FIRST ATTEMPT TO BREAK THE 10 KWH/KG BARRIER USING A WIDE CELL DESIGN

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In his last year ALUMINIUM article [1], the author selected breaking the 11 kWh/kg cell energy consumption barrier as short-term design goal, as a step toward ultimately breaking the 10 kWh/kg cell energy consumption barrier.

In the study presented in that last year article [1], the lowest value of 10.85 kWh/kg was obtained using the 100% downstream side current extraction cell design option. In its upcoming TMS 2019 paper [2], the author continues working exclusively on that 100% downstream side current extraction cell design option, and this time reached 10.44 kWh/kg.

In the present study, the author shifted working exclusively this time on the wide cell design option first presented in an ALUMINIUM article two years ago [3] in a first attempt to break the 10 kWh/kg cell energy consumption barrier.

Introduction

The modeling and design work presented in this article is part of a continuing effort to design a cell operating at the lowest possible cell energy consumption. The initial results were first reported in a TMS 2017 paper [4] and were them reported in [1], [5] and soon in [2].

As discuss in the section "Comparison of the two very low energy consumption cell design options" in [5], at the same ACD and anode current density, the 100% downstream side current extraction cell design option will operate at a lower cell voltage than the wide cell design option. That could be considered as an advantage to produce the lowest possible cell energy consumption cell design.

Yet, as first reported in [3] the wide cell design option reduced the heat loss per unit production, so at a given cell ACD and anodic current density and corresponding cell internal heat per unit production, the wide cell design option will systematically produced a cell operating at a highest cell superheat for the same lining design.

Technically there is nothing preventing the reduction of the anode current density that would correspond on a cell operating at 10 kWh/kg. Using the 100% downstream side current extraction cell design option presented in [4], that anode current density was calculated to be about 0.64 A/cm^2.

On the other hand, there is definitively a limit on the lowest possible cell superheat a cell can be operated at. Not surprisingly it turned out that this cell operation parameter is one of the key parameters preventing the reduction of the cell energy consumption. In that context, the wide cell design option is the best of the two cell design options to attempt to break the 10 kWh/kg cell energy consumption barrier.

Modeling and design methodology

Since the very beginning of this effort to design a cell operating at the lowest possible energy consumption and even before that, the author relied on the usage of 4 different modeling tools: HHCellvolt, Dyna/Marc, MHD-Valdis and 3D ANSYS based thermo-electric anode and cathode models to perform his studies.

HHCellVolt developed and commercialized by Peter Entner [6] is the best modeling tool available to very quickly producing a cell layout as the one presented in figure 1 for the current wide cell design. HHCellVolt is also the perfect tool to calculate directly from enthalpy data the energy required to operate the cell which is more than the minimum energy required to produce the metal. That subject was recently covered in [7] and will be discuss again in [2]. HHCellVolt is also the most up to date tool to compute the cell voltage based on inputs for the anode, cathode and busbar ohmic resistances and the choice of ACD, bath chemistry, bubble model and cell amperage. HHCellVolt finally computes the cell internal heat based on the calculated cell voltage and energy requirement to operate the cell and report it numerically and graphically generating an Haupin Diagram as the one presented in figure 2 for the initial wide cell design operating at 762.5 kA [3].

The next tool required is the steady state part of the Dyna/Marc cell simulator developed and commercialized by the author [8]. Dyna/Marc is solving for the cell heat balance so based on additional inputs like the anode panel heat loss and the cathode bottom heat loss, the bath and metal level and some lining material thickness and thermal conductivity, Dyna/Marc will calculate the cell superheat and bath and metal ledge thickness.

3D ANSYS based thermo-electric anode and cathode models developed and commercialized by the author [9] are used to compute the anode and cathode voltage drop and the anode and cathode heat loss. The 3D ANSYS based thermo-electric cathode model, also calculate more accurately that Dyna/Marc the cell ledge profile using the user defined cell superheat.

Finally, MHD-Valdis, the MHD cell stability solver developed by Valdis Bojarevics from Greenwich University and commercially available through the author is used to design the cell busbar and analyze the corresponding cell stability. MHD-Valdis will directly compute the busbar voltage drop but the busbar network generated by MHD-Valdis can also be converted into an ANSYS model to compute the busbar voltage drop.

Reducing the metal pad thickness from 20 cm to 10 cm

It is quite well known that reducing the metal pad thickness is a very efficient way to reduce the cell heat loss at a constant cell superheat. Because the initial wide cell design was operating at a quite high anode current density, I typical value of 20 cm was selected then for the metal pad thickness. All the 3D ANSYS based thermo-electric runs and MHD-Valdis cell stability runs up to now were done using that metal pad thickness value.

It is also well known that reducing the metal pad thickness reduces the cell stability as it is increasing the metal pad horizontal current. Yet, since there is a need to reduce that cathode side wall heat loss without further reducing the cell superheat, it was decided to investigate the option to reduce the metal pad thickness from 20 to 10 cm. With the usage of huge copper collector bars there is essentially no horizontal current in the metal pad so the risk to destabilize the cell by reducing the metal pad thickness is minimum but this of course must be confirmed by an MHD-Valdis cell stability analysis.

MHD-Valdis cell stability analysis at 570 kA and 10 cm of metal pad thickness

At 762.5 kA, the amperage selected for the initial wide cell design 2 years ago, the anode current density is 0.93 A/cm^2. At 650 kA, the amperage selected last year, the anode current density is 0.81 A/cm^2 and the cell is running at 11.0 kWh/kg of cell energy consumption. It is clear that to continue to decrease the cell energy consumption, the cell amperage will need to be decreased again. To run the MHD-Valdis cell stability with 10 cm of metal pad thickness, a cell amperage of 570 kA was selected which correspond to an anode current density of 0.71 A/cm^2.

The obtained metal pad horizontal currents are presented in figure 3 and the corresponding metal pad flow field is presented in figure 4. The busbar drop is calculated to be 112 mV.

3D ANSYS based thermo-electric results at 570 kA

On the anode side, the only change to the design was a refinement of the design feature that is limiting the anode stubs heat loss that will be revealed in the author's TMS 2019 paper [2]. That design refinement will not be revealed in this article. Using that anode design at 570 kA and the new boundary of the cell described in [2], the model is predicting an internal anode drop of 207 mV and an external anode drop of 78 mV. The heat loss of the internal part of the anode is predicted to be 221 kW.

On the cathode side, 3 changes were made, the metal pad thickness was decreased to 10 cm, the ramming slop was decreased accordingly and the design feature that is limiting the collector bars heat loss was also refined. Using that cathode design at 570 kA and the new boundary of the cell, the model is predicting an internal cathode drop of 97 mV and an external cathode drop of 49 mV. The heat loss of the internal part of the cathode at 7 °C of cell superheat is predicted to be 417 kW.

Dyna/Marc global analysis of the wide cell design at 570 kA

Using many of the above results as inputs, Dyna/Marc is used to calculate the steady-state cell conditions at 570 kA and 2.8 cm ACD. Table I presents the Dyna/Marc results summary, the cell voltage is predicted to be 3.36 V, the cell internal heat using Haupin's equation to calculate the equivalent voltage to make the metal is 613 kW at the calculated current efficiency of 94.4% and the cell superheat is predicted to be 7.5 °C. Finally, the cell power consumption is calculated to be 10.61 kWh/kg, still quite far from 10 kWh/kg!

