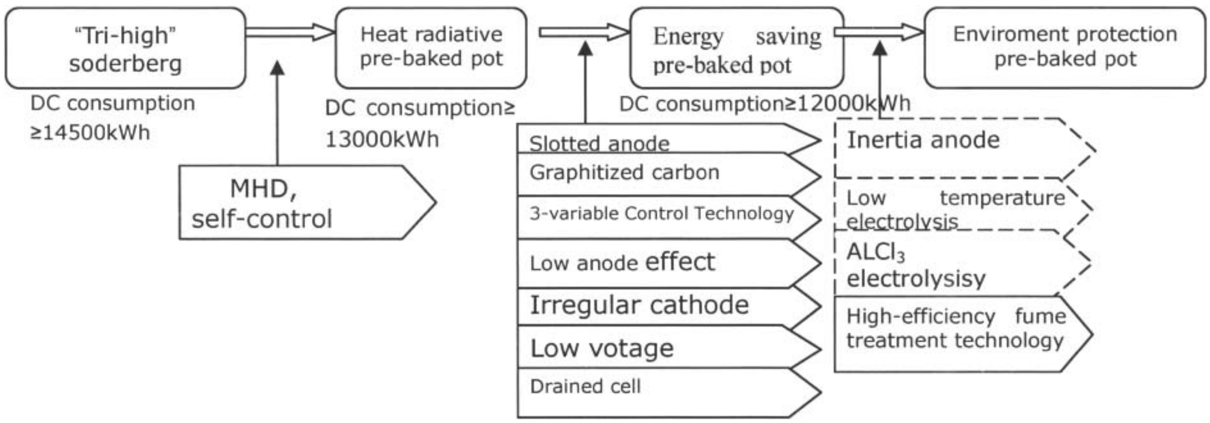
**Table 1-2 power price paid by aluminium enterprises of China in recent years Unit: Yuan/kWh**

| Year | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | World |
|---|---|---|---|---|---|---|---|---|---|
| Average price | 0.306 | 0.316 | 0.350 | 0.351 | 0.392 | 0.422 | 0.433 | 0.461 | 0.172 |

Followed with state policy of coal-power linkage at the end of 2004, compounded by the increasing collision of "market-oriented coal" and "planning power", the regulation on structure of power vs reform on power price could be inevitable. in despite of being the largest customer of power generation plant, aluminium industry was involved in the difficulty of surviving.So, for purpose of self-saving, aluminium industry in China should greatly conserve the energy at first, especially develop the technology of "energy saving at all levels" to be the only option.

## 2 Track of techonolgy "energy saving development" on aluminium industry in China

**Table 2-1 The following chart shows the track of techonolgy "energy saving development" in China:**




### 3 Principle of energy saving in aluminium industry

To have a better development and application of technology" energy saving at all levels" at alumiium cell, the necessity of analyzing the principle of energy saving is conducted.

**3.1 Cellentiality of energy saving in aluminium industry**

Principlly speaking, energy consumption in aluminium industry could be calculated by the following Ohm theorem and formula:

$$V = 2.98\frac{V}{\eta} = 2.98\frac{I \times R}{\eta} \qquad (1)$$

Apparently, the way to save the energy is either decrease of resistivity R or increase of current efficiency η.

To have a clean analysis of ptentiality of energy saving on aluminium cell,the voltage balance and energy balance of cell AP30 is adopted for illustration.

