DEPTH ANALYSIS AND POTENTIALITY EXPLOITATION ON ENERGY-SAVING AND CONSUMPTION-REDUCTION OF ALUMINUM REDUCTION POT

Zhou Jianfei[1], Marc Dupuis[2], Yan Feiya[1], Huang Jun[1], Yi Xiaobing[1]

[1]CHALIECO GAMI Guiyang Guizhou China 550081
[2]GéniSim Inc., 3111 Alger St., Jonquière, QC, Canada, G7S 2M9

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Abstract

In view of the existing status with aluminum overcapacity and lower aluminum price in China, many companies adopted various measures to reduce the production cost and the energy consumption, but there has been no a normalization theory and method as yet. Aimed at the existing status and the market demand, this paper puts forward the evident effects of energy-saving and consumption-reduction in aluminum reduction pot using new thermal insulation pot lining design, application of optimal cathode structure, reduction of horizontal current device, proper application of new lining materials and proper combination of relevant process parameters based on the finite element software ANSYS and using the thermal field simulation software of international simulation Prof. Mr. Dupuis as the calculation method, combining the actual production data. 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 a upsurge of scientific and technological innovation activities on quality and capacity increase, energy-saving and consumption-reduction as well as environment protection. The key technologies in aluminum reduction area such as low-temperature reduction, intensifying current, on-line measurement of superheat, "3-variable " control technology, anode slotting technology, irregular cathode technology, thermal insulation lining structure, cathode for horizontal current reduction, application of new lining materials, inert anode etc. are studied and developed, which raises Chinese aluminum reduction technology to the world advanced level soon. Moreover, the consumption of energy and raw material for aluminum reduction production is very high in recent years, especially power consumption. With the energy crisis, the aluminum reduction production costs must be reduced without delay. For this, the most efficient method is to reduce the DC consumption by increasing current efficiency (CE) and reducing cell 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 in [1].

The heat input and output may be divided into the followings:

Heat input

1. Current (variable)
2. Voltage
 2.1 Anode (constant)
 2.2 Cathode (constant)
 2.3 ACD
  2.3.1 Bubble voltage drop (variable)
  2.3.2 Bath voltage drop—ACD, bath ratio (variable)
  2.3.3 Back-EMF (constant)

Heat output

1. Heat dissipation at pot top (internal cause: Topr)
   (External cause: material and thickness of anode covering materials, flue gas velocity and sealing degree of pot hood)
2. Heat dissipation at pot side (internal cause: Tsuper)
   (External cause: bath level, metal level, pot lining design)
3. Heat dissipation at pot bottom (internal cause: Topr)
   (External cause: material and thickness of cathode lining)

The object of voltage reduction is the voltage combination in the heat input, the majority of which is voltage drop of ACD (anode cathode distance).

It should be pointed out that the high-temperature production during aluminum reduction mainly depends on the Joule heat generated from current passing in the bath between the anode and 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 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 heat dissipation of heat output

About half of the total power input in pot is used for aluminum production and the other half is lost through heat dissipation, so the focus of the pot voltage reduction is to reduce the heat dissipation loss. The proper specification of the thickness of the side ledge is at the core during voltage reduction. Both too thick ledge or too thin ledge have a negative effect on the pot stability during production, thus affecting the voltage reduction effect and the CE, even cause the pot leaking. Therefore, the reasonable heat dissipation distribution and the proper side ledge formation are the core of new thermal insulation lining optimization design.

Heat dissipation at pot top

The heat dissipation at the top of the pot accounts for about half of total heat output, so the focus of the heat output reduction is to reduce the heat dissipation at this point. For the conventional pot, the top heat dissipation is in the range of 1.0V to 1.2V, and the pot voltage is required to be above 4.16V. However, based on the statistics of the pots with different currents, the top heat dissipation is below 0.98V for the pots with al voltage lower than 3.9V. This is to say that the top heat dissipation reduction provides the larger space for the total heat dissipation reduction, which contributes greater to the pot voltage reduction.

There is an important relationship between top heat dissipation and pot voltage. Using the actual data from a 320 kA pot in a Chinese smelter, this paper will try to explain it. A first type of pot (Type A), with a thinner covering material, a voltage of 4.16 to 4.18V and a heat dissipation of 1.153V in the anode area, is shown in Table 1.

