Review of Thermal and Electrical Modelling and Validation Approaches for Anode Design in Aluminium Reduction Cells

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Abstract

Anode assembly design has great impact on cell voltage and heat loss; therefore, it is one of the key elements of aluminium reduction cell design. Accurate measurements of anode voltage drops and heat loss on operating cells are difficult as they depend on anode age and anode cover. Mathematical modelling appears to be an easier way to take into account complex geometry and time dependence, but different modelling approaches still give significantly different results and conclusions on total anode assembly voltage drop as well as on different anode voltage components, heat loss and the potential for optimization. This paper discusses different aspects of anode assembly evaluation, such as thermo-electrical modelling and measurements for model and design validation. Special attention is given to anode stub-to-carbon contact resistance and anode-to-bath interface modelling.

1. Introduction

Anode assembly design has great impact on cell voltage and heat loss and therefore, it is one of the key elements of aluminium reduction cell design. The aluminium reduction cell loses up to 50 % of heat from the top while the anode voltage drop (AVD) contributes approximately 10 % to net cell voltage. Today, many smelters are focusing on increasing amperage and/or reduction of specific energy consumption which requires an accurate knowledge of the anode assembly heat loss and anode voltage drop in order to calculate them with adequate accuracy to support the design or operational parameters change.

Obtaining accurate measurements of anode voltage drops and heat loss on operating cells are difficult as they depend on anode age and anode cover thickness and composition. Another factor which makes it difficult to measure the required parameters precisely is harsh conditions in and around the cells as well as safety rules.

There are different approaches for modelling cell electric and heat balance. Some of them consider anodes and cathodes together with molten bath and metal in one model [1-3], others consider anode and cathode models separately or together but exclude liquid bath and metal from the model [4-6] and represent heat transfer from molten layers to cathode and anode by heat transfer coefficients. Some authors include only bath for anode modelling [7-9].

From heat transfer point of view, we suppose that all methods can give adequate results with proper validation of the model. But for electrical calculations in the anodes, inclusion of the bath and to a lesser extent the metal is obviously required because the bath has much higher electrical resistivity than the anode. Moreover, there is a bubble layer below the anode and back EMF on the bottom surface of the anode.

The bubble layer creates additional resistance in the bath which depends on the fraction of anode bottom covered by the bubbles; this resistance is not present on the anode sides, because the bubbles travel up the anode sides mostly detached from the anode surface. The bubble layer is assumed to be 5 mm thick, covering 50 % of anode bottom surface. To compensate, this is simulated by increasing the bath resistivity by a factor of 2 two in the bubble layer.

For anode modelling we consider only anodic part of back EMF, excluding cathode overvoltage, about 0.04 V, which is on the top of the metal pad away from the anode. Back EMF changes very little with current since it is proportional to the logarithm of the current. It can be linearized in the neighborhood of the current operating point and separated into a constant part, equal to the value at zero current, also called extrapolated voltage [10], and into the part proportional to the current, which we interpret as the resistive part. This is shown in Figure 1, where the back EMF is calculated from formulas in [10]. The constant part in the case shown is 1.65 V and the resistive part is equal to 0.150 V to make 1.80 V for the cell effective operating current density, which accounts for anode fanning (i.e., that some current flows out of the anode on the sides in the bath immersion). The resistive part of anodic back EMF is included in the model as contact resistance on anode bottom and sides, such that the resistive voltage drop across bath-anode interface is 0.150 V.