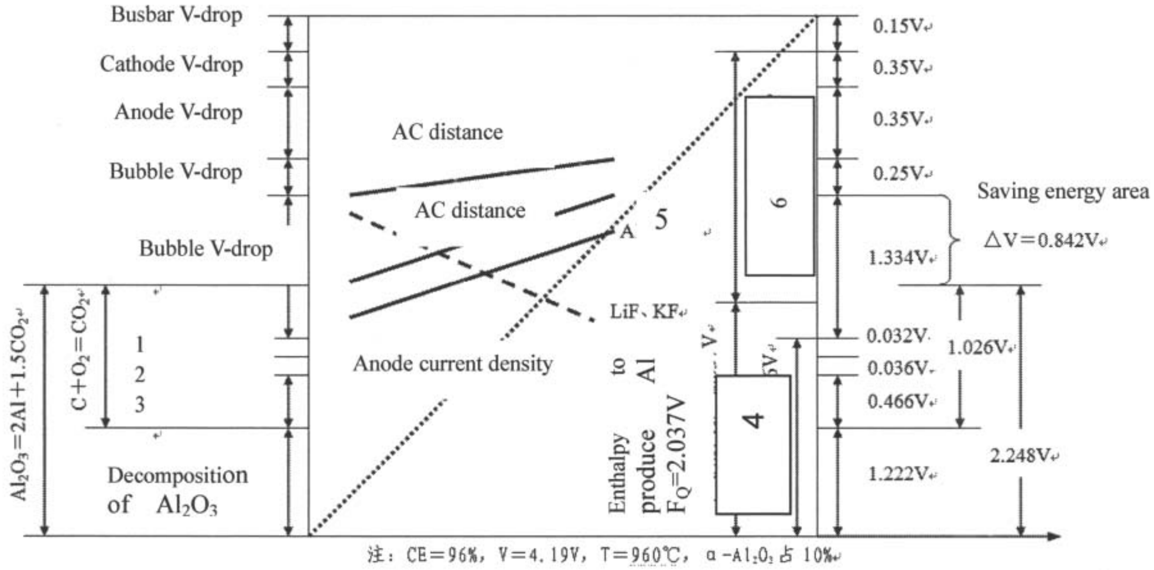



**Table 3-1： Pechiney voltage balance and energy balance of cell AP30**

1: cathode concentration overvoltage
2. anode concentration overvoltage
3: anode overvoltage
4: anti-equilibrium potential
5: excessive AlF3
6. heat loss 2.013V

From table3-1, the basic voltage to keep the cell in production is: :

V1 + V2 + V3 + V4 + V5 = 3.348V

V1: equivalent voltage

V2: bubble voltage

V3: anode voltage

V4: cathode voltage

V5: busbar voltage

However, the voltage of cathode-anode to keep the aluminium reduction production is:

$$2.248 - 1.756 = 0.492V$$

In case of postulation that voltage drop 0.300V of electrolyte at each cathode-anode by 1cm accepated, the minimum ACD is equally to the theoretical value of 1.6cm.

From table3-1, the voltage drop of electrolyte 1.334V (about4.45cm cathode-anode gap) requires1.334 - 0.492 = 0.842V (equal to 2.8cm ACD ) for compensation of heat loss, formation of profile, and compensation of energy consumption at cathode-anode gap for fluctuation of metal.

The movement of electrolyte and ACD could be indicated by the chart:

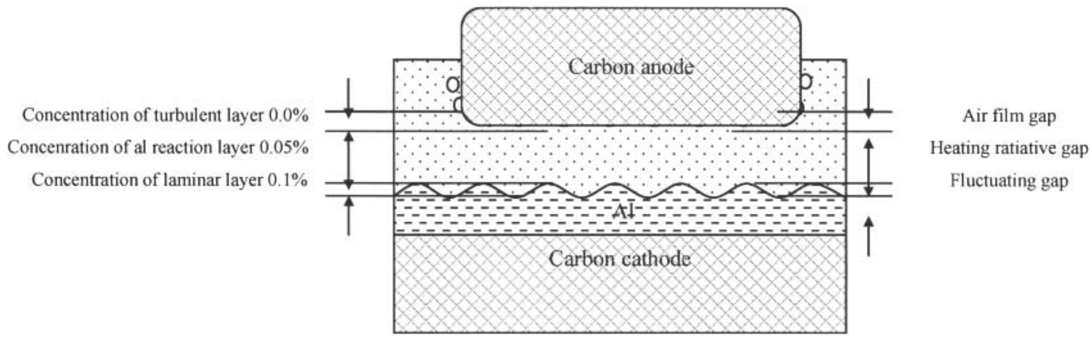



**Table3-2：movement of electrolyte and ACD**

Table 3-2 shows that , a minimum ACD , namely "distance of heat radiation" (could guarantee the normal production of aluminium reduction, and keep heat balance of cell), as well as"air film gap" required by bubble turbulent layer and "fluctating gap" caused by distorted metal (affected by magnetic field) and fluctuation.

The analysis mentioned-above indicates the 4 ways to save the energy by alumium cell.

1：Decrease of busbar voltage drop, cathode voltage drop and anode voltage drop；

2：Decrease of electrolyte voltage drop, including ACD reduced or increase of conductivity of electrolyte；

3：Lessen the fluctuation of metal；

4：Increase current efficiency.

