HEATING NEW ANODES USING THE WASTE HEAT OF ANODE BUTTS ESTABLISHING THE INTERFACE THERMAL CONTACT RESISTANCE

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Abstract

In order to be able to assess the rate of heat transfer between a new anode and an anode butt, it is critical to measure the interface thermal contact resistance between them. For that purpose, a lab experiment has been setup and tests have been carried out to record the thermal response of the system after a cold anode block is put in contact with a hot anode block. Finally, a model of the same system has been developed in order to identify the value of the thermal contact resistance that permit to reproduce the thermal experimental thermal response.

Introduction

Carbon anodes are replaced on a regular basis in aluminum electrolysis cells as they are consumed by electrochemical reactions [1]. Upon insertion of new anodes, bath will freeze locally as a result of low bath superheat and comparatively low anode temperature, creating an insulating layer on the anode surface, thereby delaying and disrupting further production [2, 3, 4]. Moreover, the heating of the newly inserted anode comes at an energy premium of approximately 0.13 kWh/kg produced Al. The thermal issues arising due to anode change can be reduced by pre-heating the anodes, as demonstrated by Fortini et al. [5], using induction, and Jassim et al. [6], using a gas fired heating station. Evidently, the efficiency and availability of the heat source has to be assessed carefully so that the benefits from pre-heating are not negated by increased energy consumption.

As discussed by Nowicki and Gosselin [7], there are several heat sources in an aluminium plant which could be used for heat recovery, some of which in sufficient proximity to the cell to allow for anode pre-heating. Approximately 1/4 of the anode mass typically remains as a so-called butt, with temperatures close to the operational temperature of the cell upon removal. Butts are normally cooled down without heat recovery in the pot room before they recycled, dissipating the heat to the environment. A preliminary study by Grimstad et al. [8] was performed in industry where butts were used to pre-heat new anodes, saving up to 0.02 kWh/kg Al when heated in 4 hours. Although promising, the concept had some shortcomings related to logistics – inparticular relating to the fact that two butts were needed to heat a single new anode – and that the proposed side-by-side configuration did not effectively transfer heat to the bottom of the new anode where it is most needed.

In the current work, we propose an improved configuration in which the bottom face of a butt is placed in contact with the bottom face of a new anode. The efficiency of the heat transfer is dependent on the available thermal masses of butt and new anode, but also upon the interfacial thermal conductivity (inverse thermal contact resistance) between butt and anode. To our best knowledge, this contact resistance has not yet been reported in the open literature. Hence, lab scale experiments were performed in order to determine this parameter under different operating conditions, enabling new numerical simulations from which the potential of the proposed configuration could be assessed.

Experimental

Two lab-scale anodes with dimensions 10x10x10 cm were cut from an industrial anode. Three holes (Ø1.6 mm) were drilled in each anode at 3, 12 and 21 mm from the bottom face in which thermocouples (Type K with Inconel 600 sleeve. Diameter is 1.5mm, Max Sievert, Oslo, Norway) were introduced, as sketched in Figure 1. The anode sample representing the butt had a 50 cm steel tube attached to its top surface, in order to facilitate transport from the furnace to the pre-heating station.

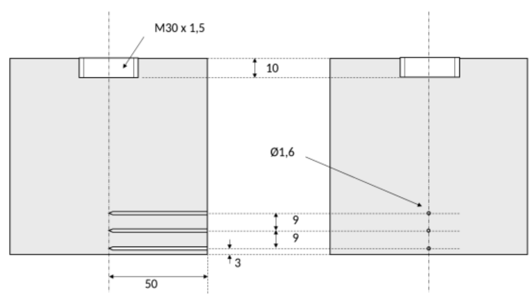

Figure 1: Sketch of anode samples with relevant dimensions given in mm. The samples were cubic with 10 cm side walls.

For each experiment, the sample representing the new anode was placed in a thermally insulated container with its bottom face pointing up, cf. Figure 2a, while the sample representing the butt was heated to approximately 980 ºC . The butt was then placed in the container in such a way that its bottom face was aligned with the new anode, cf. Figure 2b, before the container was covered with insulating material. The temperatures were logged using Keithley 2000 with 10 channel multiplexer at a sampling frequency of 0.5 Hz for both samples for each of the three positions indicated in Figure 1.