MHD-Valdis cell stability analysis at 530 kA and 10 cm of metal pad thickness

The good news is that when compared with the solution at 650 kA presented in [1], the reduction of the metal pad thickness permitted to reduce the cell internal heat from 804 kW to 613 kW while maintaining the cell superheat about the same around 7.5 °C. Assuming that it is possible to operate the cell at 5.0 °C of cell superheat, the next step is to simply reduce the cell amperage until that value of cell superheat is reached. It turned out that that cell amperage is about 530 kA which corresponds to 0.66 A/cm^2 of anode current density. Figure 5 is presenting the obtained busbar drop at 530 kA, that busbar drop is calculated to be 104 mV. There is no need to report the rest of the MHD-Valdis cell stability results as an operation at 530 kA would be more stable that an operation at 570 kA unless the ledge toe growth get problematic which is not the case.

3D ANSYS based thermo-electric results at 530 kA

Using exactly the same anode design at 530 kA, the internal anode drop is predicted to be 191 mV and the external anode drop which include the studs outside the crust, the yoke and the rod is predicted to be 72 mV. The internal anode heat loss is 218 kW, it includes only the heat loss of the curst surface by convection and radiation and the heat loss of the studs by conduction where they exit the crust.

The cathode design also remained the same. Figure 6 is showing the cathode side slice model mesh with the converged ledge profile at 5 °C of cell superheat while figure 7 is showing the corresponding temperature solution. The model is predicting an internal cathode drop of 90 mV and an external cathode drop of 45 mV. The heat loss of the internal part of the cathode at 5 °C of cell superheat is 311 kW. About 40% of that cathode heat loss is going through the ledge, 35% escape by conduction in the collector bars and the remaining 25% is going out down thought the cell lining.

HHCellVolt model results at 530 kA

At that stage, HHCellvolt can be used to calculate the cell voltage and the cell internal heat assuming a value for the cell current efficiency. Figure 8 is presenting HHCellvolt busbar panel where the user enters the anode, cathode and busbar voltage drop. That figure illustrates clearly the new boundary between the internal voltage drop and the external voltage drop. The external section goes from the location where the collector bars exit the cell to the location where the stubs enter into the anode cover material. Figure 9 is showing the HHCellVolt bath voltage drop results using user inputs for the ACD, the bubble model, and the anodic current density calculated from the anode layout presented in figure 1 and 530 kA cell amperage. Finally, the main HHCellVolt panel presented in figure 10 is showing the global results using that user assumed current efficiency.

Dyna/Marc global analysis of the wide cell design at 530 kA

Finally using the same inputs except for the cell current efficiency that is part of the solution, Dyna/Marc is used to calculate the steady-state cell conditions at 530 kA and 2.8 cm ACD. Table II presents the Dyna/Marc results summary, the cell voltage is predicted to be 3.24 V, the cell internal heat using Haupin's equation to calculate the equivalent voltage to make the metal is 516 kW at the calculated current efficiency of 94.3% and the cell superheat is predicted to be 5.0 °C. Finally, the cell power consumption is calculated to be 10.23 kWh/kg, not quite 10 kWh/kg unfortunately!

Discussion and future work

Table III summarizes the results of the 4 wide cell designs presented so far all using the same wide potshell platform. The cell operating at 530 kA, 0.66 A/cm^2 and 10.23 kWh/kg dissipates only 39% of the heat dissipated by the cell operating at 762.5 kA, 0.94 A/cm^2 and 12.85 kWh/kg. Both HHCellVolt and Dyna/Marc can easily be used to quickly investigate what would be the cell amperage required to operate at 10.0 kWh/kg assuming to other changes, the answer is 505 kA, 0.63 A/cm^2 and 436 kW of cell internal heat. 436 kW represents 33% of the heat dissipated by the cell operating at 762.5 kA and 12.85 kWh/kg and 84% of the heat dissipated by the cell operating at 530 kA and 10.23 kWh/kg.

This 15% extra reduction of the cell heat loss must be achieved without further reducing the cell superheat. It is also fair to assume that it would not be safe to further reduce the metal pad thickness. Yet as it can be seen in figure 6, after the reduction of that metal pad thickness there is now plenty of spare cell cavity. This is providing the opportunity to increase the thickness of the cell lining below the cathode block. New semi-insulating lining material that resist sodium vapor have also become available, this combination may provide an opportunity to design a more insulating cathode lining and hence reduce the cathode heat loss at constant cell superheat without risking to have that cathode lining degraded by exposing it to high temperature and sodium vapor.

Conclusions

Two extra steps toward the design of a cell operating at 10.0 kWh/kg have been presented in this article. The last step is the design of a wide cell operating at 530 kA, 0.66 A/cm^2 and 10.23 kWh/kg. That cell is operating at the assumed lowest ACD of 2.8 cm, the lowest assumed metal pad thickness of 10 cm and the lowest assumed cell superheat of 5 °C. That cell is also operating at 25 cm of anode cover thickness, that may not be the highest value possible but must be quite close to it. Despite that, and the usage of refined design features to limit the studs and collector bars heat loss (more details will be presented in [2] on this), it was not possible to design a cell operating at 10.0 kWh/kg in the current study. Yet the ultimate goal is getting more and more accessible and should be reach quite soon now, still using the wide cell design option.

References

[1] M. Dupuis, “Breaking the 11 kWh/kg Al barrier”, ALUMINIUM, 94 (1/2), 2018, 48-52.

[2] M. Dupuis, “How to limit the heat loss of anode stubs and cathode collector bars in order to reduce cell energy consumption”, TMS Light Metals, 2019, to be published.

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[4] M. Dupuis, “Low energy consumption cell design involving copper inserts and innovative busbar network layout”, TMS Light Metals, 2017, 693-703.

[5] M. Dupuis, “Very low energy consumption cell designs: the cell heat balance challenge”, TMS Light Metals, 2018, 689-687.

[6] P. Entner, HHCellVolt AlWeb application: http://peter-entner.com/ug/windows/hhcellvolt/toc.aspx

[7] P. Entner and M. Dupuis, “Extended energy balance for Hall-Héroult electrolysis cells”, 12th Australasian Aluminium Smelting Technology Conference, 2018, to be published.

[8] M. Dupuis and H. Côté, “Dyna/Marc 14.0 user’s guide”, GeniSim, 2012.

[9] M. Dupuis, “Computation of Aluminum reduction Cell Energy Balance Using ANSYS® Finite Element Models”, TMS Light Metals, 1998, 409-417.

Author

Dr. Marc Dupuis is a consultant specialized in the applications of mathematical modeling for the aluminium industry since 1994, the year when he founded his own consulting company GeniSim Inc (www.genisim.com). Before that, he graduated with a Ph.D. in chemical engineering from Laval University in Quebec City in 1984, and then worked 10 years as a research engineer for Alcan International. His main research interests are the development of mathematical models of the Hall-Héroult cell dealing with the thermo-electric, thermo-mechanic, electro-magnetic and hydrodynamic aspects of the problem. He was also involved in the design of experimental high amperage cells and the retrofit of many existing cell technologies.

