Light Metals 2014
Edited by: John Grandfield
TMS (The Minerals, Metals & Materials Society), 2014

SIMULATION AND OPTIMIZATION OF CATHODE CURRENT DISTRIBUTION TO REDUCE THE HORIZONTAL CURRENT IN THE ALUMINUM LIQUID

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Keywords: Horizontal Current, Cathode, Simulation, Aluminum Reduction Cells

Abstract

In an aluminum electrolysis cell, the movement of molten aluminum is driven by electromagnetic forces resulting from the current fields in the cell. A rapid movement of the aluminum liquid results in a noisy operation of the cell with an increase in both the voltage and the energy consumption. For a long time designers have endeavored to reduce the magnetic field intensity and decrease the Lorenz force to lower the flow speed of the aluminum liquid by optimizing the layout of the bus bars. In the present work, the effect of the design and the material of the cathode on the horizontal current in aluminum liquid were studied by simulation research of an aluminum electrolysis cell. Solutions to reduce the horizontal current in the molten aluminum pad by optimizing the cathode are provided to achieve a decrease in the electromagnetic force and, hence, improvement of cell stability.

Introduction

After about 120 years of development and progress, the Hall-Heroult cell have been extended to a capacity range of 300 to 500 kA. Now, the 600 kA cell is being developed and tested in some smelters. The basic structural design of the cell that determines the current flow has not changed significantly. The current is passed vertically through the anode, bath, molten aluminum pad, cathode blocks, and flow horizontally through collector bars to the risers to the next cell. In this design, with the electrical conductivity differences in the metal pad, cathode block and collector bars, the outer one-third of the collector bar and cathode carries most of the current load. This results in significant horizontal currents in the metal pad. The more horizontal current the stronger the Lorenz forces. This is the basis for instability in the cell, such as the warp, rotation of the molten metal and the interface deformation, which will increase the cell voltage and the energy consumption.

It has long been the endeavor of cell designers to find solutions to decrease the Lorenz forces, to lower the flow speed of the aluminum liquid, by optimizing the layout of the bus bars to compensate for the magnetic field [1]. At present, with the continuing enlargement of cells, the enlargement of the cathode width lead to more uneven current distribution in the cell. Although the magnetic field of these large cells is continually optimized, increased horizontal current is still impacting the cells negatively. Some studies on the current distribution in Hall-Heroult cells have been done [2, 3]. Recently, new studies on reducing the horizontal current in the metal pad to enhance the stability of cells have been started. Zhang et al. did some research on horizontal current in molten pad related to cathodes [4]. Das et al. [5] studied the inclined cathode to reduce the horizontal component of the current density. Zhou et al. [6] studied a new collector bar to reduce the horizontal current in the metal pad. In this work, a numeric model is built to study the change in the horizontal current in the metal pad along with variations of the cathode design, material property (including cathode blocks and collector bars), etc.

Horizontal Current in the Metal Pad and the Model

Neglecting the effect of the anode gas bubbles and the temperature gradient, the main driving force for the metal pad movement is the Lorenz force generated from the magnetic field. The interaction with the current is according to the following relations.

$$\vec{F} = \vec{J} \times \vec{B} + \overrightarrow{\rho g} \quad (1)$$

$$\vec{F} = (J_y \times B_z - J_z \times B_y)i + (J_z \times B_x - J_x \times B_z)j + (J_x \times B_y - J_y \times B_x + \rho g)k \quad (2)$$

where the variables are the current density, J, the magnetic flux density, B, the density of the metal pad, ρ, and the gravity, g.

The main cause of the metal movement is the vertical component of the rotation of the electromagnetic force:

$$(\nabla \times \vec{F})_z = \begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & 0 \\ F_x & F_y & 0 \end{vmatrix} \quad (3)$$

According to the current flow direction Jx is close to 0, and $\frac{\partial B_x}{\partial x}$ can also be neglected due to the change of B_x along x-direction is very small, simplifying Equation (3) as follows

$$(\nabla \times \vec{F})_z = \frac{\partial J_z}{\partial y} B_y + \frac{\partial B_y}{\partial y} J_z - \frac{\partial J_y}{\partial y} B_z - \frac{\partial B_z}{\partial y} J_y \quad (4)$$

The vertical component of the rotation of the electromagnetic force is mainly caused by J_y, B_z, B_y. Besides optimizing the magnetic field, a reduction in the horizontal current is another way to improve the stability of cells.