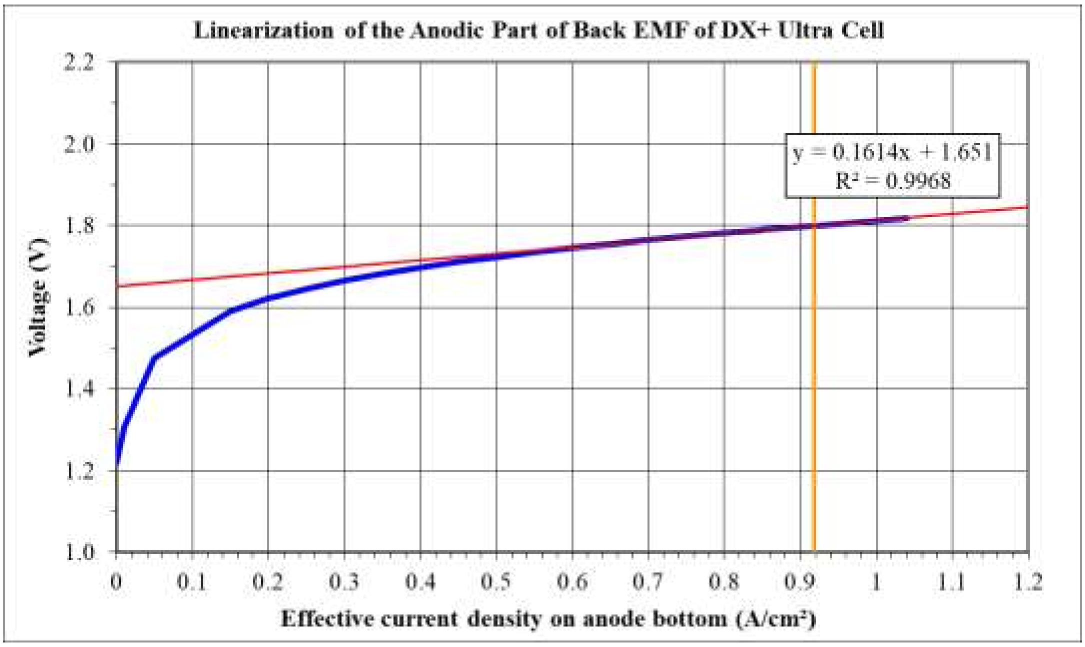

Figure 1. Linearization (red) of the anodic part of back EMF (blue) in the neighbourhood of the cell operating point (yellow).

To clarify these questions the ANSYS Mechanical 19.1 commercial finite element software package was used for modelling where several cases are explained below to establish the best method for the future consisting of omitting or including bath and metal, the bubble layer and the resistive part of anodic back EMF.

Voltage drop and anode current distribution depend on anode age since the anodes are consumed and there is less and less carbon below the stubs. The temperature in the upper part of the anode increases with time and in the stub area as well; thus increasing the pressure in the stub-cast-iron-carbon contact area while decreasing the contact resistance. Out of the cases studied in steady state, the best model was chosen to also calculate the voltage drops for different anode ages and the results are compared with measurements.

Impact of symmetry on AVD was checked because with amperage increase in the smelters the anode length is increased as much as possible to decrease the impact of amperage increase on anode-cathode distance (ACD), MHD stability and heat balance of the cell. Increasing the length towards the central whole bath; nevertheless, it is good to have them in the model as they do not bring additional complexity to the model or increase the solution time.

Measured anode voltage drop from the top of the anode rod to the point near the back-wall corner of the anode overestimates the average AVD to an increasing extent from younger to older anodes. Only for young anodes the measurement gives AVD close to the calculated average AVD. For a given cell voltage this leads to a few mm lower ACD, calculated from the measurements than ACD estimated by models. In spite of that, the models still have to be validated with measurements, because of unknown contact resistance in the stub-cast iron-carbon joints. This study demonstrates that the model calibration will be better if the modelled AVD to the measurement point is used instead of average AVD. It is also clear that a larger contact resistance in the cast iron – carbon joint should be used in the model for new anodes in comparison to mid-age and old anodes. As a refinement of the model, anode area reduction for mid-age and old anodes should be taken into account and the model sensitivity to greater curvature of the anode bottom surface should be tested; both may reduce the difference between the measured AVD and the average from the model.

Anode voltage drop is nearly the same for symmetric and asymmetric anodes, but the measured anode voltage drop is more overestimated in asymmetric anodes because of increased distance from stub to anode side at the back-wall.

Efforts to decrease ETJ voltage drop should be focused on the steel part because the aluminium part contributes very little to ETJ voltage drop.

11. References

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