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Heat balance simulation of drained aluminum reduction cell ①

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Abstract: Compared with a conventional Hall-Heroult cell(H-H cell), the interpolar distance of a drained cell can be reduced significantly and the cell voltage and heat produced in the electrolysis will decrease greatly as well, which makes it crucial to achieve a new heat balance in the drained cell. A half anode-cathode slice model of a hypothetical drained cell retrofitted from a 160 kA currently used in H-H cell was developed for the thermo-electric calculation and simulation. The results were presented and analyzed and possible approaches for setting up a new heat balance in a drained cell were discussed.

Key words: drained cell; thermal-electrical calculation and simulation; half anode and cathode slice model; heat balance
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1 INTRODUCTION

The carbon-lined bottom of the existing Hall-Heroult(H-H) cell works as the cathode and also as a container, in which the molten aluminum pad is accumulated to a height of about 18 to 20 cm. The metal pad is beneficial to the wettability of the carbon cathode and the reduction of contact resistance between the carbon cathode and aluminum liquid. However, because the molten aluminum pad which also serves as the cell cathode can become irregular and variable in thickness due to electromagnetic effects and bath circulation, it is required that the anode cathode distance (ACD) should be kept at a safe range from 40 to 45 mm to keep the metal pad from contacting with the carbon anode and to ensure relatively high current efficiencies. Such gap distances result in a voltage drop on the bath resistance from 1.3 to 1.8 V, which is in addition to the bubble induced voltage drop and the energy required for the electrochemical reaction itself, and average cell voltages from 4.0 to 4.7 V, with an average energy consumption close to 15.0 kWh/kg Al[1].

Because of the drawbacks mentioned above, great efforts have been made to seek alternatives for the existing H-H cell. It is found that drained cell is a good choice. Since 1960's, many patents on drained cells have been filed. For example, the "mushroom" shaped cathodes protruding above the metal pool to form the cathode surface instead of the carbon cathode were tested in the aluminum reduction[2]. Major efforts were made on the sloped drained cathode with a layer of aluminum wettable materials coated on its surface, on which the metal was produced and drained to a central sump[3, 4].

From 1987 to 1998, great work had been done on the drained cell in Comalco, Australia; 25 drained cells were set up and operated at 120 kA, 1.15A/cm^2 anode current density and 2.5 cm ACD, with an energy consumption of 13.2 MW·h·t^{-1} Al. The cell bottom was V-shaped and the sump located at its center[5].

2 HEAT INPUT AND OUTPUT OF DRAINED CELL

For a running cell, heat is lost on the outside surface of the pot shell through convection and radiation, or is carried away by the fume. Joule heat resulting from the electric current flowing in the cell along with the superheat in the liquid metal and electrolyte constitute the heat input.

Since except the cathode and anode block, slight changes are to be made on the cell construction, if the cell amperage and temperature keep unchanged, the heat losses from the top and the bottom of the cell will change only a little.

Elimination of the metal pad promises large heat saving through minimizing convective heat loss to the cell walls. Typical heat loss from the side wall is about 40% of the total heat loss of the existing H-H cell[6].

The voltage drop which contributes to the heat input inside a cell including back electromotive force:

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(BEMF), voltage drop caused by the bath resistance, bubble induced voltage drop, anode voltage drop, and cathode voltage drop. First, when a drained cell is retrofitted from an existing H-H cell, if the same carbon anode and cathode are used, the BEMF, anode voltage drop and cathode voltage drop will bear little changes. Second, if the single sloped anode is adopted, nearly all of the bubbles travel the length of the anode, the distance between the position of initial formation of the gas bubbles and the exit point from the ACD gap may be quite long and the bubble volume will tend to accumulate with distance under the anode[7], which makes that the bubble-induced voltage drop probably cannot be reduced much. Third, the voltage drop reduction on the bath resistance is greater when reducing the ACD from more than 40 mm to 20 - 25 mm, which imposes a large impact on the heat balance of a drained cell.

How to reestablish a workable heat balance in the drained cell has become a key issue concerning the retrofitting.

A half anode-cathode slice model (Fig. 1) of a hypothetical drained cell retrofitted from a 160 kA conventional H-H cell was developed using the finite element code for thermo-electric calculation and simulation, especially the voltage drop on the bath resistance under different cell amperages was calculated. The results are presented and analyzed in this paper, and possible approaches of achieving a heat balance in a drained cell are discussed.

3 CALCULATIONS

3.1 Relevant parameters of 160 kA H-H cell

Some relevant parameters of a 160 kA conventional H-H cell are listed in Table 1.

