VERY LOW ENERGY CONSUMPTION CELL DESIGNS: THE CELL HEAT BALANCE CHALLENGE

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Abstract

At last year TMS, the author presented the electrical design of a cell operating at 500 kA, 0.8 A/cm^2 of anode current density and 3.2 cm ACD. This cell is predicted to have an energy consumption of about 11.2 kWh/kg [1].

That cell would only dissipate 700 kW while a cell design of the same "platform" was previously designed to operate at 600 kA and 13.26 kWh/kg comfortably dissipating 1140 kW [2].

Reducing the cell heat dissipation by about 40% is presenting a tremendous cell lining design challenge. This paper is describing it and is trying to address it.

Introduction

A 500 kA cell incorporating many innovative design features aiming at minimizing the cell voltage has been presented in [1]. Those features included the usage of big copper collector bars, the extraction of the cell current only on the downstream side of the cell, the usage of a busbar network made only of anodic risers and the usage of a stub hole design that creates an electrical contact between the stub and the bottom of the carbon stub hole.

As a result, the predicted anode drop, cathode drop and busbar drop are 224 mV, 130 mV and 134 mV respectively. At 0.8 A/cm^2 of anode current density and 3.2 cm ACD, this leads to a predicted cell voltage of only 3.59V corresponding to an operation at 11.2 kWh/kg.

Such a cell would only generate 700 kW of internal heat while the previously presented lining design of a cell operating at 600 kA and 13.26 kWh/kg using the same platform is comfortably dissipating 1140 kW [2].

Ref. [1] finished without addressing that tremendous cell lining design challenge. The present work wants to take up the challenge.

600 kA, 13.26 kWh/kg cell heat balance

Table I: Anode heat balance

**** HEAT BALANCE TABLE ****
**** Half Anode Model : 600 kA ****

ANODE PANEL HEAT LOST	kW	W/m^2	%
Crust to air	183.70	2393.80	40.95
Studs to air	216.19	4213.26	48.20
Aluminum rod to air	48.65	1470.04	10.85
Total Anode Panel Heat Lost	448.54		100.00

Table II: Cathode heat balance

**** HEAT BALANCE TABLE ****
**** Side Slice Model: 600 kA ****

CATHODE HEAT LOST	kW	W/m^2	%
Shell wall above bath level	73.46	1249.07	10.61
Shell wall opposite to bath	69.01	6379.11	9.97
Shell wall opposite to metal	39.96	9159.80	5.77
Shell wall opposite to block	136.53	5081.64	19.73
Shell wall below block	8.03	440.10	1.16
Shell floor	34.25	420.30	4.95
Cradle above bath level	0.00	0.00	0.00
Cradle opposite to bath	19.09	2096.87	2.76
Cradle opposite to metal	5.94	2940.99	0.86
Cradle opposite to block	32.19	702.14	4.65
Cradle opposite to brick	3.85	91.21	0.56
Cradle below floor level	19.68	107.35	2.84
Bar and flex to air	143.31	10010.74	20.71
End of flex to busbar	106.85	231870.61	15.44
Cathode bottom estimate	400.32		57.84
Total Cathode Heat Lost	692.14		100.00

Table I and II are presenting the ANSYS® based thermo-electric models predictions for the anode and the cathode heat balance while the left column of Table III summarizes the key design features and key model predictions for the 600 kA cell.