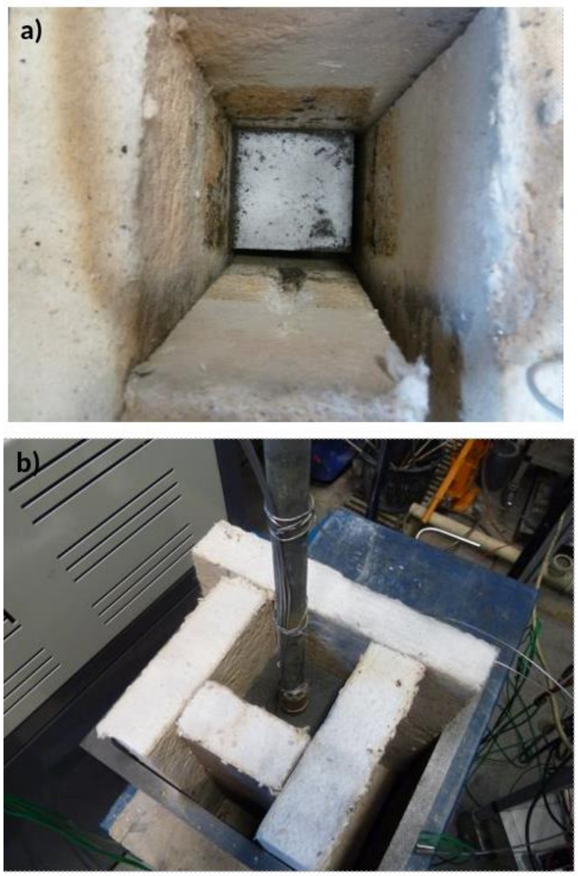

Figure 2: View of new placement of sample representing the new anode (a) and placement of sample representing butt (b).

Experiment 1: The sample representing the butt was heated in Entech tube furnace until the temperature reached 980 ºC before being placed on the new anode. Temperatures were logged for approximately 2 hours.

Experiment 2: The sample representing the butt was heated in Entech tube furnace until the temperature reached 987 ºC before being placed in the anode container in such a way that there was a 3 mm gap between the surfaces. Temperatures were logged for approximately 2 hours. The reason for keeping a distance between the two surfaces was to represent the imperfect contact expected in an industrial setting, where the bottom of the butt will not be a perfect flat surface.

Experiment 3: The sample representing the butt was heated in industrial bath until the temperature reached 995 ºC before being placed on the new anode. Temperatures were logged for approximately 2 hours. Upon removal, the anode sample representing the butt was covered by a bath film and is thus expected to be more representative of real conditions when compared to experiments 1 and 2.

Figure 3 presents the temperature recording of the 6 thermocouples for the first hour. As the curves evolution indicate, the system quickly evolves toward a uniform average temperature.

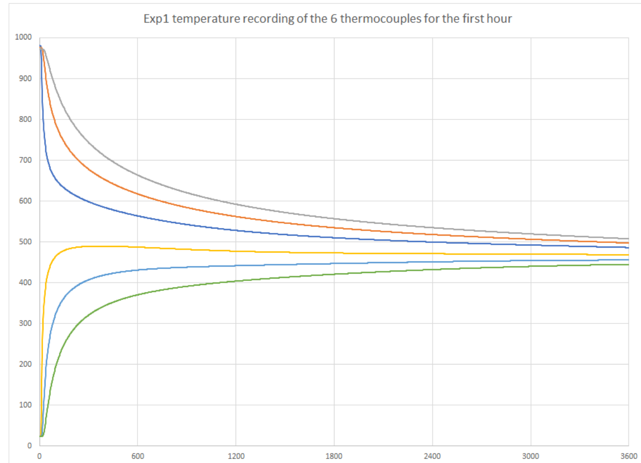

Figure 3: Temperature recording of the 6 thermocouples for the first hour for the experiment No 1.

Mathematical model of the lab experiment

In order to reproduce the lab experiment, it was initially decided to build a 3D model. The geometry is quite simple, it consists of 2 cubes of 10x10x10 cm on top of each other. The top steel rod was not represented in the model.

Building the full 3D geometry leaves the flexibility of applying asymmetric boundary conditions. Yet, as a first approximation, it was decided to apply adiabatic boundary conditions on all surfaces. This approximation is valid for the first hour of cooling where the impact of the system heat loss on the temperature evolution is negligible. This way it was not necessary to characterize the lab experiment insulation characteristics and reproduce them in the model.