Table 1 Some parameters of 160 kA prebaked cell

Parameter	Value
Inside potshell size	9.45 m × 4.1 m × 0.52 m
Anode dimension	1.45 m × 0.66 m × 0.54 m
Cathode dimension	3.25 m × 0.515 m × 0.45 m
Width of central channel	250 mm
ACD	42 mm
ASD*	475 mm
No. of anodes	24
Anode density	0.697 A/cm^2
Operating temperature	955 ℃
Field temperature	35 ℃
Anode cover thickness	160 mm

ASD*: anode sidewall distance

3.2 Design of hypothetical drained cell

Concepts applied to retrofitting the existing 160 kA H-H cell to a drained cell can be described as follows:

1) A V-shaped cathode bottom was adopted

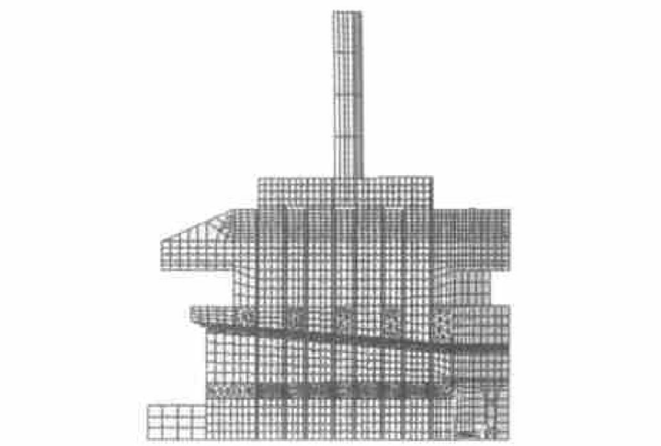

Fig. 1 Meshed plot of half cell slice model

with a coating of aluminum-wettable material (TiB_2) and a wedge-shaped carbon cathode with a slope of 7.5° was added directly to the top of the ordinary cathode. Anodes with a relevant slope to the cathode were used[8].

2) ACD was 25 mm; frozen sideledge thickness was 200 mm; the thickness of the TiB_2 coating on the cathode was 25 mm with a resistivity of 29×10^{-8} Ω/m[9].

3) The width of the sump was 250 mm and the depth 150 mm, for it was reported that the width of the sump should be at least larger than its depth[10, 11].

4) The side of the anode adjacent to the side wall was immerged to the melt bath at a depth of 150 mm.

5) No other major cell constructional changes were made.

3.3 Boundary conditions

The meshed slice of the model is shown in Fig. 1.

Besides the parameters listed in Table 1, some assumptions were made and added to the model as boundary conditions:

1) It was assumed that the current distribution in every anode rod was equal to 160 000/24 = 6 666.7 A.

2) The voltage drop of the bottom surface of the metal pad was zero.

3) Metal film on the cathode was about 3 - 5 mm, the current resistance of the metal pad was very small and the voltage drop on it was negligible[5].

4) The temperature of the melting bath and metal pad was constantly 955 ℃.

Based on the above conditions, calculations were carried out by using finite element code.

4 RESULTS AND ANALYSES

4.1 Results of calculations

The total voltage drop of the whole slice model calculated(from the aluminum rod of anode to the iron collector bar of the cathode) is 1 282 mV. Voltage of every part of the model and the relevant parameters of the 160 kA conventional H-H cell are listed in Table 2.

Table 2 Voltage drop in 160 kA conventional H-H cell and hypothetical drained cell

	Conventional H-H cell(measured) / mV[12]	Drained cell (calculated) / mV
Anode	348	352. 3
Bath	1 334	853. 3
Cathode	354	360. 0

Table 2 lists the anode voltage of the H-H cell is 348 mV. Fig. 2 shows the equipotentialities of the anode calculated, the total voltage drop on which is 352. 3 mV, and the two are very close to each other. Fig. 3 shows the equipotentialities of the cathode, the voltage loss on which is 360. 0 mV, which is higher than that of the carbon cathode of a 160 kA H-H cell (see in Table 2) by 6 mV, nevertheless, the difference is quite small.