Area	Heat dissipation area		Heat dissipation (kW)	Heat dissipation (V)	%
Anode area	Pot hood	Pot side cover plate	112.8	0.346	18.4
		Pot rim plate	15.5	0.047	2.5
		Pot end cover plate	15.0	0.046	2.4
		Sub-total	143.2	0.439	23.4
	Pot superstructure	Pot top	43.4	0.133	7.1
		Anode guide bar	7.4	0.023	1.2
		Fume	181.5	0.557	29.7
		Sub-total	232.3	0.713	38.0
	Total		375.5	1.152	61.4

Table 1. Heat dissipation distribution (anode area) for a Type A pot

The second type of pot (Type B), which presents a thicker covering material, a pot voltage of 3.8 to 3.85V and a heat dissipation of 0.98V in the anode area, is shown in Table 2.

Area	Heat dissipation area		Heat dissipation (kW)	Heat dissipation (V)	%
Anode area	Pot hood	Pot side cover plate	97.1	0.298	16.1
		Pot rim plate	21.0	0.064	3.5
		Pot end cover plate	16.3	0.050	2.7
		Sub-total	134.4	0.412	22.2
	Pot superstructure	Pot top	67.1	0.206	11.1
		Anode guide bar	6.9	0.021	1.1
		Fume	111.5	0.342	18.5
		Sub-total	185.5	0.569	30.7
	Total		319.8	0.981	52.9

Table 2. Heat dissipation distribution (anode area) for Type B pot

Material and thickness of covering materials

The pot thermal balance shall be regulated by controlling the alumina content as well as the thickness of covering materials. For large-scale pots, it is necessary to take the insulation measures at the middle and end of pot, make use of the different thickness of the covering materials to adjust the total thermal balance uniformity of pot, thus guaranteeing the uniformity and regularity of the side ledge.

The material composition of the covering materials is relevant to the alumina content and the bath crushing size in the covering materials, it is shown as Figure 1.

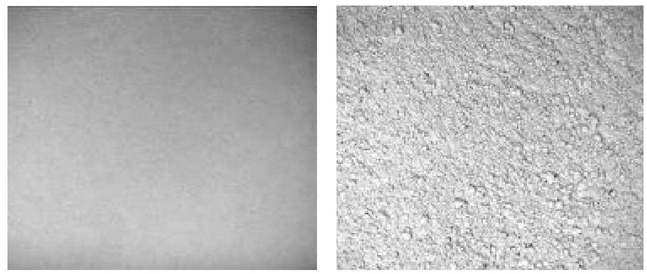

Figure 1. Covering materials sample with above 93% Al_2O_3 left, covering materials sample with below 13% Al_2O_3 and 0.5-8mm bath crushing size right

The thickness of covering materials has a major impact on the heat dissipation at the top of the pot. Taking a 350 kA pot as an example, its simulation is performed (bath content and alumina content in the proportion of 1/1 in covering materials).

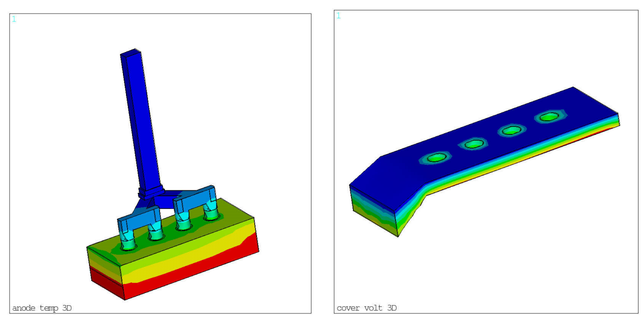

Figure 2. 350 kA, covering materials with a thickness of 10 cm

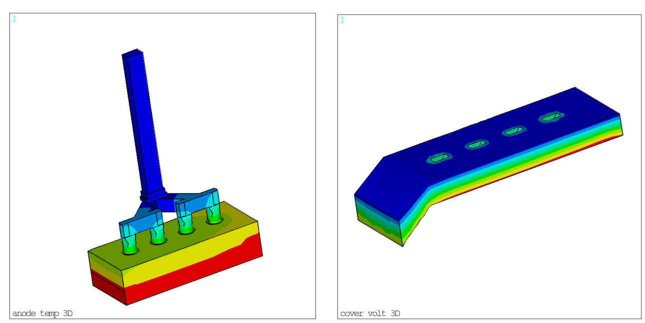

Figure 3. 350 kA, covering materials with a thickness of 18 cm

As shown in Table 3, for the covering materials with alumina content and bath content in the proportion of 1/1, when the thickness is respectively 10 cm and 18 cm, the reduced voltage of heat dissipation is respectively 1.046V and 0.883V. This shows that the voltage can be reduced by about 20 mV using the covering materials.