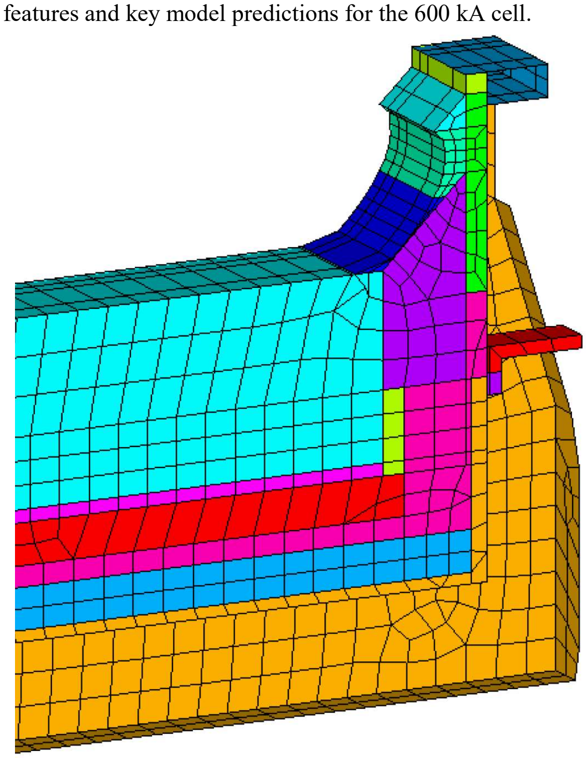

Figure 1: 600 kA cathode side slice model mesh

Figure 1 is presenting the mesh of the cathode slice model highlighting the cathode lining design. The lining under the block consists of 35 mm of calcium silicate, 2 rows or 130 mm of insulating brick, 1 row or 65 mm of semi-insulating brick and 2 rows or 130 mm of fire brick. The pier stops just above the top of the collector bars. The side block is 70 mm thick and is made of silicon carbide.

Table III: Design and predicted operational data

Amperage	600 kA	500 kA
Nb. of anodes	48	64
Anode size	2.0 m × .665 m	1.95 m × .5 m
Nb. of anode studs	4 per anode	4 per anode
Anode stud diameter	17.5 cm	17.5 cm
Anode cover thickness	10 cm	20 cm
Nb. of cathode blocks	24	24
Cathode block length	4.17 m	4.17 m
Type of cathode block	HC10	HC10
Collector bar size	20 cm × 10 cm	20 cm × 20 cm
Type of side block	SiC	HC3
Side block thickness	7 cm	7 cm
Anode side wall distance: ASD	28 cm	30 cm
Calcium silicate thickness	3.5 cm	6.0 cm
Inside potshell size	17.8 × 4.85 m	17.8 × 4.85 m
Anode cathode distance: ACD	3.5 cm	3.2 cm
Excess AlF_3	12.00 %	12.00 %
Anode drop (A)	318 mV	238 mV
Cathode drop (A)	104 mV	123 mV
Busbar drop (A)	311 mV	134 mV
Anode panel heat loss (A)	449 kW	292 kW
Cathode total heat loss (A)	692 kW	402 kW
Operating temperature (D/M)	964.8 °C	958.4 °C
Liquidus superheat (D/M)	11.8 °C	5.4 °C
Bath ledge thickness (A)	6.36 cm	11.84 cm
Metal ledge thickness (A)	1.76 cm	3.48 cm
Current efficiency (D/M)	96.40 %	96.30 %
Internal heat (D/M)	1140 kW	699 kW
Energy consumption	13.26 kWh/kg	11.2 kWh/kg

There are 24 double bar cathode blocks, so there are in total 96 20 cm × 10 cm copper collector bars in that cell. We can see in Table II that those 96 bars dissipate in total 250 kW or about 35% of the cathode heat loss. They would dissipate far more without a special design feature that prevent them to do so.

500 kA, 11.2 kWh/kg cell heat balance

The retrofitted 500 kA kept only 48 collector bars exiting on the downstream side but those bars were doubled in size to 20 cm × 20 cm in order to maintain the collector bar current density and avoid the formation of horizontal current in the metal pad despite of the new configuration (see Figure 5 in ref. [1]).