A finite element model of half a cathode block was built up to simulate the variation of the current distribution for different cathode designs and cathode properties. Figure 1 shows the model setup; from top to bottom is the anode, bath, molten metal pad, cathode block and collector bars.

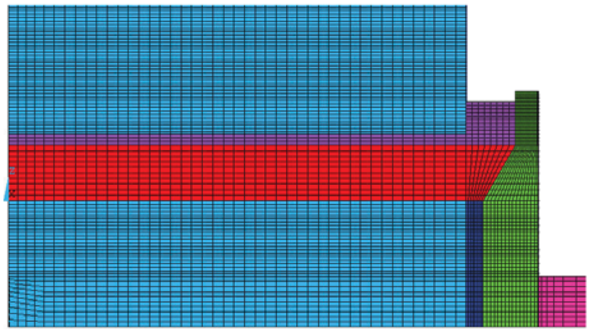

Figure 1. A finite element model of a block of a whole cathode.

The equations used to solve the current distribution are:

The Laplace equation

$$\sigma_x \frac{\partial^2 V}{\partial x^2} + \sigma_y \frac{\partial^2 V}{\partial y^2} + \sigma_z \frac{\partial^2 V}{\partial z^2} = 0 \qquad (5)$$

Ohm's law

$$\sum V = \sum I \cdot R \qquad (6)$$

where variables are the electric potential, V, the current, I, the resistance, R, and the electrical conductivity, σ.

Modeling Results and Discussion

The typical design of the cells is shown in Figure 2. The drawing shows a cathode of a 350 kA cell in China. In Figure 1, there are 1 carbon block, 2 collector bars and 3 binder phases.

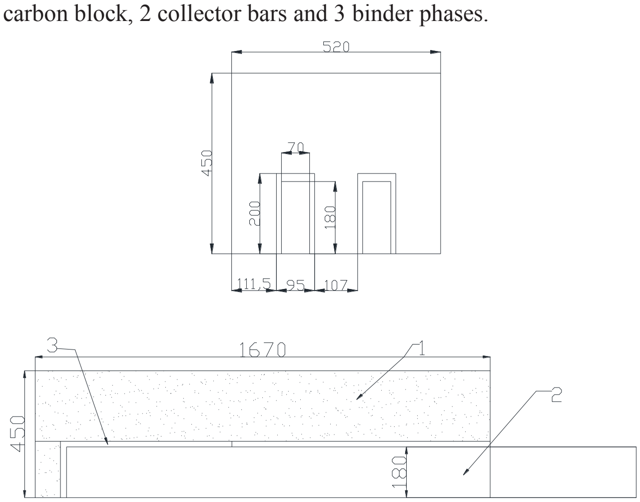

Figure 2. Cathode dimensions in mm. Top: End view. Bottom: Side view.

The typical current distribution in the molten metal pad in the cells is shown in Figure 3. It is apparent that the outer third of the cathode carries most of the current load. The current flows relatively vertically in the cryolite due to the high electrical conductivity of the molten metal. In the molten metal it is apparent that the horizontal components of the current are large. The directions of current flow in the molten metal depend mostly on the collector bar output position and the path of least resistance between the metal and the collector bar.

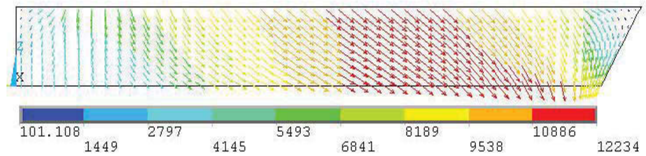

Figure 3. The vector plot of current in the molten metal pad (A/m^2).