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Covering materials with 10 cm thickness
                                                      kW/V          %
Heat dissipation of aluminum guide bar :          20.480/0.059    2.75
Heat dissipation of anode stub:                  150.976/0.431   20.31
Heat dissipation of horizontal covering layer:   169.116/0.483   22.75
Heat dissipation of slope covering layer:         23.869/0.068    3.21
Heat dissipation of inner rim plate at pot side:   0.492/0.001    0.07
Heat dissipation of inner rim plate at pot end:    1.089/0.003    0.15

Heat dissipation of anode area:                  366.022/1.046   49.23


Covering materials with 18 cm thickness

Heat dissipation of aluminum guide bar:           22.759/0.065    3.31
Heat dissipation of anode stub:                  136.407/0.390   19.87
Heat dissipation of horizontal covering layer:   124.906/0.357   18.19
Heat dissipation of slope covering layer:         23.505/0.067    3.42
Heat dissipation of inner rim plate at pot side:   0.492/0.001    0.07
Heat dissipation of inner rim plate at pot end:    1.089/0.003    0.16

Heat dissipation of anode area:                  309.158/0.883   45.03
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Table 3. Impact of different thickness covering materials on voltage reduction

<u>Application of new pot hood</u>

The new energy-saving sealed pot hood has a layer of high temperature fire resistant and thermal insulation composites on the hood internal face. This layer can prevent the heat in the pot from transferring outside through the side hood, thus reducing a lot of the heat loss, which complies with energy-saving goals. Through testing, the pot hood surface temperature shall be reduced by more than 10°C and the reduced voltage shall be reduced by 5 to 15mV using the new pot hood compared to the conventional pot hood.

Heat dissipation at pot side and pot bottom

The heat dissipation at the pot side and bottom accounts for about half of the total heat output. The superheat is directly related with the heat dissipation, the principle of which is to maintain the production under low voltage through lower superheat in order to guarantee the energy balance. The pot lining design is indirectly related with the heat dissipation. The purpose is to form a uniform yet not excessive ledge thickness under low superheat in order to guarantee a stable and effective production. Therefore, the pot with a lower voltage must be running under the thermal balance with a lower superheat. So the proper pot lining should be match to guarantee a reasonable heat dissipation distribution and a uniform yet not excessive ledge thickness.

Based on the technical features of Chinese aluminum reduction and the market demand, the SIMULATION SOFTWARE OF ENERGY BALANCE OF ALUMINUM REDUCTION POT is currently developed by GAMI combining the thermal field simulation software of international simulation Prof. Mr. Dupuis. It aims at matching various-scale pots as well as the advanced aluminum reduction technologies and process parameters using the cathode model at pot side and at pot end as well as an anode model in a three-in-one united method[3] based on reasonable heat dissipation and proper ledge thickness after it has been modified through years of checking and verification.

The relationship of optimal ledge thickness and bottom ledge length is shown in Table 4 after numerous calculations and monitoring validations (including 6, 160, 240, 300, 350, 400 and 500 kA pots) in recent years. Relationship among pot voltage, superheat and lining thermal insulation structure in 160 to 450 kA pots is shown in Table 5.

	Pot side ledge thickness (cm)	Pot side bottom ledge length(cm)	Pot end ledge thickness (cm)	Pot end bottom length(cm)
Flat-bottom cathode	8-15	5-15	12-18	8-18
Irregular-bottom cathode	10-18	20-25 (inside groove)	13-20	10-20

Table 4. Relationship of optimal ledge thickness and bottom ledge length

Pot voltage	3.7 to 3.9 V	3.9-4.1 V	4.1-4.2 V
Superheat	Below 7 °C	8-10 °C	Above 10 °C
Thermal insulation area	Thermal insulation of side, lower side and bottom	Thermal insulation of side and bottom	Thermal insulation of bottom

Table 5. Relationship among voltage, superheat and lining thermal insulation

<u>Heat dissipation distribution calculation and actual measurement comparison between conventional lining and new thermal insulation lining in 350 kA pot</u>

According to the results presented below for the comparison of cathode design: 1) conventional lining and insulation lining using flat bottom cathode fit with conventional paste to connect steel bar and 2) irregular cathode fit with cast iron pouring to connect steel bar.