Table IV: Anode heat balance

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     ****         HEAT BALANCE TABLE             ****
     ****     Half Anode Model : 500 kA          ****

==========================================================
ANODE PANEL HEAT LOST                  kW      W/m^2      %
----------------------------------------------------------
Crust to air                        85.76   1130.63    29.36
Studs to air                       165.70   2093.65    56.73
Aluminum rod to air                 40.64    449.31    13.91
----------------------------------------------------------
Total Anode Panel Heat Lost        292.10             100.00
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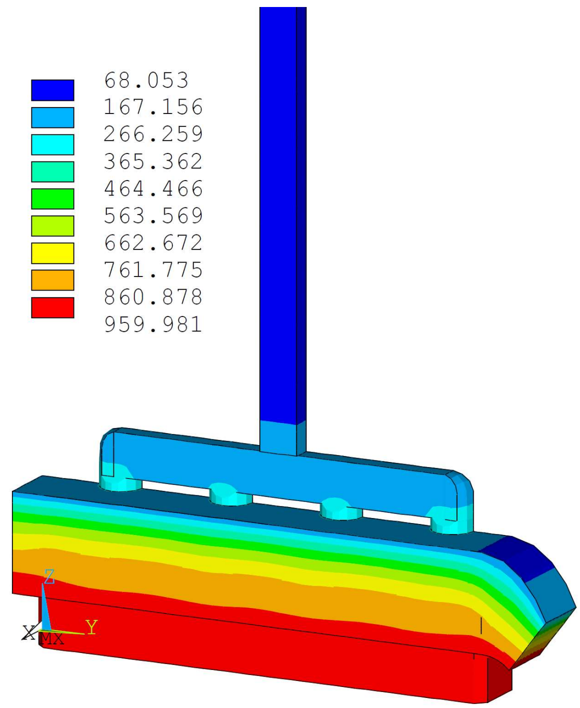

Figure 2: 500 kA half anode model temperature solution

Table IV is presenting the anode heat loss of the retrofitted 500 kA cell while Figure 2 is presenting the corresponding temperature solution. There are only 2 design changes and both concern the stubs: they are now 10 cm longer and the design feature that prevents the copper collector bars to dissipate too much heat have been incorporated in those stubs as well.

The increase of the stubs height permits to operate with 20 cm crust cover without reaching the yoke and increasing the bimetallic temperature. With those changes, the predicted anode panel heat dissipation is decreased from 449 kW to only 292 kW as presented in Table IV.

On the cathode side, apart from the changes to the collector bars, several other changes have been done in order to significantly reduce the cathode heat loss. The calcium silicate layer thickness has been increased from 35 mm to 60 mm. As discuss in [3] there is no point in raising more that thickness as calcium silicate will lose its insulating property if exposed to sodium vapor. Figure 3 presents the mesh of the 500 kA cathode model highlighting the increase of the pier that now extents almost up to the cathode surface level.