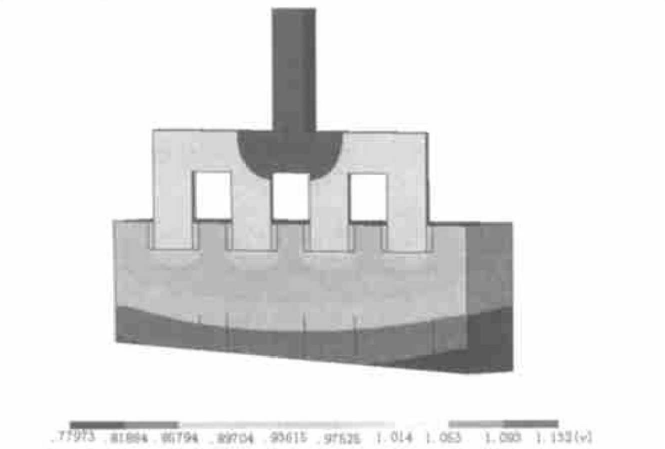

Fig. 2 Equipotentialities of anode

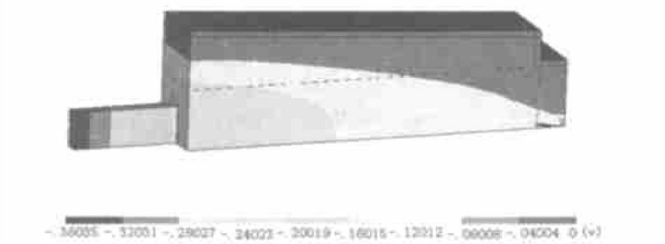

Fig. 3 Equipotentialities of cathode

The major difference of voltage drop between the drained cell and the 160 kA conventional H-H cell is the voltage drop on the melting bath. Fig. 4 shows that the calculated voltage drop of the melting bath in the drained cell is 853. 3 mV. However, the voltage drop of the melting bath in the conventional H-H cell is 1 334 mV, and the voltage drop on the metal pad can be neglected because it is too small.

This means that, compared with the 160 kA

Fig. 4 Equipotentialities of melt bath

conventional H-H cell, the drained cell will produce less heat by (1 334 – 853. 3 mV) × 160 kA = 76. 9 kW at least, which is equal to about 11. 7% of the total heat produced by a 160 kA conventional H-H cell. In order to achieve a heat balance, something should be done to reduce the heat loss from a drained cell to the surroundings or to produce more heat to meet the requirement.

4. 2 Approaches of achieving heat balance in drained cell

4. 2. 1 Change of bath chemistry

Change of bath chemistry, such as increase of the concentration of AlF_3 and adding proper amount of CaF_2 and/ or MgF_2 to the bath can lower its melting point, so that the cell can be operated at a relatively lower temperature, and the heat needed to keep the heat balance is thus reduced. Unfortunately, by doing so, the bath resistance increases, and the solubility of Al_2O_3 in the bath lowers as well.

4. 2. 2 Increasing alumina cover thickness

Removal of the metal pad can not only reduce the heat loss through the cell walls, but also make it possible to narrow the interpolar distance and lower down the anodes for about 150 mm, so the thickness of the alumina cover on the top of the crust and anode can be increased from its former thickness of 160 mm to a proper one to well prohibit the convective and radiative heat loss from the cell top.

Fig. 5 shows the isotherms of a drained cell anode and its cover, the temperature gradient in the anode cover is large, it is obvious that the heat loss from the top is great, which occupies about 50% of the whole cell heat loss typically[6]. It was reported that every 1cm increase of anode cover thickness could save heat loss from the cell top equal to the equivalent heat[12] of 60 – 90 mV voltage drop. So as the thickness of the anode cover increases, the heat loss from the top will be reduced greatly. However, as the heat loss from the cell top reduces, the sideledge thickness will become thinner, which increases the risks of the damages to the side walls caused by the melting bath and metal pad attacks.

4. 2. 3 Increasing anode current density

As the ACD is reduced, it is possible to exploit an increase of anode current density so as to produce more heat to meet the requirement of the electrolysis. When retrofitting the drained cell, the anode current density of the 160 kA conventional H-H cell is taken

