MODELLING THERMAL DYNAMIC RESPONSE TO A 3-HOUR TOTAL POWER SHUTDOWN EVENT

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Abstract

The aluminium electrolysis process is an energy-intensive alumina reduction process which is more and more suffering under the high energy cost. Under these conditions, power could become a trading asset for the aluminium industry. Partly, actual power contracts contain clauses for power supply reduction and buyback, which have to be carefully considered with regard to the compatibility of the pot technology, i.e. not harming pot life in the long term compared to making gains on the power market in the short term.

To better understand the thermal and chemical impact in a pot during power cut back or modulation a dynamic lump model was used as cell simulator to predict the pot behaviour based on a 3-hour shutdown measurement.

After calibration of the thermal and chemical response of the pot in the model, the model shows good agreement with the measurement data and allows to investigate temperature development, sludge formation, alumina solubility and changes of acidity during power shortage. With this tool an optimised pot setting and preparation can be established to avoid sludging during power shortening and an anode effect after power up.

Keywords: Aluminium electrolysis, energy cost, power modulation, dynamic lump model, Dyna/Marc, sludge formation, anode effect

Introduction

In the past, energy costs accounted for about 30% of total production costs. With the changes in the power market in Europe and elsewhere over the last 10 years, this share has risen in some cases to more than 50%. As described by Richard et al [1], more and more smelters now have a huge financial incentive by reducing their power consumption on request during peak demand periods.

Power modulation events, however, affect the smelting process [2,3]. This is why studying strategies to minimize process perturbations using mathematical models [4] prior to their actual implementation in smelters is extremely useful.

The essential prerequisite is to have a reliable and validated dynamic cell model, which contains the chemical, heat and voltage balance. An electrolysis cell is a highly non-linear, multi-physics process with solubility and sedimentation effects, the interactions of which are not fully understood. Therefore, a proven way to get a validated model is to compare the model prediction to the measured process response of a given power modulation event. With subsequent calibration or further improvement of the model, it is able to reproduce the measured response.

3-hour total power shutdown event

In this paper, a comparison between the model results and measurements taken during a 3-hour power shutdown event will be discussed. Case data from the past are used; this corresponds to a model validation exercise conducted in 1996 [5].

The measurements were made by VAW in 1991 on a 240 kA prototype cell (see Figure 1), which was about to be shutdown definitively when the hydro-electric power from the Töging smelter's own dam was directed into the power grid. The 3-hour total power shutdown was preceded by a 4-hour voltage treatment-preheating period and followed by an 8-hour voltage treatment as reheating period.

Figure 1: CA240 reduction cell, Töging

During the whole period, the thermal response was recorded continuously from just before the beginning of preheating to up to 4 hours after the end of the reheating period.

The drawback of using old data, however, is that the process data now required no longer exist. The cell heat balance and the cell voltage breakdown were not measured at today's standards, essential to the validation of the steady-state model on which the dynamic model is based.

Modelling the power modulation event

The exact power modulation event has been reproduced using 2 different dynamic cell simulators, i.e. the Dyna/Marc lump/1D cell simulator and the ANSYS-based 2D+ dynamic cell simulator [4,5,6,7,8].

Dyna/Marc, the lump/1D cell simulator, solves the heat and mass balance in the cell and takes the evolution of the anode-cathode distance (ACD) into account. To model the reduction process, 36 totally differential equations were solved using the Euler numerical scheme. To evaluate the required first order derivative of these main 36 variables, large numbers of derived variables were calculated in sub-models using equations published in the literature.

To be able to complete the cell heat balance, the heat produced and the heat dissipated must be calculated. While computation of the internal heat generation is relatively straightforward, determination of the cell heat loss is more difficult. Dyna/Marc uses a lump/1D formulation in which it is assumed that the heat produced in the system can escape from four different surfaces, namely the anode panel, the cathode panel, the ledge at bath level and the ledge at metal level. The overall heat transfer rate across each surface is the quotient of its global heat transfer resistance and its associated gradient between the operating temperature and the potroom temperature. For the two “vertical” surfaces, i.e. the ledge at bath level and the ledge at metal level, the ledge thickness constantly fluctuates, meaning that the global heat transfer resistance for these two surfaces is not constant.

The ANSYS-based 2D+ dynamic cell simulator is identical to the Dyna/Marc lump/1D cell simulator in every aspect except for the cell heat loss sub-model. The ANSYS-based 2D+ dynamic cell simulator is an ANSYS-based heat loss sub-model where the "+" in the 2D+ model stands for some crude representation of the third dimension in a 2D model. Figure 2 presents the 24-hour thermal response of both the Dyna/Marc lump/1D dynamic model and the corresponding ANSYS-based 2D+ dynamic model. Both models used 2-minute time steps. Since the 2D+ model response displayed some signs of instability, the model was rerun - this time using 1-minute time steps. The change eradicated the instabilities and produced an identical response up to the point where the cell controller took a different decision (based on a different resistance slope evaluation) after the power shutdown.