The comparison of process parameters control in Table 6, shows the following differences between the conventional lining and the irregular cathode lining: 22 and 12 cm for the aluminum level, 5.4 and 4.5 cm for the ACD, and 8 and 7°C degrees for the superheat.

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Conventional lining structure

Current density:                     350000 (A)
Metal level:                           22.0 (cm)
Bath level:                            18.0 (cm)
ACD (anode cathode distance):           5.4 (cm)
Covering material thickness:             18 (cm)
Al2O3:                                  2.5 (%)
AlF3:                                    10 (%)
LiF:                                      1 (%)
MgF2:                                   0.4 (%)
CaF2:                                   5.6 (%)
Liquidus temperature:                945.32 (°C)
Superheat:                              8.0 (°C)

New thermal insulation lining structure

Current density:                     350000 (A)
Metal level:                           12.0 (cm)
Bath level:                            18.0 (cm)
ACD (anode cathode distance):           4.5 (cm)
Covering material thickness:             18 (cm)
Al2O3:                                  2.5 (%)
AlF3:                                    10 (%)
LiF:                                      1 (%)
MgF2:                                   0.4 (%)
CaF2:                                   5.6 (%)
Liquidus temperature:                945.32 (°C)
Superheat:                              7.0 (°C)
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Table 6. Comparison of process parameter controls

The comparison of the obtained of pot voltage in Table 7, conventional lining and irregular cathode lining are: 4.17 and 3.85 V respectively ;

Conventional lining structure		
Anode voltage drop:	346	(mv)
Clamp voltage drop:	15	(mv)
Guide rod voltage drop:	26	(mv)
Explosive welding voltage drop:	8	(mv)
Anode stub voltage drop:	42	(mv)
Voltage drop of iron/carbon joint:	105	(mv)
Carbon block voltage drop:	150	(mv)
Bath layer voltage drop:	1502	(mv)
Bubble layer voltage drop:	170	(mv)
Cathode voltage drop:	284	(mv)
Cathode steel bar voltage drop:	109	(mv)
Cathode joint voltage drop:	106	(mv)
Cathode carbon block voltage drop:	69	(mv)
Counteraction electric potential:	1672	(mv)
Voltage drop for busbar around pot:	200	(mv)
Pot working voltage:	4.174	(V)
New thermal insulation lining structure		
Anode voltage drop:	347	(mv)
Clamp voltage drop:	15	(mv)
Guide rod voltage drop:	26	(mv)
Explosive welding voltage drop:	8	(mv)
Anode stub voltage drop:	42	(mv)
Voltage drop of iron/carbon joint:	104	(mv)
Carbon block voltage drop:	151	(mv)
Bath layer voltage drop:	1228	(mv)
Bubble layer voltage drop:	170	(mv)
Cathode voltage drop:	229	(mv)
Cathode steel bar voltage drop:	106	(mv)
Cathode joint voltage drop:	64	(mv)
Cathode carbon block voltage drop:	59	(mv)
Counteraction electric potential:	1672	(mv)
Voltage drop for busbar around pot:	200	(mv)
Pot working voltage:	3.846	(V)

Table 7. Comparison of voltage distribution

The comparison of the temperature distribution, the highest temperature of lateral steel plate of the side for conventional lining and irregular cathode lining are 301 and 230°C .