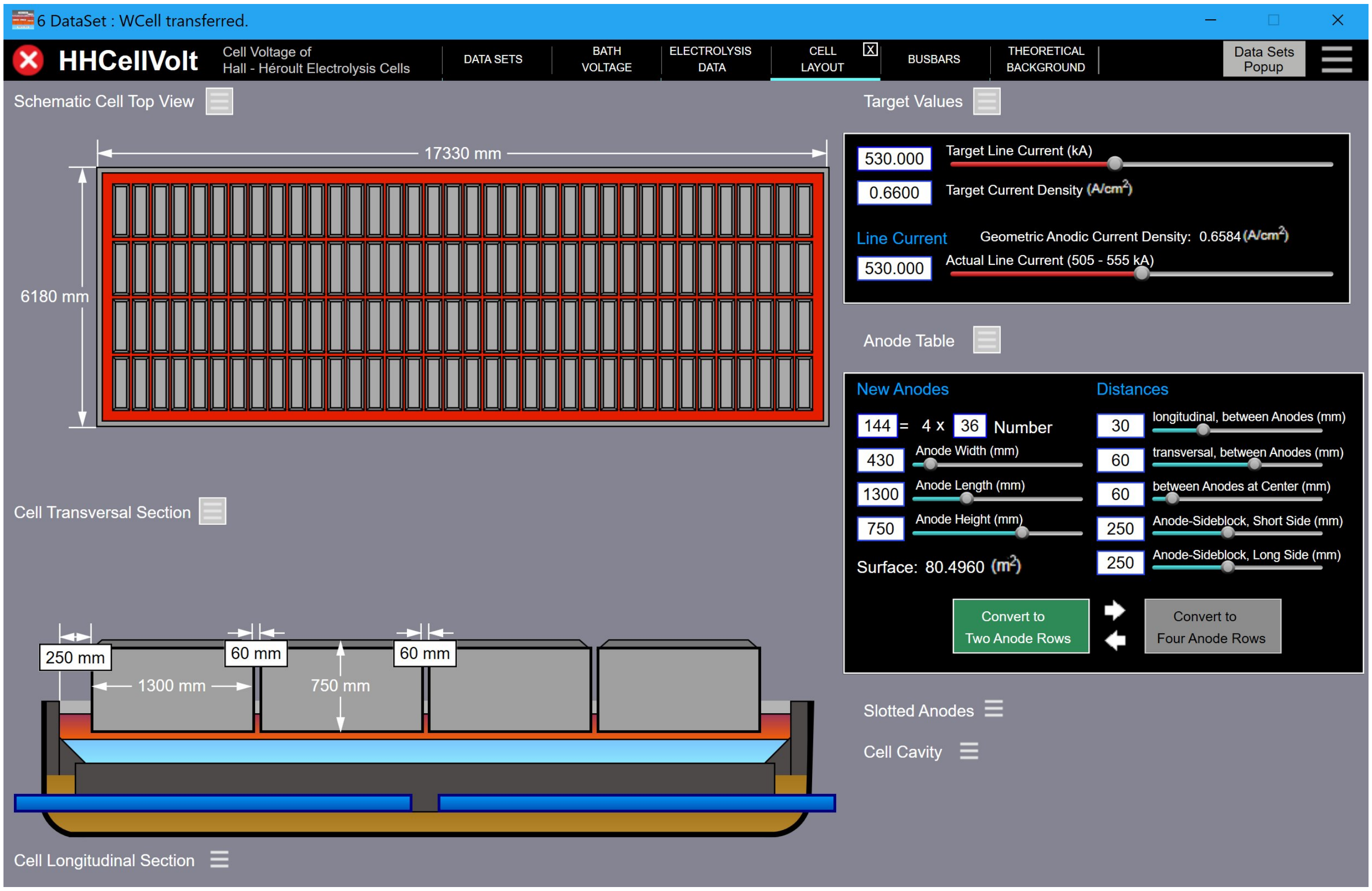

Figure 1: HHCellVolt layout of the wide cell design using 36 anodes, each having 4 carbon blocks

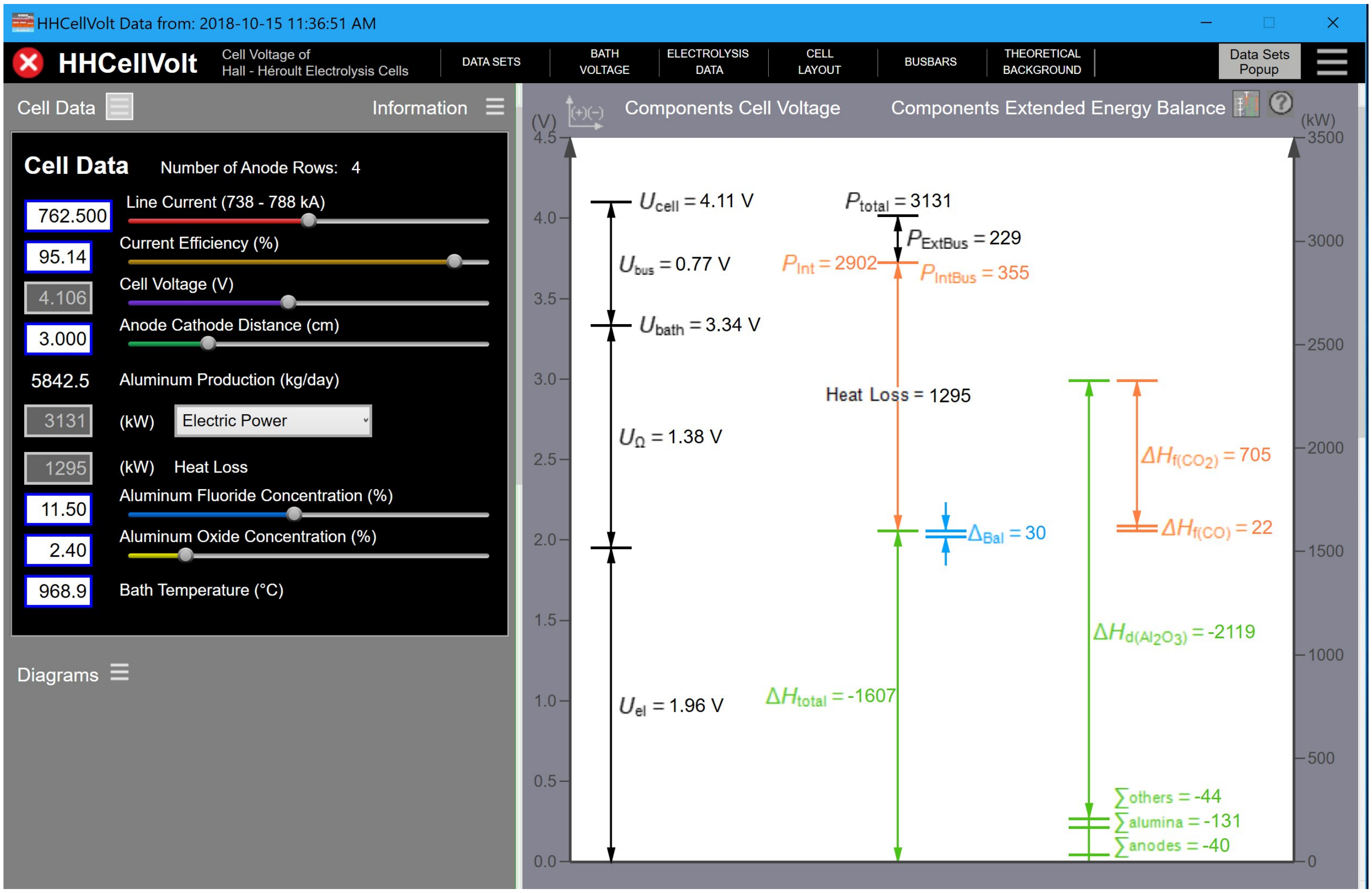

Figure 2: HHCellVolt main results for the initial wide cell design operating at 762.5 kA