### 3.2 Relation between voltage and current efficiency

A query is usually raised if the"energy saving at all levels" would affect thecurrent efficiency of aluminium reduction cell. Refers to the formula of heat balance by Mr. Shen Shiying [1]：

$$I\cdot R_{system} + (a + b\cdot\eta) = V_{heat\ radiation} \qquad (2)$$

That is to say, decrease of ACD means the decrease of $R_{system,}$ meanwhile, the current efficiency will be lower in case of $V_{heat\ radiation}$ remained. So the limit of decrease of ACD will be happened to the case when the current efficiency remained to each cells. This limit is the "heat radiative gap" foregoing.

The following 4 factors are necessary when decrease the ACD for having both "energy saving at all levels" and high current efficiency：

1）Better the composition of electrolyte, and improve the conductivity;

2）Take measures to releas the anode bubble and reduce the resistivity of air film;

3）Optimize the configuration of busbar, and improve the distortion and speed of circulatory flow of metal interface, as well as increase the statical stability of metal interface;

4）The drained cathode with flow-resist structure of lowers the interference of metal and improves the statical stability of metal interface.

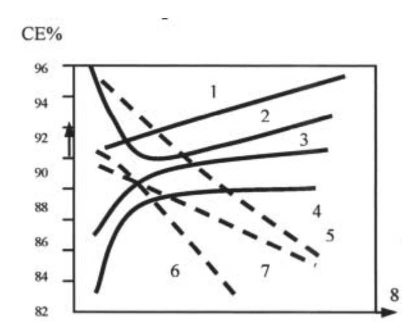
### 3.3 Factors affect the current efficiency

According to the integrative mechanism model formula of CE [2]：

$$CE(\%) = 100 - 219 d^{-1}_{en}\cdot D_{me}^{0.67}\cdot\mu^{-0.5}\cdot u_e^{-0.83}\cdot d^{-0.17}\cdot\rho^{1.5}\cdot C_{Al}(1-f) \qquad (3)$$

whereas：CE—current efficiency，%；$d_{en}$—current density of cathode，kA/m²； $D_{me}$— effective diffusion coefficient of interface tension correction；$\mu$—density of electrolyte；$u_e$—average velocity of bath flow compared with metel，m/s；$d$—ACD，m；$\rho$—desity of bath，kg/m³；$C_{Al}$ —saturated concentration of Al in bath；$f$ —proportionality coefficient of metal strength.

**Table 3-3 Dependence of factors aftect CE：**



1 . Excessvie $AlF_3$   2. Concentration of $Al_2O_3$   3. ACD
4. Current density of cathode   5. Velosity of surface metal flow
6. Distance of non-anode projection
7. Divergence of anode current distribution
8. Growth of factors invloved

## 4 New energy saving technology of aluminium reduction

The innovation on developing a number of technologies about the energy saving in aluminium reduction cellis is constantly taken. Mainly concludes:

### 4.1 Grooved anode technology

The slotted anode technology began with experiment of water model at inertia anode with groove at bottom by American Shekhar in 1990. It showed that anode bottom with groove was helpful to decrease the coverage of bubble at anode bottom and facilitate the mass transfer of alumina between anode and cathode.

There are horizontal and lenthwise types of grooves at bottom, of which the lenthwise is more popular. The experimental result of 300kA prebaked cell with grooved anode in China indicated that the grooved anode brought about 41mV [3] voltage drop than common anode.

### 4.2 Graphitized cathode technology

The cathode block of aluminium reduction cell comprises amorphous base, graphite, and graphitized carbon.

**Table 4-1**　　**Typical index of carbon blocks for aluminium**

| Material Index | Amorphous base | Graphite (10%) | Graphite (30%) | Graphite (50%) | Graphite (100%) | Graphitized carbon |
|---|---|---|---|---|---|---|
| Resistivity μΩm | 55-60 | 42-45 | 33 | 30 | 20 | 8 ~ 14 |
| Heat conductivity W/m·k | | 10 | 14 | 18 | 31 | 73 |
| Expansion of sodium , % | 0.6-1.5 | 0.3-0.5 | | | | 0.05-0.15 |
| Price , Yuan/t | 2400 | 3500 | 7000 | 10000 | 12000 | 17000 |

About 10~15% graphite of cathode has lower voltage drop than amorphous by 15 ~ 20mV , and 30% graphite of cathode is lower than amorphous by 45mV, from Pechiney AP18 cell by 2 years experiment.