However, small changes in design and material properties may reduce the horizontal current. Based on a base case model, other cases were used to study the impact of the cathode design and material properties. All the simulations are based on 350 kA cells.

<u>Effects of Material Properties of Cathode Blocks</u>

Cathode blocks are fabricated from anthracitic, semi-graphitic or graphitic carbon, with improved thermal and electrical properties in the listed order. Various cases of cathode blocks with different electrical conductivities are shown in Table I.

Table I. Modeling results of horizontal current and cathode voltage drop for various cathode blocks.

Case Number	Base-case	Case2	Case3	Case4
Cathode material	anthracite	semi-graphite		graphite
Resistivity (10^{-6} Ω·m)	50	30	20	11
J_Y|max (A/m^2)	10512	13845	16444	19716
J_Y|ave (A/m^2)	6432	8442	9984	11867
Cathode Voltage Drop (mV)	342	286	252	215
J_Y Change Rate (%)	/	31.25	55.22	84.50

The simulation results in Table I show that along with the degree of graphitization, i.e. higher electrical conductivity of the cathode, more current will go to the outer part of the cathode and cause a more uneven current distribution and a higher horizontal current in the molten metal. A higher current density at the periphery, and faster flow velocity of molten metal caused by the horizontal current, may be the reason why graphitic blocks erode more rapidly than less graphitized materials.

<u>Effects of Material Properties of Collector Bars</u>

Cases with various collector bar materials are simulated in Table II. It shows that the horizontal current is greatly reduced with decreasing resistivity of the collector bar material. It means that a lower bar resistivity will reduce the horizontal current close to zero. But, zero horizontal current is not favorable for alumina distribution and an appropriate reduction should be sought. Also, a better electrical conductivity of the collector bars will reduce the cathode voltage drop.

Table II. Modeling results of horizontal current and cathode voltage drop of various collector bar materials.

Case Number	Base-case	Case5	Case6	Case7
Bar material	M1	M2	M3	M4
Resistivity (10^{-6} Ω·m)	1.32	0.6	0.24	0.0175
J_Y|max (A/m^2)	10512	6035	2783	224
J_Y|ave (A/m^2)	6432	3702	1708	138
Cathode Voltage Drop (mV)	342	219	150	103
J_Y Change Rate (%)	/	-42.44	-73.45	-97.85

Effects of Height of Collector Bars

Cases with various heights of the collector bars are simulated in Table III. It shows that increasing the height of the collector bars is beneficial for decreasing the cathode voltage drop, but the contribution to reduce the horizontal current is small.

Table III. Modeling results of horizontal current and cathode voltage drop of various collector bar heights.

Case Number	Base-case	Case8	Case9	Case10
Height (mm)	180	200	220	240
J_Y|max (A/m^2)	10512	10328	10221	10189
J_Y|ave (A/m^2)	6432	6322	6257	6236
Cathode Voltage Drop (mV)	342	326	312	300
J_Y Change Rate (%)		-1.71	-2.72	-3.05

Effects of Width of Collector Bars

Cases with various widths of the collector bars are modeled in Table IV. It shows that increasing the width of the collector bars is beneficial for decreasing the cathode voltage drop besides a small contribution to reduce the horizontal current.

Table IV. Modeling results of horizontal current and cathode voltage drop of various collector bars widths.

Case Number	Base-case	Case11	Case12
Width (mm)	65	80	100
J_Y|max (A/m^2)	10512	9142	8082
J_Y|ave (A/m^2)	6432	5602	4922
Cathode Voltage Drop (mV)	342	319	303.5
J_Y Change Rate (%)		-12.90	-23.48

Effects of Height of Cathode Blocks

The height of the cathode blocks impact the horizontal current and cathode voltage drop as shown in Table V. The cathode voltage drop increases with increasing height of the cathode block while the horizontal current goes down slightly.