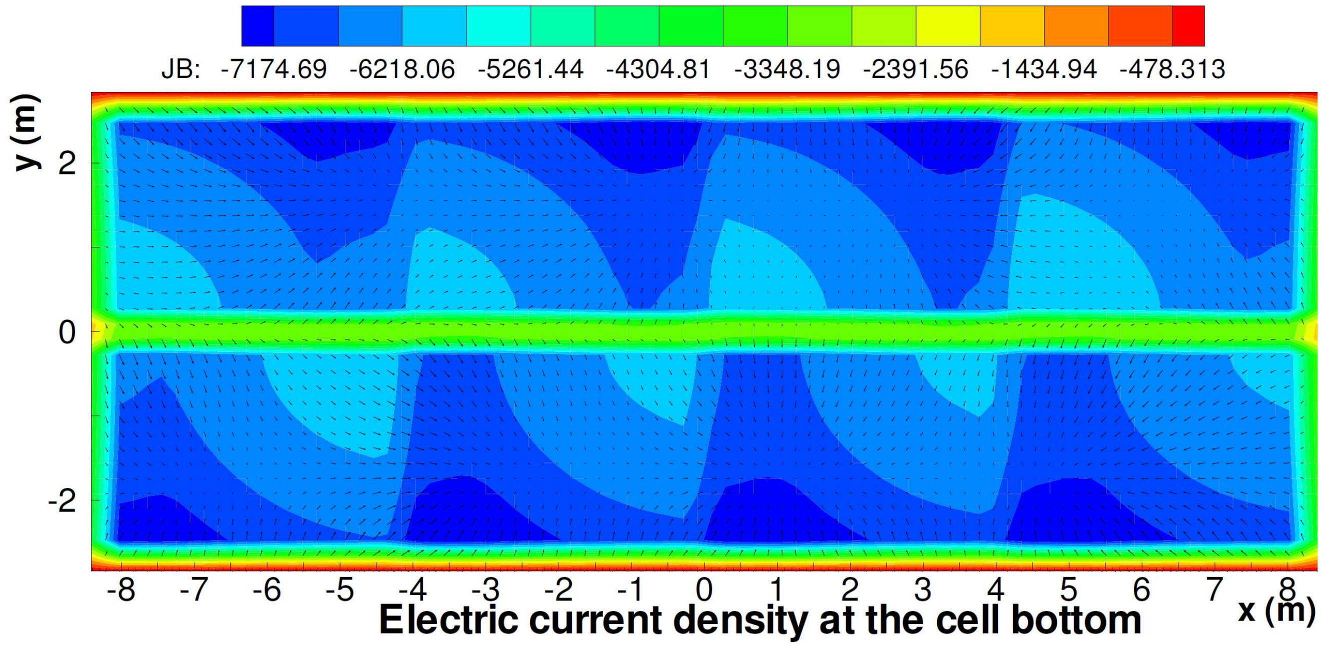

Figure 3: Cathode surface current density and mid metal pad horizontal current

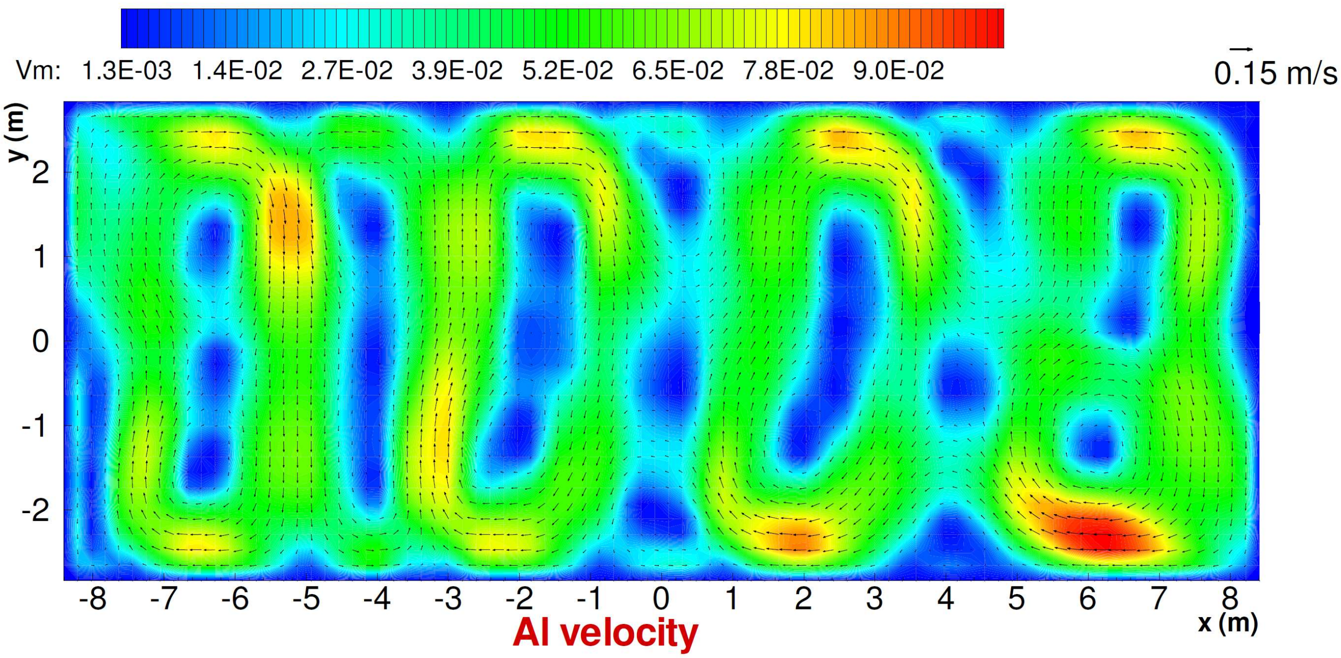

Figure 4: Metal pad average flow field

Table I: Dyna/Marc steady-state solution summary at 570 kA

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Steady State Solution
___________________________________________________________
Cell amperage                                   570.0 [kA]
Anode to cathode distance                     2.80000 [cm]
Operating temperature                         964.064 [C]
Ledge thickness, bath level                   8.90003 [cm]
Ledge thickness, metal level                  3.19020 [cm]