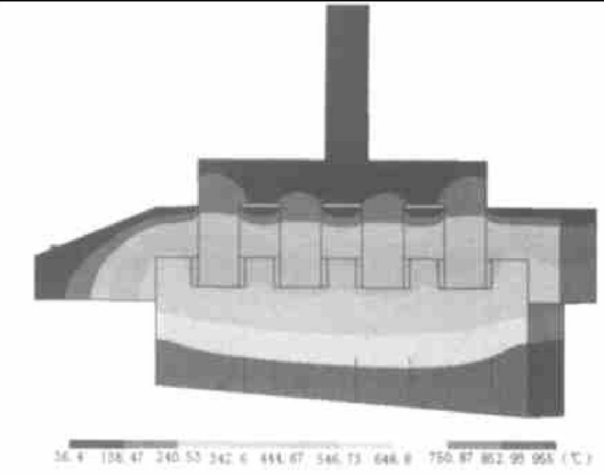

Fig. 5 Isotherms on anode and cover

as 0.697 A/cm^2 (Table 1), since the sloped bottom surface area of the anode increases, the current density decreases correspondingly, and the actual account becomes 0.695 A/cm^2. Comalco, Australia, reported that the anode current density of a drained cell could be increased from 0.97 to 1.20 A/cm^2 [5]. Two current densities of 1.0 A/cm^2 and 1.1 A/cm^2 were used in turn, i.e. to increase the cell amperage from 160 kA to 230 kA and 253 kA, to recalculate the equipotentials in the drained cell. The results are listed in Table 3.

Table 3 Voltage drops of drained cell with 1.0 A/cm^2 and 1.1 A/cm^2 current density

Current density/ (A·cm^{-2})	Anode / mV	Bath/ mV	Cathode/ mV
1.0	499	1 226	496.4
1.1	546	1 349	549.4

Noting that in Table 3, as the anode current density increases from 0.695 A/cm^2 to 1.0 A/cm^2, the voltage drop on the electrolyte increases to 1 226 mV, which is close to that of a 160 kA H-H cell. At the same time the voltage drop on the anode and the cathode increases, which is 499.0 mV and 496.4 mV, respectively. As the anode current density increases, the heat produced by the anode reaction process (overvoltage) will increase too, so the heat balance can be achieved. What's more, if the current efficiency remains unchanged, increasing the cell amperage to 230 kA can improve the cell productivity by 43.7%. Table 3 also lists the calculated results when the anode current density increases to 1.10 A/cm^2, the voltage drop on the melt bath will rise to 1 349 mV, which is larger than that of a 160 kA conventional H-H cell. That means the heat produced in the drained cell is more than that needed to keep a heat balance. And if the current efficiency does not change, the productivity of the drained cell will increase by 58.1%. So it's apparent that increasing the anode current density can effectively increase the amount of heat produced and bring a new heat balance to a drained cell.

5 CONCLUSIONS

Compared with a conventional H-H cell, since the sloped aluminum wettable cathode is applied, the drained cell is able to operate at a significantly lowered ACD, so the cell voltage can be lowered accordingly, which will cause the reduction of heat production. In order to achieve a heat balance, on one hand, the melting bath chemistry can be changed to obtain a lower melting point so that the requirement of the heat during the electrolysis can be reduced, and the drained cell itself has a decreased melting volume, which will correspondingly decrease the convective heat loss to the cell walls, and the anode cover thickness can be increased to save the heat loss from the top of the cell. On the other hand, the most effective way to achieve a heat balance of the drained cell is to increase the heat production through increasing the anode current density. Meanwhile, it can greatly increase the productivity of the drained cell.

REFERENCES

[1] Huglen R, Kvande H. Global considerations of aluminium electrolysis on energy and the environment [J]. Light Metals, 1994: 373－380.

[2] McMinn C J. A review of RHM cathode development [J]. Light Metals, 1992: 419－424.

[3] de Vittorio Nora. Cell for aluminum electrowinning[P]. US 6093304, 2000.

[4] Sierre G B, Hardie G J, Shaw R W, et al. Aluminum production cell and cathode[P]. US 6358393, 2002.

[5] Brown G D. TiB_2 coated aluminium reduction cells: status and future direction of coated cells in Comalco[A]. Welch B. Aluminum Smelting Conference[C]. Queenstown, New Zealand, 1998. 499.

[6] Kvande H, Haupin W. Inert anodes for Al smelters: energy balances and environmental impact[J]. JOM, 2001, 53(5): 29－33.

[7] Stedman I G, Houston G J, Shaw R W. Aluminum smelting cells[P]. US 5043047, 1991.

[8] Boxall L G, Gamson B W, Green J A S, et al. Low energy aluminum reduction cell with induced bath flow[P]. US 4602990, 1986.

[9] LIU Ye-xiang. Functional Electrode Materials and Their Applications[M]. Changsha: Central South University Press, 1996. 169. (in Chinese)

[10] de Vittorio Nora. Cell for aluminium electrowinning employing a cathode cell bottom made of carbon blocks which have parallel channels therein[P]. US 5683559, 1997.

[11] Keniry J. The economics of inert anodes and wettable cathodes for aluminum reduction cells[J]. JOM, 2001, 53(5): 43－47.

[12] YIN En-sheng. Production Technology and Management of 160 kA Prebaked H-H Cells with Center Feeders[M]. Changsha: Central South University Press, 1997. 104. (in Chinese)

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