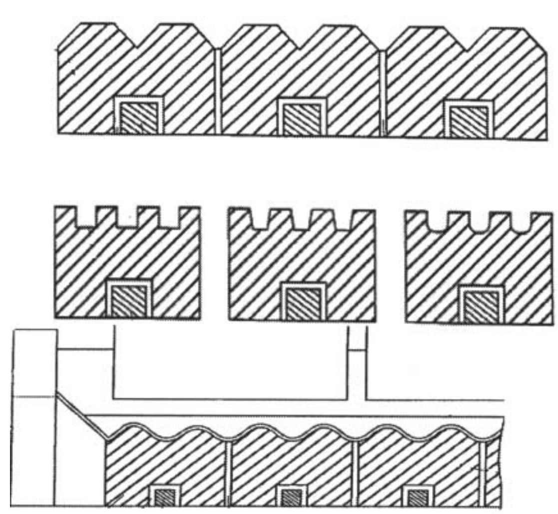
The graphite content 40% of cathode applied in Guizhou aluminium smelter 230kA cell brought about voltage drop by 53 ~ 83mV lower than 9% graphite of cathode. The graphite content 50% of cathode applied in 22 cells in Yunnan aluminium smelter showed the voltage drop of cathode block was lower by 50mV than common cathode block, as the voltage drop of cathode block around282 ~ 338mV, with average value 325mV. The graphitized carbon cathode applied in 16x 300kA cells of Wanji Aluminium smelter saved 80mV voltage compared with the graphite content 10% of cathode. Furthermore, the life up to 1216 days of cell could realize the profit and loss break-even point through calculation of application of graphitized cathode.

Due to the low thermal dilatation ( < 0.25% ) of graphitized cathode, the non-heating paste with low shrinage value ( < 0.15% ) is adopted to get rid of lining breakage at early stage..

After the partial 400kA pilot cells of Lanzhou aluminium smelter adopted graphitized cathode, the temperature at bottom of cell was inclinable to fall off somewhat as the current density of anode less than 0.8 ~ 0.82A/cm$^2$. However, after Wanji aluminium smelter adopted graphitized cathode on 300kA potlines, the current density of anode was increased to about 0.82A/cm$^2$ with current density up to 330kA 。

### 4.3 Flow resist technology of drained cathode

The flow resist techonology of drained cathode was early presented as “a series parallel channel or grooves struacture” of drained cathode in US patent (application number 6093304) by Vittorio de Noro and Nassau Bahamas in 2000., consisting of following 4 structures:



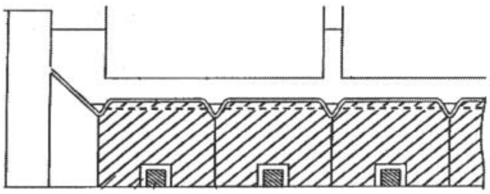


**Table4-1 : views of drainded cathode struture by foreign patent**

In China, Northeastern University, Yunnan aluminium smelter, Chalieco, etc had applied the patent. But the partial patents of China had been covered as the structures showed in table 4-1.

In the meanwhile, the applied achievement had been identified in Tiantail auminium, Yunnan aluminium, and East China aluminium. It indicated that the 1112, 743 and 817kWh was saved. After study on 10 smelters using flow resist techonology of drained cathode, the conclusion was summerized by the author:

1) The flow-resist block applied in drained cathode breaks the circular eddy of aluminium liquid and reduces both velocity of flow and fluctuation of interface of aluminium liquid, which improves the dynamic stability.

2) The cell, adopts insulating lining of drained cathode, could compensate 100mV voltage around the cell itself during heat radiation.

3) The flow-resist protruding part is neither small nor high. The top of protruding part has to be lower than the aluminium liquid by over 6cm, otherwise the protruding part would be worn badly during unequal current distribution at early stage and reduction at high temperature.

4) The cells with low current density of anode, or big processing side ( < 200kA), is inclinable to decrease in temperature and current efficiency when voltage drop > 0.2V.

5) Subject to to the heat balance formula (2) of cell, the voltage drop will be over 0.3V, and current efficiency will be lower by 0.5 ~ 2%.

Although the flow resist of cathode techonology is required to be improved somewhat, the great achievement of power saving become a technical attraction point in energy saving of aluminium industry in China.

### 4.4 Technology of low voltage to save the energy

The low voltage technology means not only the low voltage to be applied in busbar, anode, cathode conductor, and contact points between busbars, anodes, cathode conductors but also the further shortened ACD properly applied in a stable operation of the cell by utilizing the existing potentialities of ACD. The low voltage of energy saving technology depending on contraction of ACD requires the high ACD of cell ( > 4.5cm ) and is potentially stable.