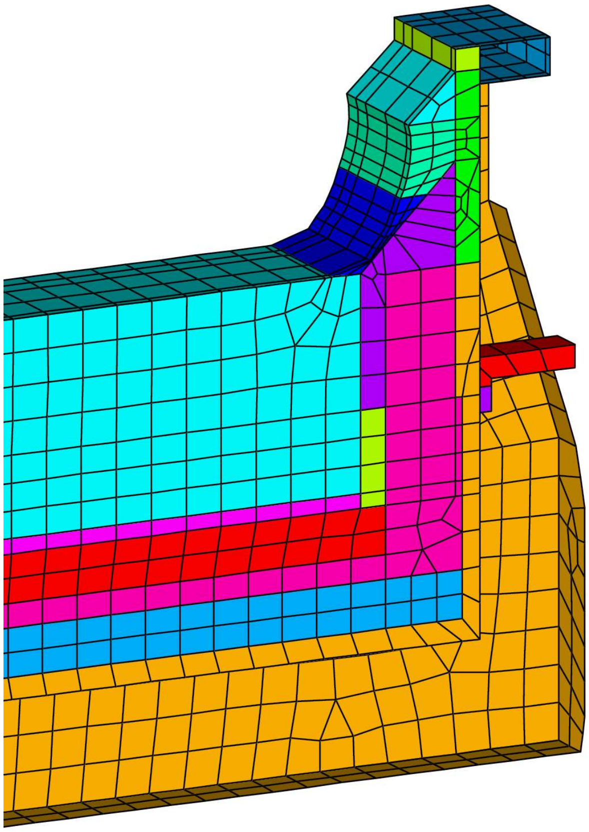

Figure 3: 500 kA cathode side slice model mesh

Table V: Cathode heat balance

**** HEAT BALANCE TABLE ****
**** Side Slice Model: 500 kA ****

CATHODE HEAT LOST	kW	W/m^2	%
Shell wall above bath level	48.00	779.66	11.96
Shell wall opposite to bath	35.82	3620.92	8.92
Shell wall opposite to metal	23.04	5124.05	5.74
Shell wall opposite to block	60.50	2356.32	15.07
Shell wall below block	7.77	396.23	1.94
Shell floor	30.41	373.24	7.57
Cradle above bath level	2.08	936.98	0.52
Cradle opposite to bath	9.79	1403.73	2.44
Cradle opposite to metal	3.84	1615.32	0.96
Cradle opposite to block	18.12	386.58	4.51
Cradle opposite to brick	3.39	75.35	0.84
Cradle below floor level	35.58	97.40	8.86
Bar and flex to air	64.74	9903.13	16.13
End of flex to busbar	76.20	264566.31	18.98
Cathode bottom estimate	257.40		64.11
Total Cathode Heat Lost	401.50		100.00

In addition to the increase of the pier height, the SiC side block has been replaced by a 30% graphitic carbon side block. With those lining changes the ledge thickness do not increasing too much despite the reduction of the cell superheat. Figure 4 is presenting the converged ledge on the downstream side where 100% of the current is going out. Table V is presenting the predicted cathode heat loss. The collector bar heat loss has been reduced from 250 kW to 141 kW or by 44% and the heat flux through the ledge has been reduced by about 40%.

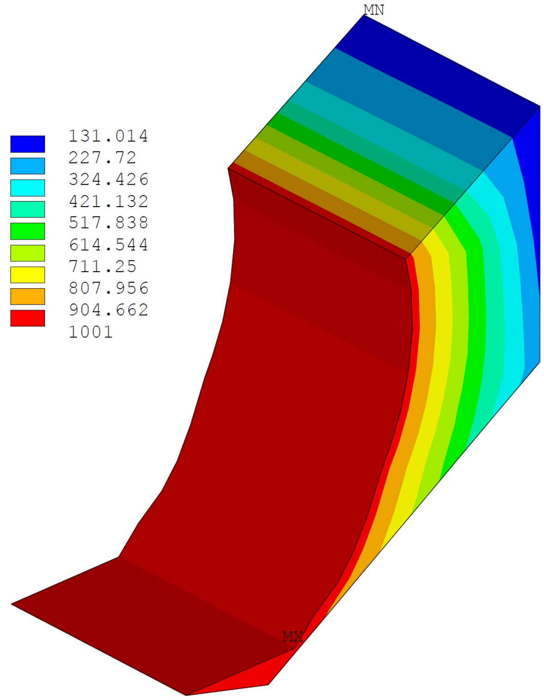

Figure 4: 500 kA model downstream side ledge temperature

The right column of Table III is presenting the main design features and key model prediction for that retrofitted 500 kA cell operating in thermal balance at 11.2 kWh/kg.