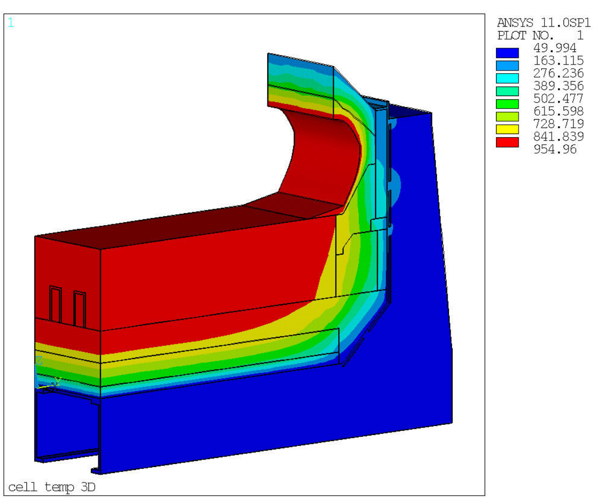

Figure 4. Conventional lining structure, pot side temperature

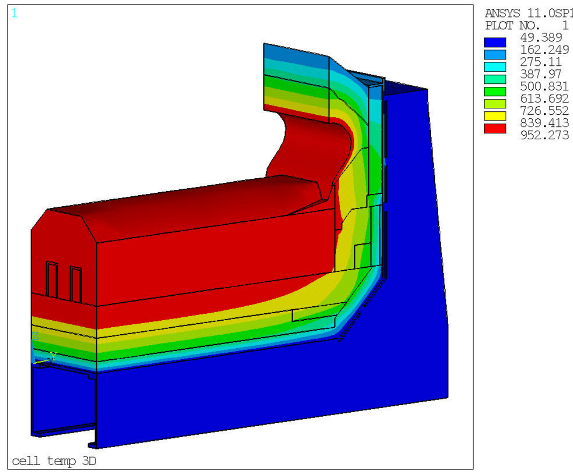

Figure 5. New thermal insulation lining structure, pot side temperature

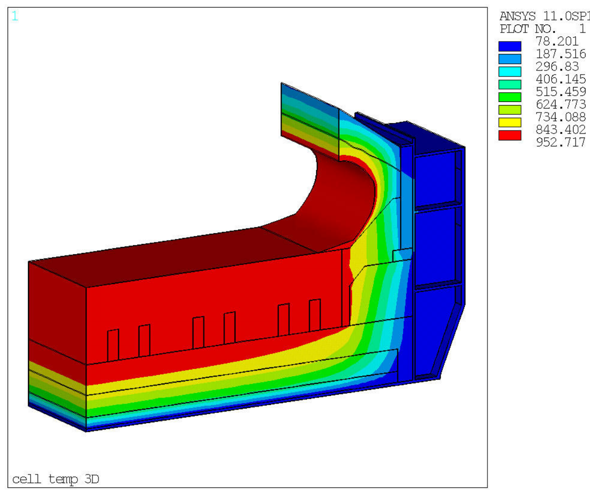

Figure 6. Conventional lining structure, pot end temperature

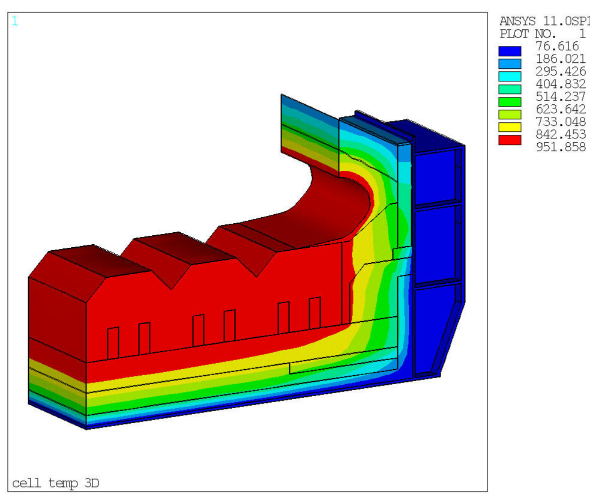

Figure 7. New thermal insulation lining structure, pot end temperature

Comparing the two linings show also 10.9 and 12.4 cm for the thickness of the profile ledge of the side, 16.7 and 17.6 cm for the thickness of the profile ledge of the end, 18 and 30 cm for the ledge toe of the side and finally 13.8 and 27 cm for the ledge toe of the end.