Bath chemistry:
  Cryolite ratio                               2.20470 [mole/mole]
  Bath ratio                                   1.10235 [kg/kg]
  Conc. of excess aluminum fluoride           11.50000 [%]
  Conc. of dissolved alumina                   2.80000 [%]
  Conc. of calcium fluoride                    6.00000 [%]

Heat balance:
  Superheat                                     7.5402 [C]
  Cell energy consumption                      10.6072 [kWhr/kg]
  Total heat loss                              612.992 [kW]

Electrical characteristics:
  Current efficiency                           94.3733 [%]
  Anode current density                       0.708110 [A/cm*cm]
  Bath resistivity                            0.454942 [ohm-cm]
  Cell pseudo-resistance                       2.99735 [micro-ohm]
  Bath voltage                                 0.94007 [V]
  Electrolysis voltage                         1.87543 [V]
  Cell voltage                                 3.35849 [V]
  Voltage to make the metal                    2.03522 [V]
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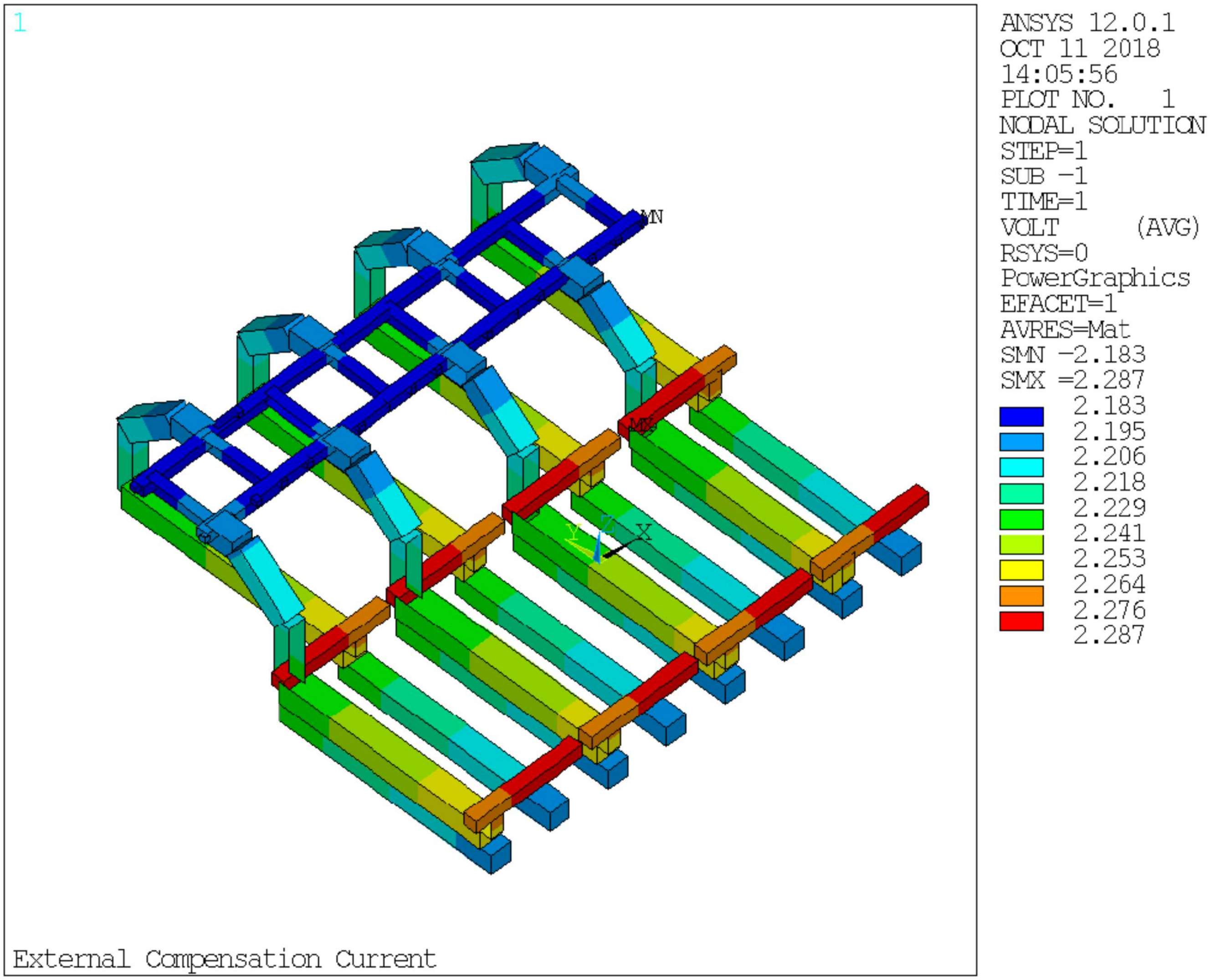