Simplified this way, the problem reduces to a 1D thermal diffusion problem. That problem can be modelled in 3D without much extra CPU penalty by using a very fine mesh in the vertical direction where the thermal diffusion is taking place and using only one element in the cross section. Figure 4 presents the model mesh. The element aspect ratio would be problematic to solve a real 3D problem but is well adapted to solve a 1D thermal diffusion problem as is the case here.

The vertical mesh density was selected to ensure that there is a node at the location of the thermocouples, especially the one the closest to the interface between the blocks.

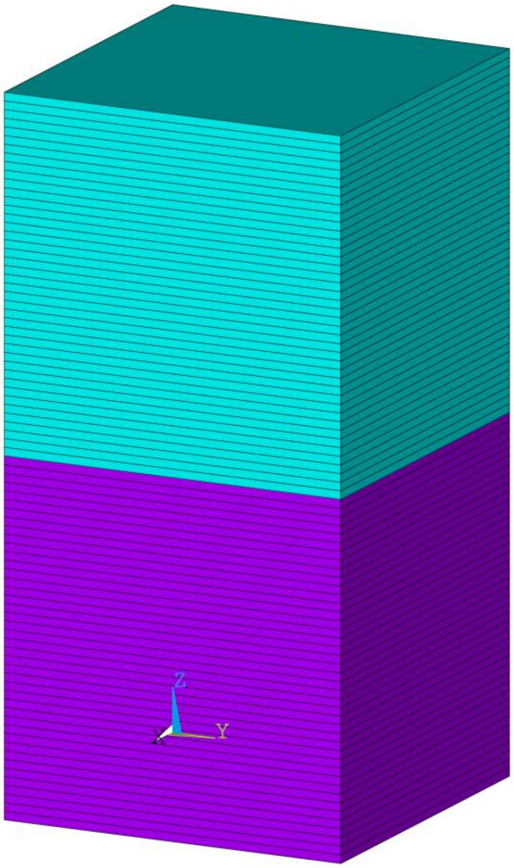

Figure 4: Mesh of the lab experiment model.

Since the boundaries are adiabatic and hence no heat loss, the thermal evolution only depends on the initial conditions presented in figure 5, the thermal diffusivity of the anode carbon blocks and the unknown thermal contact conductivity at the interface of the 2 blocks.

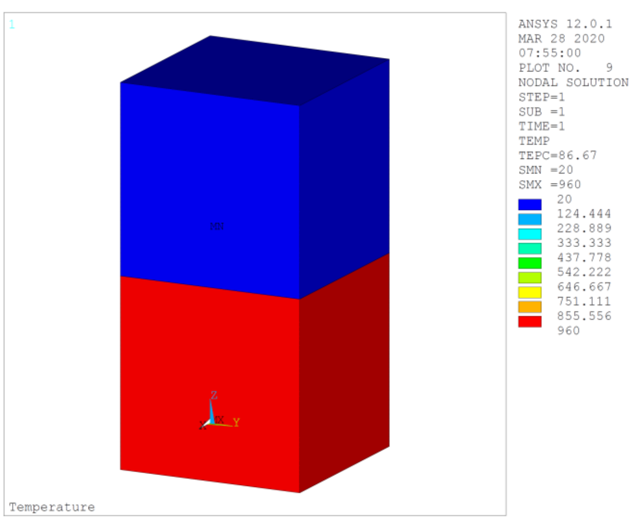

Figure 5: Temperature of the model at time 0.

From the initial conditions, the transient evolution of the system is calculated for 1 hour. The initial time step was set to 5 seconds, ANSYS is performing equilibrium iterations as the problem is non linear due to the temperature dependent carbon properties. ANSYS requires 2 equilibrium iterations to converge the first time step. The time step size was gradually increased as time advanced, up to a maximum of 20 seconds.

The temperature profile after 10 minutes of thermal diffusion is shown in Figure 6. There is still a temperature gradient at the interface between the two blocks, and the evolution of this gradient depends mostly on the value of the thermal contact conductivity.