762.5 kA, 12.8 kWh/kg cell heat balance

The above 500 kA cell relies on a key design feature to be able to minimize both the busbar voltage drop and the collector bars heat loss: the fact that 100% of cell current is extracted directly on the downstream side. Following Barry Welch lead, the author then took advantage of the usage of big copper collector bars to design wider cells. The resulting about one meter wider 762.5 kA, 0.94 A/cm^2, 3.0 cm ACD, 12.8 kWh/kg cell design was presented in [4]. That cell design is using reversed compensation current (RCC) busbar design with downstream risers. On one hand, the fact that it is a wider cell means that it would be easier to dissipate less heat through the cell but on the other hand, the fact that the busbar path is much longer means that it will be close to impossible to achieve the same extremely low cell voltage and hence the same extremely low cell energy consumption. The next retrofit work is an attempt to do so.

Table VI: Anode heat balance

**** HEAT BALANCE TABLE ****
**** Half Anode Model: 762 kA ****

ANODE PANEL HEAT LOST	kW	W/m^2	%
Crust to air	189.29	1948.20	34.22
Studs to air	305.84	4289.88	55.30
Aluminum rod to air	57.98	686.46	10.48
Total Anode Panel Heat Lost	553.11		100.00

Table VII: Cathode heat balance

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      ****          HEAT BALANCE TABLE          ****
      ****     Side Slice Model: 762 kA         ****

CATHODE HEAT LOST                     kW      W/m^2        %
------------------------------------------------------------
Shell wall above bath level         74.06   1188.24     10.35
Shell wall opposite to bath         65.26   5955.26      9.12
Shell wall opposite to metal        73.88   8972.15     10.33
Shell wall opposite to block        99.97   3982.30     13.98
Shell wall below block               7.97    413.00      1.11
Shell floor                         41.35    428.26      5.78
Cradle above bath level              0.00      0.00      0.00
Cradle opposite to bath             17.64   2083.91      2.47
Cradle opposite to metal            12.25   2818.96      1.71
Cradle opposite to block            31.60    622.71      4.42
Cradle opposite to brick             3.93     89.39      0.55
Cradle below floor level            25.12    112.82      3.51
Bar and flex to air                149.43  10438.13     20.89
End of flex to busbar              112.84 244880.63     15.78
Cathode bottom estimate            406.43               56.82
------------------------------------------------------------
Total Cathode Heat Lost            715.30              100.00
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650 kA, 11.3 kWh/kg cell heat balance

Tables VI and VII present the model predicted anode and cathode heat balance not presented in ref. [4] for the 762.5 kA cell. For comparison purpose, it was first decided to reduce the anode current density to 0.8 A/cm^2 and hence the cell amperage to 650 kA and to minimize the busbar drop by using the biggest possible busbar sections. Figure 5 presents the obtained result for a simplified RCC busbar concept with alternating upstream and downstream risers.

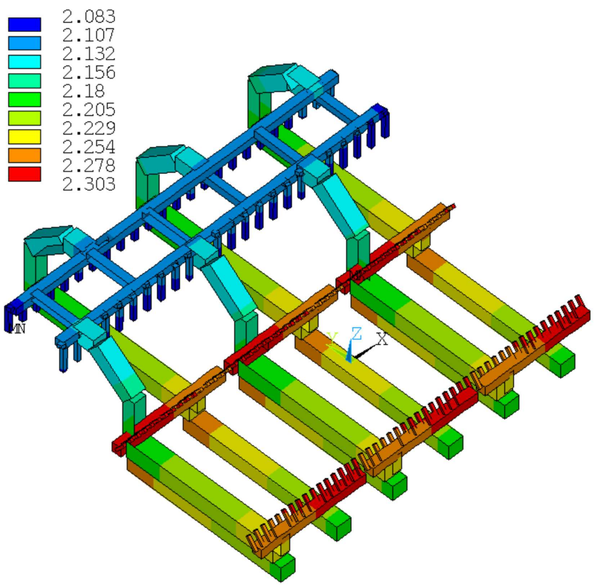

Figure 5: 650 kA model predicted busbar voltage drop

As we can see in Figure 5, that RCC busbar concept with alternating upstream and downstream risers is very simple. The upstream collector bars are feeding the 3 upstream risers, while the downstream collector bars are feeding the 3 downstream risers. As a result, the length of the 6 busbars passing under the cell is the same and the 6 risers are identical. For the selected busbar current density, which is less than 20 A/cm^2, the total busbar drop is 220 mV.