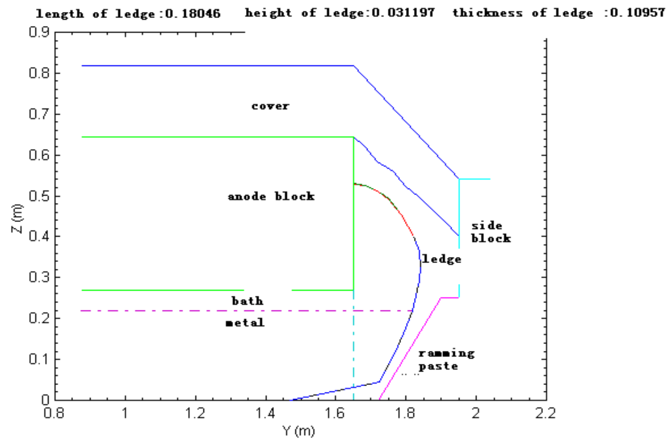

Figure 8. Conventional lining structure, profile of pot side ledge

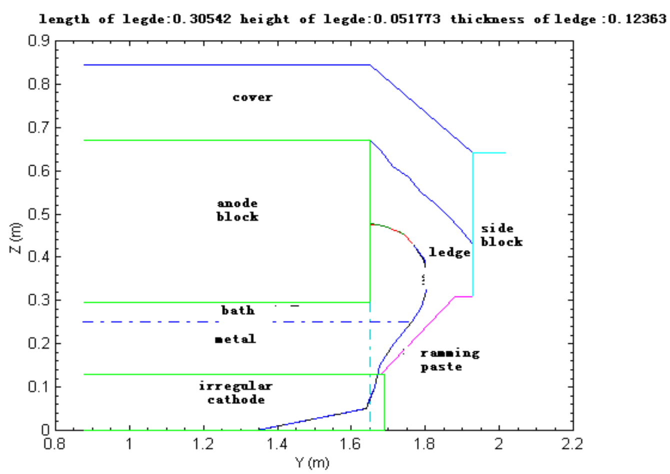

Figure 9. New thermal insulation lining structure, profile of pot side ledge

From the comparison of the heat dissipation distribution, the main realization of reduced of heat dissipation loss is in the cathode area. The reduced heat dissipation quantity in the cathode area corresponds to 300 mV and reduced heat dissipation in the anode area corresponds to 50 mV. In the cathode area, the reduced heat dissipation at lateral part accounted for the most, with approximately 275 mV. The heat dissipation distribution proportion, anode area and cathode area of conventional lining are 47.02% : 52.98% and 54.16% : 45.84% for the new thermal insulation with irregular cathode lining. The proportions of the two linings are reverse.

Conventional lining structure

	V	%
Anode area:	0.971	47.02
Cathode area:	1.094	52.98
—Side part of pot:	0.663	32.11
—Pot rim plate:	0.103	4.99
—Bottom of pot:	0.163	7.90
—Steel bar head:	0.165	7.98

Energy utilization ratio: 45.21%

New thermal insulation lining structure

	V	%
Anode area:	0.928	54.16
Cathode area:	0.785	45.84
—Side part of pot:	0.388	22.65
—Pot rim plate:	0.068	3.97
—Bottom of pot:	0.143	8.33
—Steel bar head:	0.187	10.89

Energy utilization ratio: 50.25%

Table 8. Comparison of heat dissipation distribution

For the economic benefit, with the prerequisite that efficiency loss of insulation lining is 1-2% of the conventional lining, it can still save 900 kWh/T of electric energy consumption.

Conventional lining structure

Current efficiency:	94 %
Daily aluminum production:	2650 kg
Direct current consumption:	13231 kWh/T

New thermal insulation lining structure

Current efficiency:	93 %
Daily aluminum production:	2622 kg
Direct current consumption:	12323 kWh/T

Table 9. Comparison of economic benefit

Heat dissipation distribution comparison between conventional lining and new thermal insulation lining

		Convention al lining	New thermal insulation lining
Heat dissipation distribution %	Anode area	43	>54
	Cathode area	57	<46
	Lateral part of pot	35	<25
	Pot rim plate	7	6
	Bottom of pot	7	7
	Collector bar head	8	8

Table 10. Heat dissipation distribution comparison between the conventional and the new thermal insulation lining

According to Table 10, heat dissipation distribution proportion of cathode and anode for new thermal insulation with irregular cathode lining is reverse the one observed for conventional lining. The cathode area is decreased from 57% to 45%, the biggest decrease (35% to 25%) being at the pot side.

Rational application of new lining insulation material

In the last two years, in the quest to decrease pot voltage and introduce new thermal insulation lining, the application and popularization of new insulation lining material have become the focus for aluminum industry. Ceramics fiber, compound silica acid magnesium aluminum type thermal insulation material are now widely used at inner and outside insulation structure of pot.

Conclusions

From the above mentioned, by the way of lots of industrialized experiments, testing at the site, computer simulation and comparisons, the ways and the methods to decrease energy consumption through pot voltage reduction with respect to heat dissipation are as follows: material and thickness of anode covering material, new-type thermal insulating lining and new-type thermal insulating lining material.

Comparing with the conventional pot, the reduced cell voltage is around 200-450 mV. The reduced energy consumption per ton aluminum is around 640-1440 kWh/T based on the calculation of 93% current efficiency. The annual reduced energy consumption of the pot line is around $32*10^7$-$72*10^7$ kWh per year based on the calculation of an annual capacity of 500 thousand tons. The operation cost savings are in the range of 160 to 360 million Yuan per year as per 0.5 Yuan per kWh convertion for the power price.

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