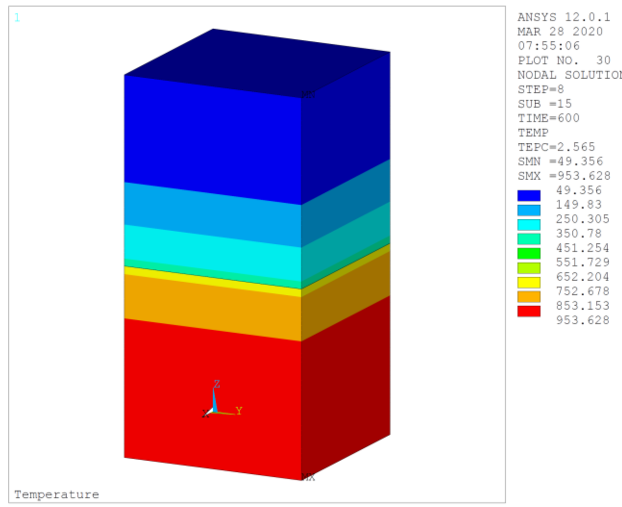

Figure 6: Temperature of the model after 10 minutes.

The evolution of the temperature gradient at different points in time from 5 to 3600 seconds is shown in Figure 7. The curve denoted by 600 represents the same solution as figure 6. Notice that in the lab experiment setup, the hot block was put on top of the cold block while the opposite was done in the model.

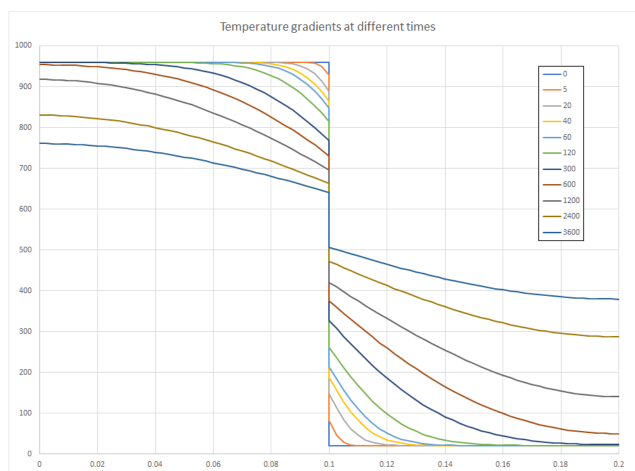

Figure 7: Temperature gradients in the carbon blocks at different times.

Comparison of lab and model results

The mathematical results will only reproduce the lab measurements is the proper thermal contact conductivity was selected in the model. Figure 8 presents the comparison between the lab results and the model results for the location of the thermocouple near the hot block interface. The evolution of the thermal gradient between the two thermocouples located each side of the interface depends mostly on the thermal contact conductivity. As seen in figure 8, a choice of 300 W/m^{2o}C in the model, results in a greater cooling rate than that measured experimentally.

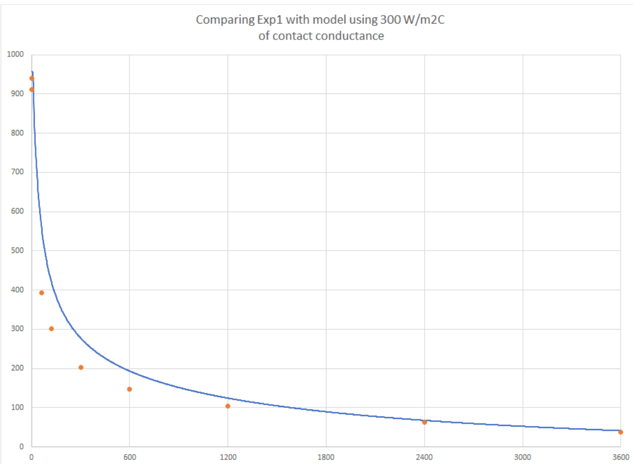

Figure 8: Comparison of experimental and modeled temperature difference between the thermocouples located each side of the interface with 300 W/m^{2o}C of thermal contact conductance for experiment 1.

The proper value of that thermal contact conductivity in order for the model to reproduce the measured thermal gradient is obtained by trials and errors. As we can see in figure 9, when a value of 225 W/m^{2o}C is selected, the model reproduced very well the measurements.