The 7 aluminium enterprises of China using low voltage technology to save energy are investigated and listed in table 4-2

The effect of this technology shows the normal operation of cell working at 3.85 ~ 4.01V. The main characters are:

1) Followed with ACD closed to limitation of stability, the elaborated operation of operators are required highly.

2) To maximize the affection on dynamic stability of cell caused by shortened ACD, the aluminium liquid is generally increased.

The current is accordingly intensified if apply the shortened ACD directly onto the operating cell which brings into the insufficient internal heat.

**Table 4-2** **7 aluminium enterprises of Chalco using low voltage technology**

| Enterprises | Fa Xiang | Long Xiang | Zhong Fu | Lin Feng | Yugang Longquan | Wan Ji | Qin Yang |
|---|---|---|---|---|---|---|---|
| Capacity , kt | 85 | 60 | 460 | 360 | 860 | 650 | 18.6 |
| Current , kA | 190 ~ 215 | 173 | 338、414 | 221、400 | 304、400 | 175、330、428 | 162、320 |
| Setting voltage , V | 3.75 ~ 3.80 | — | — | 3.80 | — | 3.95 | — |
| Average votage , V | 3.85 | 3.90 | 3.85/400kA | 3.86 | 4.01 | 3.99 | 3.92、4.00 |
| Effect coefficient | 0.05 | 0.05 | 0.002 | 0.05 | 0.05 | 0.05 | 0.03 |
| Concentration of alumina , % | 1.5 ~ 2.5 | 2.0 ~ 2.5 | — | 2.5 ~ 3.0 | 2.5 ~ 3.0 | — | 2.8 |
| Aluminium liquid level , cm | 27 ~ 28 | 24 ~ 26 | 27 ~ 28 | 42 ~ 47 | 26 ~ 28 | 26 ~ 30 | 20 ~ 22 |
| Bath level , cm | 17 ~ 21 | 18 ~ 20 | 17 ~ 20 | 18 ~ 20 | 18 ~ 21 | 18 ~ 20 | 19 ~ 21 |
| Temperature of reduction , ℃ | 930 ~ 940 | 925 ~ 935 | 940 ~ 950 | 945 ~ 950 | 945 | 940 ~ 960 | 935 ~ 940 |
| Molecular ratio | 2.4 ~ 2.6 | 2.4 ~ 2.5 | 2.4 ~ 2.5 | 2.45 ~ 2.5 | 2.5 ~ 2.7 | 2.6 ~ 2.7 | 2.4 ~ 2.5 |
| Cathode voltage drop , V | 363 | 400 | 350 | 360 | 320 | 280 | 351、320 |
| CE , % | 90 ~ 91 | 91 ~ 92 | 92.5 | 90 ~ 91 | 92 | 92.5 | 93 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Comprehensive AC consumption，kWh | 13740 | 13550 | 13740 | 13525 | 13700 | 13900 | 14700 |

### 4.5 Drained aluminium reduction cell technology

The new drained aluminium reduction cell technology jointly developed by Zhengzhou Research Institute of Chalco, SAMI and GAMI was identified that it saved 1220kWh per ton of aluminium by China Non-ferrous Metals Industry Association in April, 2009

The drained cell was initially presented in "Mushroom" shaped TiB2 coating of graphite cathode by American Kaiser Mead smelter. In 1986, Austrialia Comalco conducted the titanium boride coating and drained cathode industry experiments on 92.5kA cell. But the cell was only working for 700 days.Afterwards, there was no any progress in the world.

The main feature of new Chalco cell is $TiB_2$-C coating cathode, netted drained grooves for flush flow. As the $TiB_2$-C cathode increase the wettability of aluminium liquid, and the netted drained grooves for flush flow enhance the dynamic stability of cell, the prospective possibility for having further shortened ACD to save energy become more wide. The pilot cell of Qinyang, and the application in Lanzhou smelter, and Jiaozuo Wanfang, etc indicates that the voltage of cell could be decreased by 3.69 ~ 3.75V (ACD less than 3.7 cm).

Competitively, the potentiality of new cell developed by Chalco is farther on saving energy.