Figure 5: Wider 530 kA 8 risers RCC busbar voltage drop

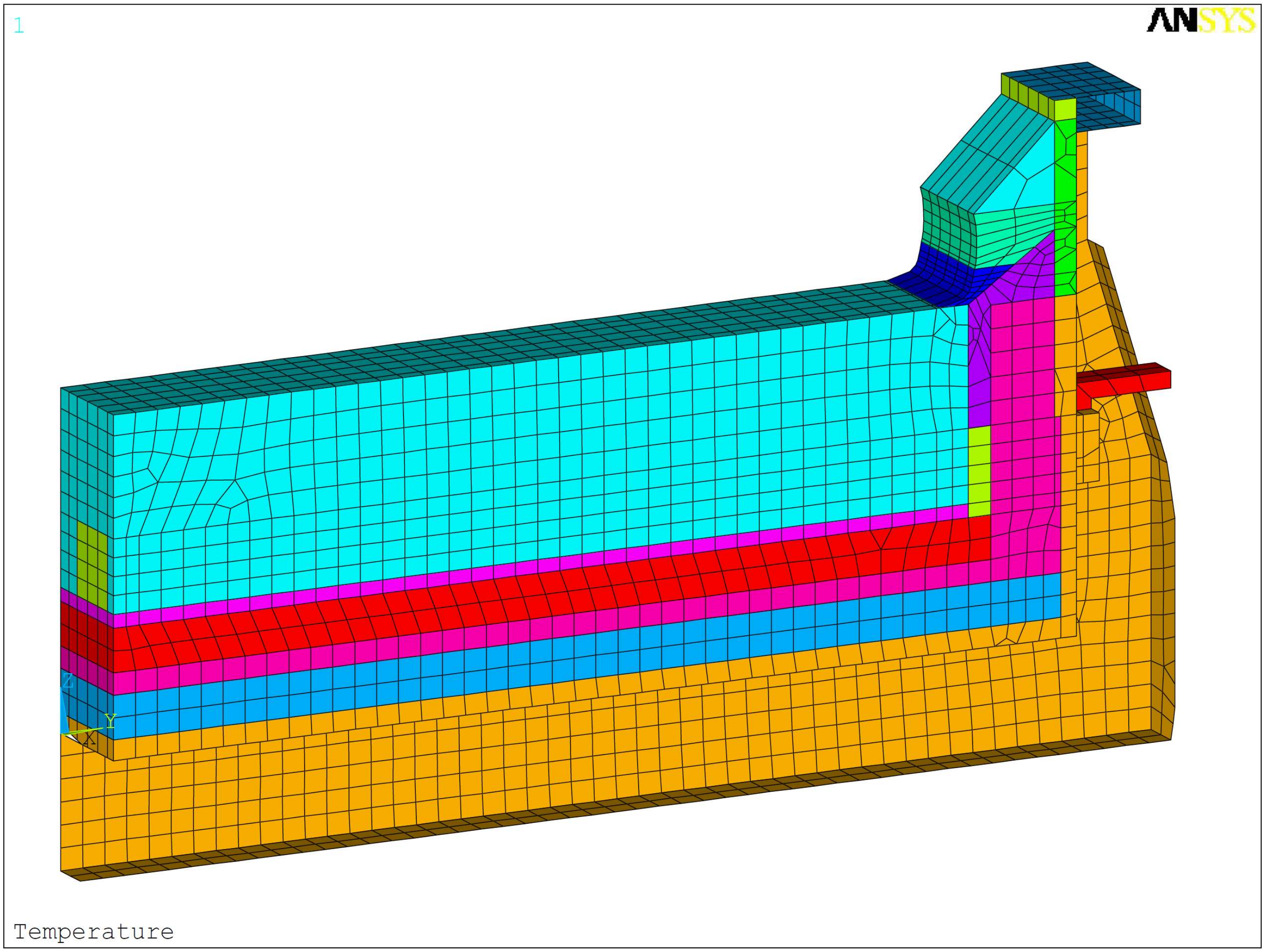

Figure 6: ANSYS based cathode side slice thermo-electric model mesh with converged ledge profile

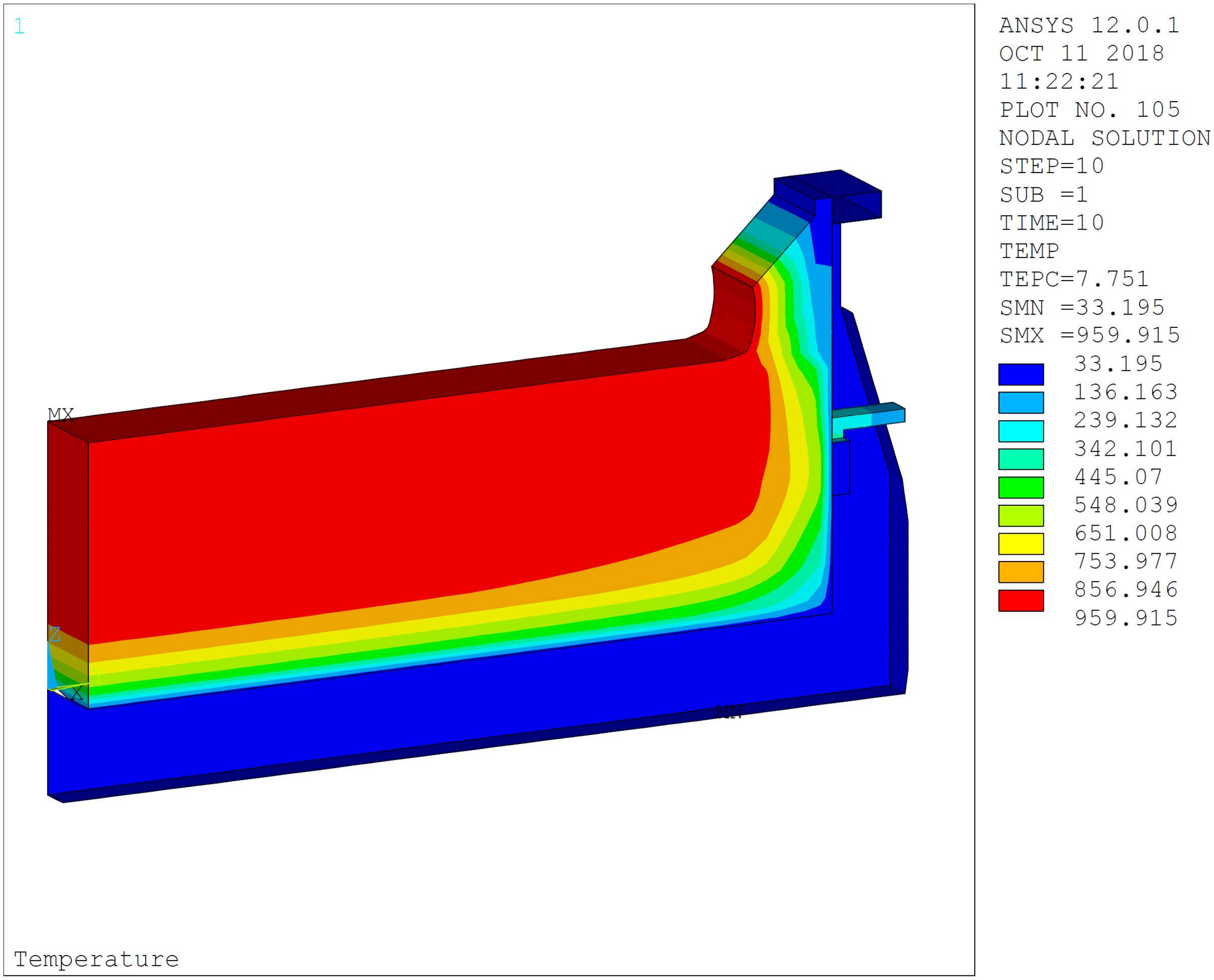

Figure 7: ANSYS based cathode side slice thermo-electric model isotherms with converged ledge profile