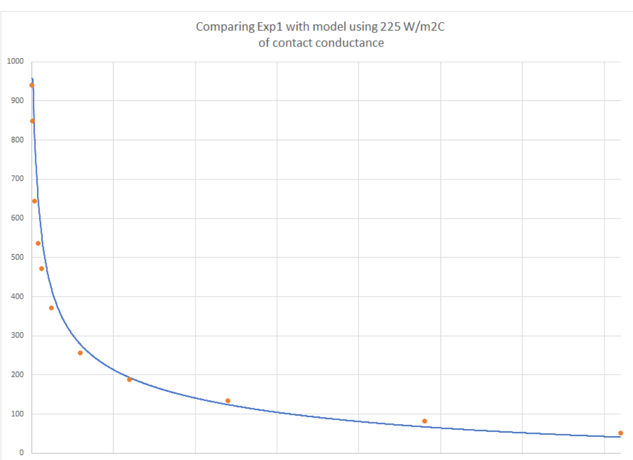

Figure 9: Comparison of experimental and modeled temperature difference between the thermocouples located each side of the interface with 225 W/m^{2o}C of thermal contact conductance for experiment 1.

The same exercise has been repeated for experiment 2 and 3, figure 10 and 11 present the obtained match when the proper thermal conductivity is selected. That value turned out to be 80 W/m^{2o}C for experiment 2 and 100 W/m^{2o}C for experiment 3.

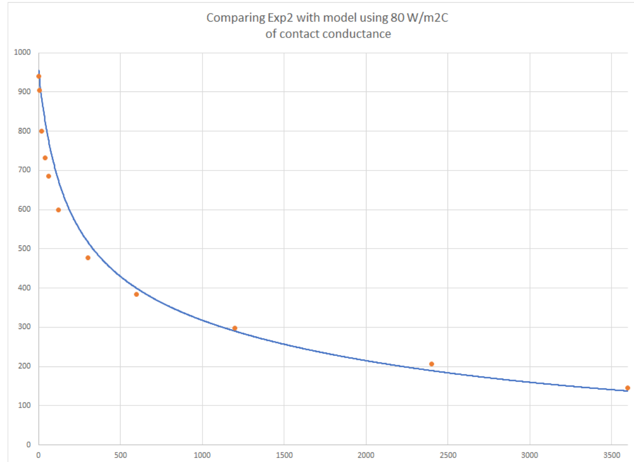

Figure 10: Comparison of experimental and modeled temperature difference between the thermocouples located each side of the interface with 80 W/m^{2o}C of thermal contact conductance for experiment 2.

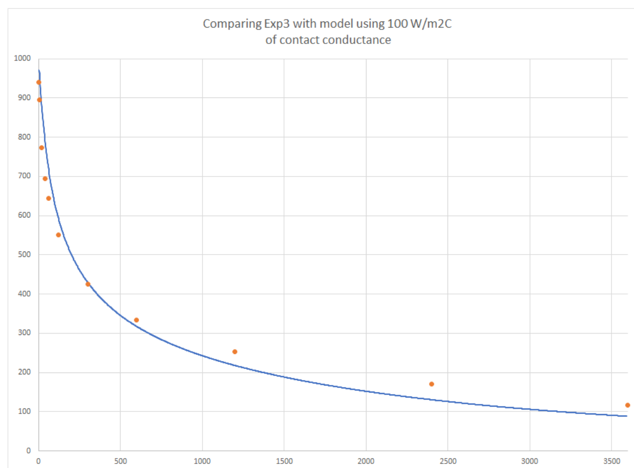

Figure 11: Comparison of experimental and modeled temperature difference between the thermocouples located each side of the interface with 100 W/m^{2o}C of thermal contact conductance for experiment 3.

This series of 3 experiences demonstrate the importance of the value of the thermal contact conductance in the initial rate of heat transfer between the two anode blocks. Unfortunately, this series of experiences in not giving us a definitive value to use to model the heat exchange between an anode butt and a new anode in industrial conditions just a range of possible values to be expected. Industrial tests would need to be performed to more precisely assess the thermal contact conductance between an anode butt just out of a cell and a new anode if the two are put in direct contact. Pending those industrial tests, the modeling of the following proposed heat exchange configuration has been model using all 3 measured thermal contact conductance.

Modeling a new proposed preheating configuration

It is proposed to preheat a new anode using a single anode butt by placing the bottom face of the anode butt in contact with the bottom face of the new anode in order to preheat directly the part of the new anode that will be in contact with the bath when that new anode in put in the cell. Figure 12 presents the proposed contact configuration and the assumed initial temperature of both anodes.