### 4.6 CE increase by '3-Variable'Control Technology

A very important indication of cell having high efficient energy saving is both the material balance and electroheating balance achieving the optimum controllability. There are 2 main techinical features of GAMI's '3-Variable'Control Technology as follows:

1 ) Material "deficiency" control

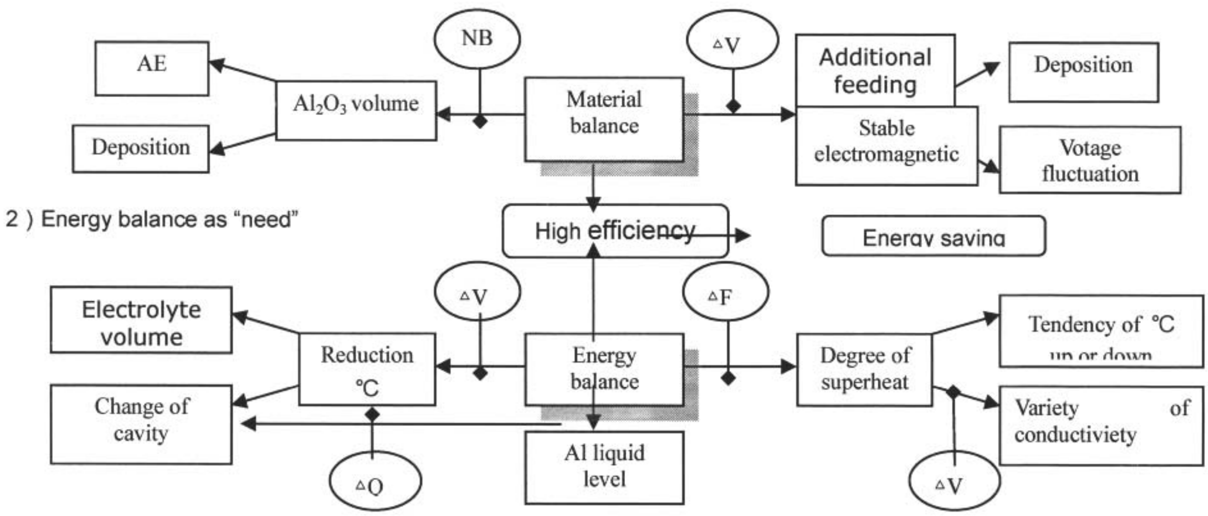



**Table 4-2**

Optimum control on material balance is aiming at controlling "deficiency" through timely trim the feeding interval to match cell production, in order that the bad cell operation may be encountered due to excessive feeding. And, the electroheating balance is to keep the degree of superheat, regulation of cavity, and increase of CE via regulating ACD, aluminium volume and excessive AlF3. This is the core of '3-Variable'control technology, of which the application brings the increase of CE by 1 ~ 2.5% efficiently.

From talbe 3-3, accompanied with decrease of molecular ratio but increase of excessive AlF3 volume, CE will be improved. However, the decreased molecular ratio would lead to reduce the conductivety of electrolyte and cell temperature, which may cause heat out of balance and decreased solubility of alumina. The pracitise tells that the voltage drop of electrolyte will be increased about 30mV as molecular ratio decreased by 0.1. The bath conductivity ρis of direct ratio for molecular ratio CR and temperature T of molten bath derived from the formula [4] in respect to additives against conductivity ρ of molten bath:

$$\ln\rho = 2.0156 - 0.0207Al_2O_3\% - 0.005CaF_2\% - 0.0166MgF_2\% + 0.0178LiF\% + 0.0077Li_3AlF_6\% + 0.0063NaCl\% + 0.4349CR - 2068.4/T$$

So, there are 3 measure to be taken to increase the CE by decreasing the molecular ratio: □increase the voltage according to the decreased molecular ratio;or □improve the solubility of alumina; or □enhance the conductivity of bath. The affection of additives are versatile and complicated, for instance, LiF could increase the bath conductivity greatly but lead to a big fall of temperature, and the high concentration of LiF ( > 3% ) may also result in bad affection in case of improper control.

### 5 Conclusion

Under the multi-pressures at present, aluminium industry of China has to carry out the policies of energy saving at all levels and cost reduction. In respect of principle of energy saving, the cell is potentially to be excuted with energy saving but never only on 1 factor. As the loss of CE by 1% equally to increased voltage drop by 100mV subject to the cost of primary aluminium, the shortened ACD technology to save energy is favorable to avoid possible bad cell operation and big loss of CE.

The newly developed energy saving technology in China have different features and bring about diversly good effect in saving. In despite of a gap in front of the Chinese CE coefficient to world top level, the great contribution had been made by Chinese aluminium industry to the world. By Chinese unremitting effort, the DC coeffieient of alumium reduction cell could be 12500KWh and even realize the energy consumption and high efficeint index of 12000kWh in the future. So, the date of Chinese aluminium industry catches up with and surpasses the top level is not too far.

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【4】 Aluminium Smelter Technology , K. Grjotheim and B.J.Welch