Table VIII: Design and predicted operational data

Amperage	762.5 kA	650 kA
Nb. of anodes	48	48
Anode size	2.6 m × .65 m	2.6 m × .65 m
Nb. of anode studs	4 per anode	4 per anode
Anode stud diameter	21.0 cm	24.0 cm
Anode cover thickness	15 cm	24 cm
Nb. of cathode blocks	24	24
Cathode block length	5.37 m	5.37 m
Type of cathode block	HC10	HC10
Collector bar size	20 cm × 12 cm	20 cm × 15 cm
Type of side block	HC3	HC3
Side block thickness	7 cm	7 cm
Anode side wall distance: ASD	25 cm	25 cm
Calcium silicate thickness	3.5 cm	6.0 cm
Inside potshell size	17.02 × 5.88 m	17.02 × 5.88 m
Anode cathode distance: ACD	3.0 cm	2.8 cm
Excess AlF_3	11.50 %	11.50 %
Anode drop (A)	347 mV	296 mV
Cathode drop (A)	118 mV	109 mV
Busbar drop (A)	300 mV	220 mV
Anode panel heat loss (A)	553 kW	327 kW
Cathode total heat loss (A)	715 kW	499 kW
Operating temperature (D/M)	968.9 °C	967.0 °C
Liquidus superheat (D/M)	10.0 °C	8.1 °C
Bath ledge thickness (A)	6.82 cm	11.86 cm
Metal ledge thickness (A)	1.85 cm	3.38 cm
Current efficiency (D/M)	95.14 %	94.80 %
Internal heat (D/M)	1328 kW	832 kW
Energy consumption	12.85 kWh/kg	11.3 kWh/kg

The anode design of this wide cell is of a completely new style with its front and back carbon blocks. The current model has two stubs per carbon block for a total of four stubs in line per anode. In order to minimize the anode voltage drop, the stub diameter of the 650 kA has been increased from 21 cm to 24 cm despite the reduction on the anode current density. The stub length has been increased by 14 cm to accommodate both an increase of the stub hole depth and an increase of the anode cover thickness from 15 cm to 24 cm. As for the previous anode retrofit, a design feature has been added to reduce the stubs heat loss. Table IX summarizes the predicted anode heat balance while Figure 6 is presenting the corresponding temperature solution.

Table IX: Anode heat balance

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      ****          HEAT BALANCE TABLE          ****
      ****      Half Anode Model: 650 kA        ****

ANODE PANEL HEAT LOST                 kW      W/m^2        %
------------------------------------------------------------
Crust to air                       105.63   1078.21     32.32
Studs to air                       177.39   2233.02     54.27
Aluminum rod to air                 43.81    552.05     13.40
------------------------------------------------------------
Total Anode Panel Heat Lost        326.83              100.00
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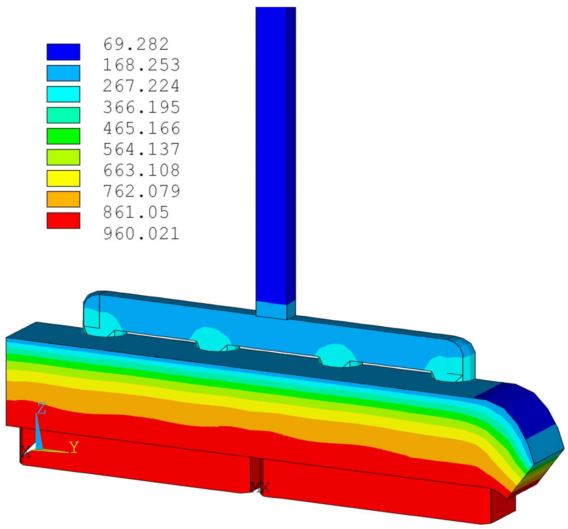

Figure 6: 650 kA half anode model temperature solution

Table VIII presents the key design features and key model predictions for both the initial 762.5 kA cell in the left column and the retrofitted 650 kA cell in the right column. The half anode model predictions for the retrofitted anode design are 296 mV for the anode voltage drop and 327 kW for the anode panel heat loss.