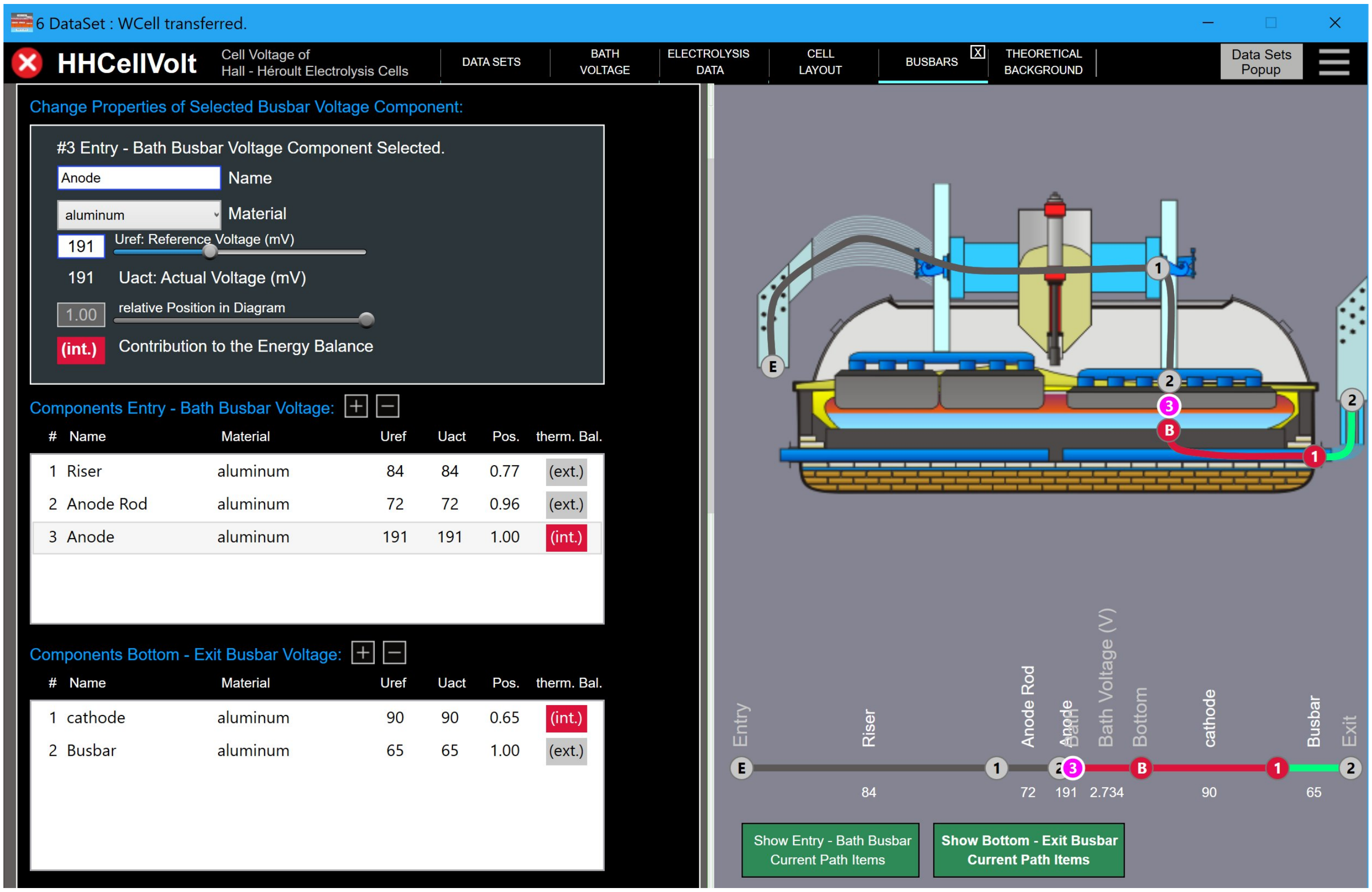

Figure 8: HHCellVolt barbars voltage drop input panel

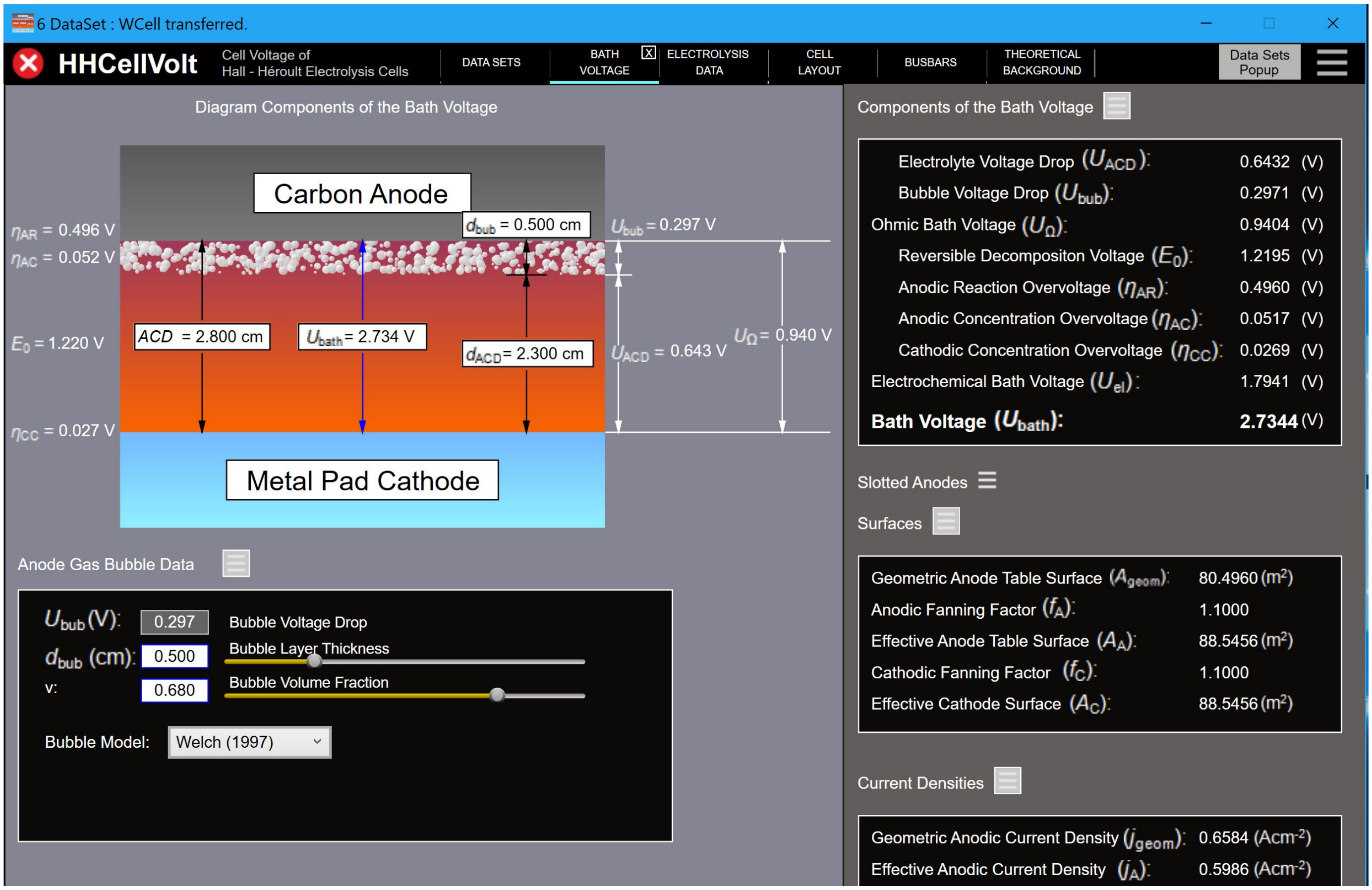

Figure 9: HHCellVolt bath voltage drop results panel

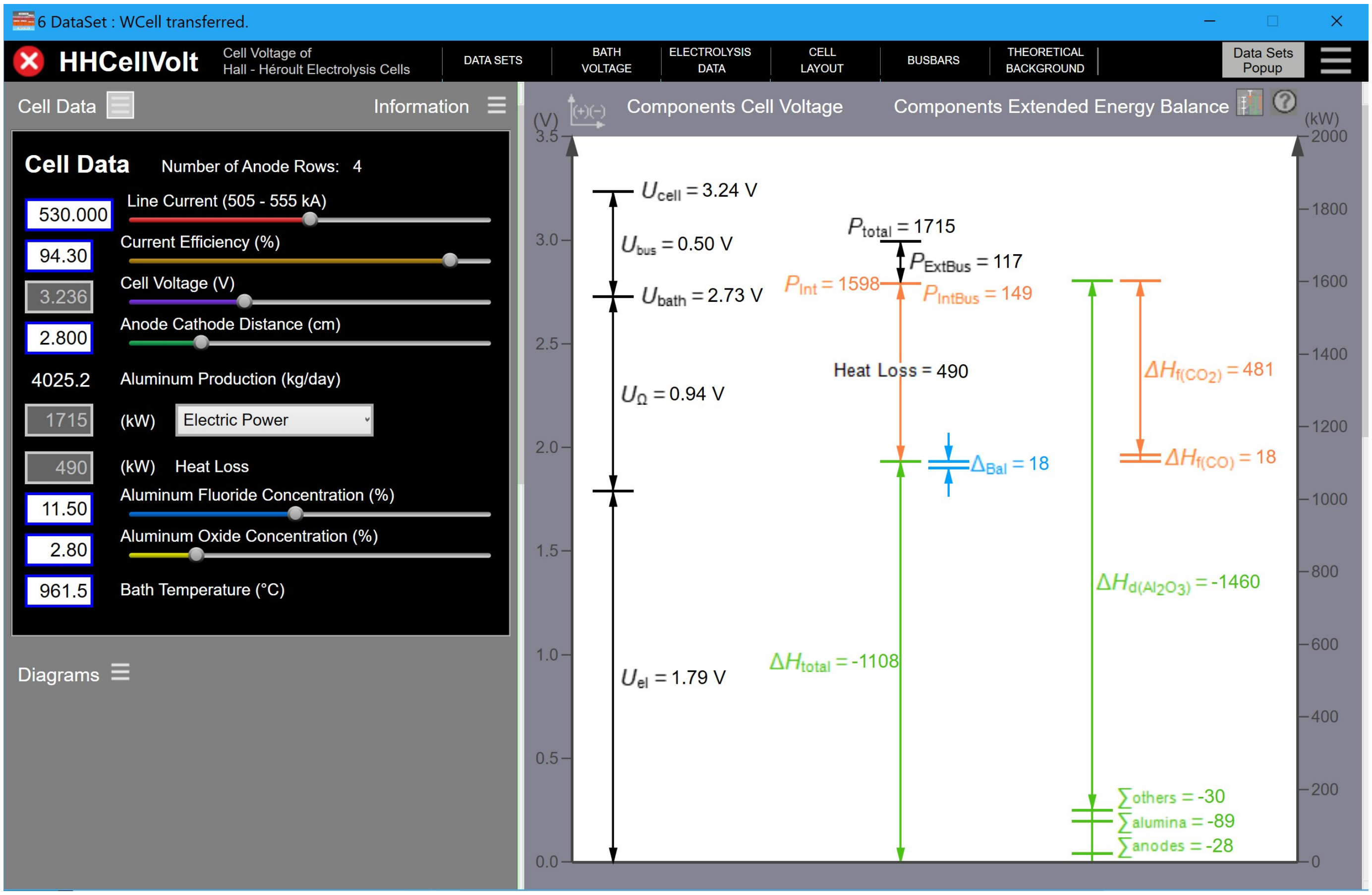

Figure 10: HHCellVolt main results for the final wide cell design operating at 530 kA

Table II: Dyna/Marc steady-state solution summary at 530 kA

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Steady State Solution
___________________________________________________________
Cell amperage                                  530.0 [kA]
Anode to cathode distance                    2.80000 [cm]
Operating temperature                        961.560 [C]
Ledge thickness, bath level                 15.79983 [cm]
Ledge thickness, metal level                 9.99283 [cm]

Bath chemistry:
  Cryolite ratio                              2.20470 [mole/mole]
  Bath ratio                                  1.10235 [kg/kg]
  Conc. of excess aluminum fluoride          11.50000 [%]
  Conc. of dissolved alumina                  2.80000 [%]
  Conc. of calcium fluoride                   6.00000 [%]

Heat balance:
  Superheat                                    5.0367 [C]
  Cell energy consumption                     10.2313 [kWhr/kg]
  Total heat loss                             516.203 [kW]

Electrical characteristics:
  Current efficiency                          94.3031 [%]
  Anode current density                      0.658418 [A/cm*cm]
  Bath resistivity                           0.456250 [ohm-cm]
  Cell pseudo-resistance                      2.99443 [micro-ohm]
  Bath voltage                                0.87661 [V]
  Electrolysis voltage                        1.85844 [V]
  Cell voltage                                3.23705 [V]