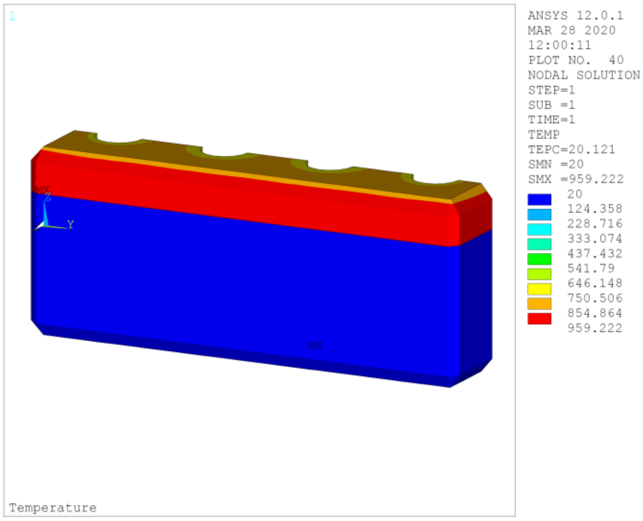

Figure 12: Proposed bottom face to bottom face preheat configuration and initial anode carbon blocks temperature.

The initial temperature of the anode butt is obtained by solving the thermo-electric model of the old anode still in operation. After obtaining that old anode operating temperature, a new anode is added under it, and the boundary conditions of the new system updated to remove the operating conditions of the old anode and add the new boundary conditions. Figure 13 presents the full heat exchange model with the full model initial temperature.

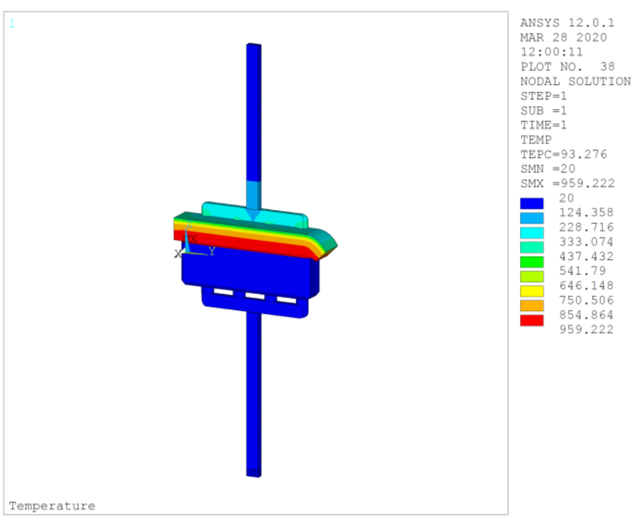

Figure 13: Proposed bottom face to bottom face preheat configuration and initial anode butt and new anode temperature.

It is assumed that both anodes are placed in a well-insulated box so heat loss boundary conditions are only applied on the anode rods outside of the box. The crust on top of the anode butt is kept intact from the operating condition for simplicity as removing the crust above the side channel would not affect the temperature evolution of the new anode.

What is affecting the new anode temperature evolution, in particular at the very beginning of the heat exchange, is the selected value of the thermal contact conductivity between the anode butt and the new anode. All 3 values obtained for the lab experiments have been used. Figure 14 presents the vertical evolution of the vertical temperature gradient in the new anode, from the bottom face up while figure 15 presents the obtained new anode temperature after hours of exchange using 225 W/m^2°C for the thermal contact conductance. As can be seen in figure 14, the bottom face reaches a maximum temperature after about 40 minutes and then slowly starts to cool down. The average new anode block temperature continues to increase up to 2 hours of heat exchange but more and more slowly.

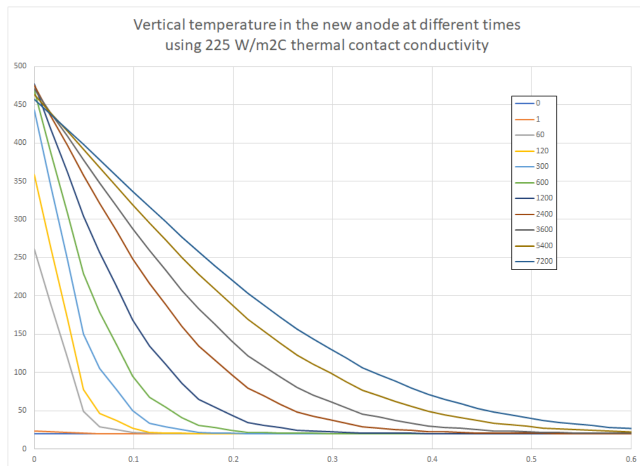

Figure 14: Evolution of the vertical thermal gradient in the new anode vs time up to 2 hours using 225 W/m^2°C thermal contact conductance.