On the cathode side, the lining retrofit for the 650 kA cell is very similar to the one of the previous 500 kA cell. The thickness of the bottom calcium silicate layer has been increased from 35 mm to 60 mm, the pier height has been increased to almost the cathode surface level. The size of the copper collector bar has been increased from 20 cm × 12 cm to 20 cm × 15 cm in order to further decrease the cathode voltage drop. Table X summarizes the predicted cathode heat balance while Figure 7 is presenting the corresponding temperature solution.

The cathode side slice model predictions for the retrofitted cathode lining design are 109 mV for the cathode voltage drop and 499 kW for the cathode heat loss. So globally the retrofitted 650 kA wide cell is dissipating 826 kW at a slightly reduced cell superheat as compared to the 762.5 kA wide cell.

Table X: Cathode heat balance

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      ****          HEAT BALANCE TABLE          ****
      ****       Side Slice Model: 650 kA       ****

CATHODE HEAT LOST                  kW      W/m^2        %
------------------------------------------------------------
Shell wall above bath level      53.42    769.17    10.70
Shell wall opposite to bath      39.51   3540.15     7.91
Shell wall opposite to metal     25.30   4986.43     5.07
Shell wall opposite to block     66.30   2235.30    13.28
Shell wall below block            8.29    372.59     1.66
Shell floor                      35.36    366.17     7.08
Cradle above bath level           2.44    925.21     0.49
Cradle opposite to bath          11.46   1383.66     2.29
Cradle opposite to metal          4.48   1587.32     0.90
Cradle opposite to block         20.98    376.99     4.20
Cradle opposite to brick          3.82     74.79     0.76
Cradle below floor level         21.85     98.68     4.38
Bar and flex to air             113.28  10545.17    22.69
End of flex to busbar            92.87 257964.26    18.60
Cathode bottom estimate         319.10              63.90
------------------------------------------------------------
Total Cathode Heat Lost         499.35             100.00
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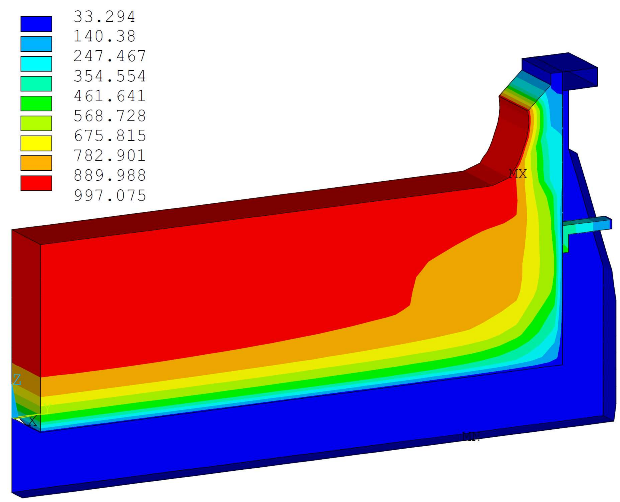

Figure 7: 650 kA cathode side slice model temperature solution

Comparison of the two very low energy consumption cell design options

The two very low energy consumption cell designs presented here are relatively different. The 500 kA cell was specifically designed to minimize the cell voltage and hence the cell internal heat [1]. The fact that all the current is extracted on the downstream side leads to the shortest possible path for the busbar and hence to this extremely low busbar drop. The anode carbon block was also dimension to minimize the carbon drop and hence the global anode drop to an extremely low value. For that reason, the minimization of the 500 kA cell energy consumption is limited by the lining design capacity to reduce the cell heat loss.