  Voltage to make the metal                   2.03346 [V]
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Table III: Wide cell design studies results summary

Amperage	762.5 kA	650 kA	570 kA	530 kA
Nb. of anodes	48	36	36	36
Anode size	2.6m X .65m	2.6m X .86m	2.6m X .86m	2.6m X .86m
Nb. of anode studs	4 per anode	12 per anode	12 per anode	12 per anode
Anode stud diameter	21.0 cm	16.0 cm	18.0 cm	18.0 cm
Anode cover thickness	15 cm	25 cm	25 cm	25 cm
Nb. of cathode blocks	24	24	24	24
Cathode block length	5.37 m	5.37 m	5.37 m	5.37 m
Type of cathode block	HC10	HC10	HC10	HC10
Collector bar size	20 cm X 12 cm	20 cm X 15 cm	20 cm X 15 cm	20 cm X 15 cm
Type of side block	HC3	HC3	HC3	HC3
Side block thickness	7 cm	7 cm	7 cm	7 cm
ASD	25 cm	25 cm	25 cm	25 cm
Calcium silicate thickness	3.5 cm	6.0 cm	6.0 cm	6.0 cm
Inside potshell size	17.02 X 5.88 m	17.02 X 5.88 m	17.02 X 5.88 m	17.02 X 5.88 m
ACD	3.0 cm	2.8 cm	2.8 cm	2.8 cm
Anode current density	0.93 A/cm^2	0.81 A/cm^2	0.71 A/cm^2	0.66 A/cm^2
Metal level	20 cm	20 cm	10 cm	10 cm
Excess AlF_3	11.50%	11.50%	11.50%	11.50%
Anode drop (A)	347 mV (T)	252 mV (T)	207 mV (I)	191 mV (I)
Cathode drop (A)	118 mV (T)	109 mV (T)	91 mV (I)	90 mV (I)
Busbar/External drop (A)	300 mV (B)	170 mV (B)	227 mV (E)	221 mV (E)
Anode panel heat loss (A)	553 kW (T)	339 kW (T)	221 kW (I)	218 kW (I)
Cathode total heat loss (A)	715 kW (T)	482 kW (T)	417 kW (I)	311 kW (I)
Operating temperature (D/M)	968.9 °C	966.5 °C	964.1 °C	961.6 °C
Liquidus superheat (D/M)	10.0 °C	7.6 °C	7.5 °C	5.0 °C
Bath ledge thickness (A)	6.82 cm	14.25 cm	18.36 cm	21.38 cm
Metal ledge thickness (A)	1.85 cm	4.58 cm	6.88 cm	7.60 cm
Current efficiency (D/M)	95.1%	94.9%	94.4%	94.3%
Internal heat (D/M)	1328 kW	804 kW	613 kW	516 kW
Energy consumption	12.85 kWh/kg	11.0 kWh/kg	10.6 kWh/kg	10.2 kWh/kg