Table V. Modeling results of horizontal current and cathode voltage drop of various cathode blocks height

Case Number	Base-case	Case13	Case14
Height (mm)	450	411	490
J_Y|max (A/m^2)	10512	11825	9438
J_Y|ave (A/m^2)	6432	7242	5570
Cathode Voltage Drop (mV)	342	327	357.5
J_Y Change Rate (%)		12.6	-13.4

Effects of Material Properties of Binder

The Binder connects the collector bars and cathode blocks. It is shown in Table VI that the impact of the binder's resistivity, from 33.7 to 100 x10^{-6} Ω·m, to the horizontal current and the cathode voltage drop is negligible.

Table VI. Modeling results of horizontal current and cathode voltage drop of various binder materials

Case Number	Base-case	Case15	Case16	Case17
Binder materials	M1	M2	M3	M4
Resistivity (10^{-6} Ω·m)	33.7	55	80	100
J_Y|max (A/m^2)	0.553	0.553	0.552	0.551
J_Y|ave (A/m^2)	0.996	0.996	0.995	0.993
Cathode Voltage Drop (mV)	344	345	346	346
J_Y Change Rate (%)	/	~0	~0	~0

Optimization of Cathode to Reduce Horizontal Current

The simulation results above show:

1) By lowering the electrical resistivity of the steel bars, both the horizontal current and the cathode voltage drop are reduced significantly. If the resistivity is reduced to 0.6x10^{-6} Ω·m, the horizontal current would be reduced by 42.4 %. Looking for lower resistivity collector bars is one optimization direction for improving the cathode performance and save energy.

2) With a lower resistivity of the graphite cathodes, the cathode voltage is lowered but the horizontal current increases. With graphite cathodes the horizontal current is increased up to 84.5 % compared to non-graphitized blocks. Hence, the choice of cathode materials needs to be a compromise between horizontal current and voltage drop.

3) The effect of the steel bar height on the horizontal current is small while the effect of changing the width is more significant. Both reduce the cathode voltage drop slightly.

4) Increasing the carbon block height helps to reduce the horizontal current slightly, but it will increase the cathode voltage drop, so it is not recommended.

5) The effect of the binder material's resistivity, from 33.7-100 μΩ.m, both for the horizontal current and the cathode voltage

drop, was not significant. The results show that the difference between a phosphorus pig iron casting (33.7 μΩ.m) and a paste binder (55 μΩ.m) on the horizontal currents and the voltage drop are negligible.

From the simulations above, we see that appropriate adjustments to the cathode resistance, e.g. to increase the resistivity of the cathode where there is higher current density or to decrease the resistivity of the cathode where there is lower current density, facilitate a more even current distribution and a lower horizontal current. Shown in Figure 4 is a vector plot of the current of a case with low horizontal current. Compared to Figure 3, the direction of the vectors in Figure 4 is almost vertically downwards.

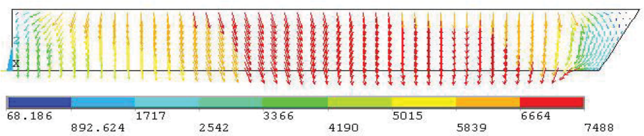

Figure 4. The vector plot of current of a case with low horizontal current (A/m^2).

According to the results above, it is shown that the ways of reducing the cathode voltage drop include using graphite cathodes and increase the size of the collector bars to improve the conductivity.

Based on an overall consideration of various factors, some recommendation can be given: Adjust material properties and size of cathode blocks and collector bars, as well as part of binder materials, to even out the current distribution. In Table VII, simulation results to obtain optimum solutions are shown. The horizontal current distributions of the simulations are shown in Figure 5.