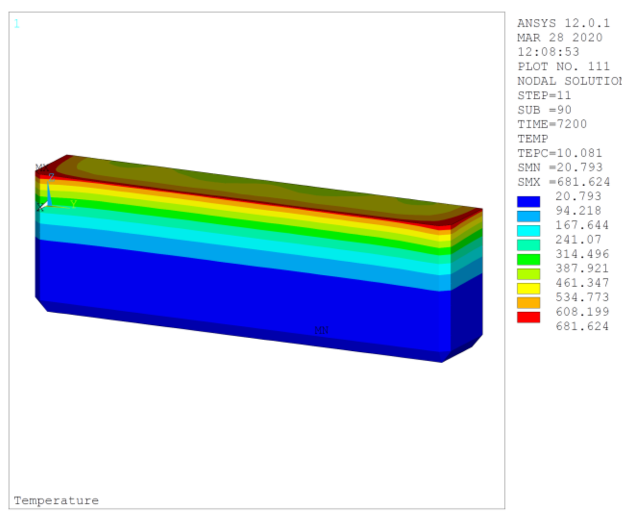

Figure 15: New anode block temperature after 2 hours using 225 W/m^2°C thermal contact conductance.

The modeling results of this new proposed preheating configuration can be summarized as follow:

With 225 W/m2ºC as interface thermal contact conductance:

Average new anode temperature after 2 hours 155.38 °C
Average bottom face temperature after 2 hours 474.29 °C

With 100 W/m2ºC as interface thermal contact conductance:

Average new anode temperature after 2 hours 143.12 °C
Average bottom face temperature after 2 hours 442.62 °C

With 80 W/m2ºC as interface thermal contact conductance:

Average new anode temperature after 2 hours 138.28 °C
Average bottom face temperature after 2 hours 429.53 °C

Compared to the original approach described by Grimstad et al. [8], the temperatures are similar to that obtained after 4 hours of heating using two butts rather than one, i.e. a total improvement of a factor 4.

For simplicity, the current modeling study has not considered the reduction of the butt length and width, this reduced the butt mass and contact surface area between the butt and the new anode. This is only a preliminary modeling study to demonstrate the potential of this proposed preheating configuration not to come up with definitive energy saving numbers.

Discussions

In order to put an anode butt and a new anode in that preheating configuration, a special insulated box would have to be engineered. Putting the anodes in that box at the beginning of the preheating and out of that box at the end of the preheating period represents additional crane operations as compared to a standard anode change operations for sure. The total anode change duration cannot be increased much (if at all), so the anode change operation will become more demanding for operators, most probably a third operator will be required. Assuming a 10 minutes anode change duration, a pipeline of 12 boxes will have to be filled before the first preheated anode become available for a 2 hours preheating period. This means that the first 12 anode changes of a new shift will be done using room temperature new anodes. This is where the tradeoff between efficiency and maximum energy transfer come in, if the preheating period is reduced to only 1 hour, the pipeline of boxes required is be reduced to 6.

This kind of extra potroom operation logistic during anode change operation is unavoidable regardless of the preheating configuration used. It is the price to pay to recuperate part of the butt otherwise waisted thermal energy and reduce this way the cell energy consumption.

Putting in the cell a new anode with a bottom face preheated up to 400 °C means that the new anode current pickup time will be significantly reduces reducing the negative effect of the anode change event on the cell stability. This may in turn permit the reduction of the ACD saving reducing even more the cell energy consumption. Trying to characterize this extra energy saving was outside the scope of the present study, although previous work has indicated a gain in current efficiency of up to 1% [5].

Although the benefit of preheating is clear, care must be taken so that the preheating process does not result in greatly increased air-burn, which ultimately leads to carbon losses and thereby also energy. Ideally, the pre-heating should thus be performed in air-tight containers, which would also contribute to keeping emissions to the potroom at a minimum.

Conclusions

If successfully implemented, proposed concept could contribute to a reduction of the cell energy consumption of approximately 0.2 kWh/kg Al. The main benefit of our proposal lies in the utilization of waste heat to achieve the pre-heating, compared to other concepts where energy consuming heat sources, e.g. gas fired furnaces, are used.

Acknowledgements:

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