On the other hand, increasing the width of the cell directly helps reducing the cell heat loss per unit production as raised in [4]. Yet, the usage of a RCC busbar concept with alternating upstream and downstream risers leads to a much longer busbar path. For that reason, at about the same busbar current density, the busbar voltage drop is about doubled. The anode is much longer and wider, each stub feeding about 70% more of carbon area. For that reason, it was not possible to reduce the anode drop to the same extent. As a result, the minimization of the wide 650 kA cell energy consumption is limited by the capacity to reduce the cell internal heat generation hence the choice of 2.8 cm for the cell ACD which is the minimum value reported in the literature [5]. This minimum cell energy consumption of the wide 650 kA cell operated at 0.8 A/cm^2 and 2.8 cm ACD is 11.3 kWh/kg which is 0.1 kWh/kg more than the 500 kA 100% downstream side current extraction cell operated at 0.8 A/cm^2 and 3.2 cm ACD.

On the OPEX side, this 0.1 kWh/kg is not that significant. On the CAPEX side, the difference is more significant. The cell to cell distance of the ECC busbar design presented in [6] and used for the 500 kA cell is 7.0 m. The cell to cell distance of the RCC busbar design first presented in [4] and simplified to be used for the wide 650 kA cell in the present work is 7.6 m. At 95% CE, the 500 kA cell produces 3.826 ton Al/day so a 1MM ton per year smelter would require 716 cells and 5 km long of potrooms to host them. At the same 95% CE, the wide 650 kA cell produces 4.974 ton Al/day so a 1MM ton per year smelter would require 550 cells and 4.2 km of potroom(s) to host them. The cost of building per km should not be very different as the potshell length of both cell is similar.

On the busbar side, the weight of busbar of the 500 kA ECC busbar concept will be less than the 650 kA RCC busbar concept despite the fact that there are more cells but that ECC busbar concept requires a return line located 60 m away for the study presented in [6]. The RCC busbar concept doesn't require a return line nor a set on independent rectifiers to power the compensation busbars as the ECC busbar concept does.

Future work

On the 500 kA cell side, some more work could be done to reduce the cell to cell distance. The current 7 m. value could be reduced as the 100% downstream current extraction concept hardly requires any space and that current 7 m. spacing came from the need of previous busbar designs. The "500" kA cell energy efficiency could be further reduced by decreasing the ACD to 2.8 cm and increasing the cell amperage in order to maintain the same internal heat.

On the wide 650 kA cell side, the current 2 studs per carbon block design could be replaced by a more appropriate 3 studs per carbon block design considering the length of those carbon blocks. This is not a technical problem but it does require the construction of a new model as the topology of the anode would not remain the same. The RCC busbar network could be further optimized in order to further reduced the busbar drop by decreasing even more the busbar current density as there is plenty of space under the potshell to do so.

Conclusions

It turned out it is possible to reduce enough the heat dissipation of a cell to be able to operate cells in thermal balance at the very low energy consumption level of around 11.2-11.3 kWh/kg. Electrically, at 0.8 A/cm^2 of anode current density, this requires operating at close to the lowest achievable ACD which is around 2.8-3.0 cm and a total ohmic resistance of the anode cathode and busbar corresponding to a total voltage drop of about 500-600 mV.

Thermally, this requires operating at the lowest possible cell superheat, a very high anode cover thickness, very high pier height, and using a special design feature to reduce the stubs and collector bars heat loss.

Electrically, it is easy to continue to decrease the cell internal heat production by reducing the anode current density of around 0.6-0.65 A/cm^2 in order to get to 10 kWh/kg level. This option was already presented in [1]. Thermally, that option have not been investigated in the present work but is now looking more feasible to the author than when [1] was written a year ago…à suivre!

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