Table VII. Modeling result of new combined solutions

Solution Number	1	2	3	4	5	6
J_Y|max (A/cm^2)	0.738	0.643	0.476	0.470	0.472	0.43
J_Y|ave (A/cm^2)	0.354	0.292	0.190	0.161	0.149	0.0358
Cathode Voltage Drop (V)	0.277	0.288	0.306	0.313	0.313	0.335
J_Y Change Rate (%)	-35.9	-47.2	-65.6	-70.9	-73.1	-93.5

Industrial Pilot Trial Results

Based on the results of the model simulations, industrial tests with three solutions were conducted in two smelters. In the first test the horizontal current is reduced by 45 % on three cells. In the second test the horizontal current is reduced by 60 % in one cell. In the third test the horizontal current was reduced by 45 % by improving the electrical conductivity of the cathode. The industrial results are shown in Table VIII and Table IX. It is obvious that the pilot cells have higher stability and are running with lower ACD and lower cell voltage (100-300 mV) than standard cells. At the same time, power consumption is reduced with about 500 kWh/t-Al. Of the three tests, the second one is not as good as expected; possibly due to too much reduction of the horizontal current.

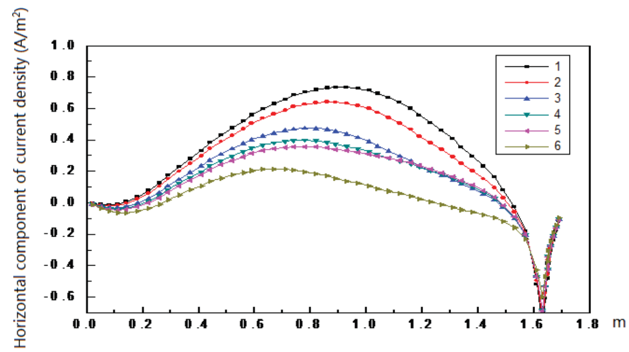

Figure 5. Modeling result of horizontal current (A/m^2).

Table VIII. The industrial pilot test results in smelter A (300kA)

	A Smelter				
Cell type	Common cell	Pilot cell			
Solution		1	1	3	
Cell No.	average	516	616	709	average
Cell voltage (mV)	3994	3758	3719	3679	3719
DC (kWh/t-Al)	12990	12282	12384	12035	12233
Operation temperature (°C)	948	954	967	944	955
Super heat (°C)	12.9	15.6	30.8	23.8	23.4
CR	2.515	2.57	2.59	2.58	2.58
Cryolite lining thickness (mm）	89.3	104	184.4	89	125.8
Liquid aluminum height (cm)	30.5	17.2	15.6	16.4	16.4
ACD (cm)	4	3.77	3.54	3.61	3.6
Cathode voltage drop (mV)	326.4	278.2	278.6	243.1	266.6

Table IX. The industrial pilot test results in smelter B (350kA).

	B Smelter			
Cell type	Common cell	Pilot cell		
	average	2	1	average
Cell No.		121	425	
Cell voltage (mV)	4142	4037	3969	4003
DC（kWh/t-Al)	13749	13252	13183	13217
Operation temperature (°C)	960.0	956	971	963.5
Superheat (°C)	11.2	13	14.5	13.8
CR	2.54	2.45	2.53	2.49
Cryolite lining thickness (mm）	91	153	157	155
Liquid aluminum height (cm)	23.5	24.4	20.8	22.6
ACD (cm)	4.2	4.21	4.07	4.1
Cathode voltage drop (mV)	300	291	274	282

Conclusion

In this work, the effects of the design and the material of cathodes to the horizontal current in the aluminum liquid were studied by a simulation of an aluminum electrolysis cells. The effects of the resistivity and the dimensions of the cathode blocks, the collector bars and the binder materials on the horizontal current and the cathode voltage drop were studied. According to the simulations, some comprehensive solutions to reduce the horizontal currents in the molten aluminum pad were obtained. Theoretical calculations show that the horizontal current may be reduced in the range of 0 – 90 %, which can be implemented according to actual needs.

Based on the cathode voltage drop and horizontal current reduction simulations, three solutions, reducing the horizontal current by 45 % to 60 %, were tested in 5 cells in two smelters. The tests show that the electromagnetic force and the horizontal current can be reduced in the aluminum liquid, resulting in better stability of the cell. The cell voltage was reduced in the range 100 - 300 mV while the power consumption was reduced about 500 kWh/t-Al. The simulations have been successfully applied in aluminum reduction cells.

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