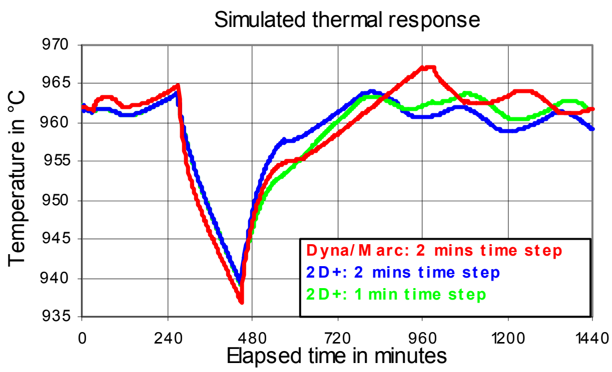

Figure 2: Simulated thermal response of a 240 kA cell to a 3-hour total power shutdown

The results in Figure 2 clearly indicate that the Dyna/Marc lump/1D model-simulated thermal response is almost identical to that of the ANSYS-based 2D+ model, which took far more computational time (hours instead of seconds). Figure 3 directly compares the Dyna/Marc-simulated response with the cell real measured response, highlighting the fact that the amplitude of both responses is significantly different.

Model calibration/validation exercise

Figure 3 is the starting point of the dynamic model validation/calibration exercise, based on all pot dimensions including shell, lining, anodes and busbar in conjunction with amperage and voltage drop. In the exercise presented here, we assume that the single measured thermal response is accurate (no measurement errors) and typical (the cell is in a stable and normal state prior to the power modulation event). This may not be the case but only more measurements can prove or disprove the assumption.

To obtain realistic pot behaviour in the model, the chemical and thermal responses have to be evaluated in addition to the pure dimensional figure. It is clearly shown in Figure 3 that the invalidated model underestimates the amplitude of the real thermal response measured. However, it is now impossible to get a clear comparison of the chemical response.

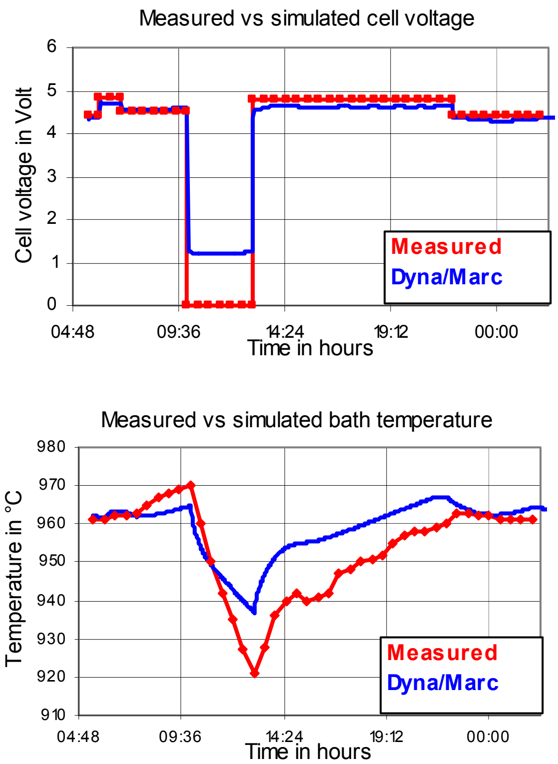

Figure 3: Comparison of the response thermal response (invalidated model)

Operational impact

In all potlines, the individual pots display different states with regard to their operation cycle (last tapping, anode changing), demand feed (over- or underfeeding), chemical stability (sludging, acidity) and thermal balance (over voltage, back-reaction or under cooling), which is difficult to reproduce in a simulation. In the model, many parameters influence the amplitude of the thermal response to a given perturbation, such as a 3-hour total power shutdown, but two main effects are seen to determine pot behaviour. These are the heat generation in the liquid bath and metal and the heat loss partition dissipating through the ledge [9,10,11]. By reducing the mass of the liquid zone (i.e. less bath and less metal) and decreasing the fraction of heat dissipated through the ledge, the exact same heat input perturbation will have a much larger impact on the thermal response of the system. Since exact measurements of these parameters were no longer possible, we had to estimate these parameters.

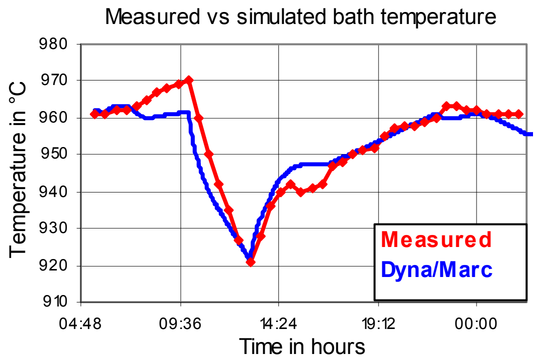

Figure 4: Comparison of the response thermal response (validated model)

After adjusting these parameters, the Dyna/Marc cell simulated thermal response almost perfectly matched the real cell measured thermal response, as can be seen in Figure 4.

During the 3-hour power shutdown, two mechanisms characterizing the thermal and chemical response of the pot were seen:

a) Without power no more heat generation in the anode, cathode and bath:
   The remaining heat in the pot, however, still maintains the convection plume around the pot so that the heat convection on the outside of the shell is almost unchanged.
   Inside the pot, no more heat is generated in the anode and no more hot process gas is emitted. The still-running exhaust gas extraction system starts to cool down the covering and anodes.
b) The electro-magnetic stirring of the bath is disrupted and the metal pad flattens out under gravity.
   On shutting down the power, the magnetic field collapses and the metal pad levels out.
   The stirring effect of the magnet field also breaks down, resulting in massive changes in the heat transfer into the ledge.
   At locations with a high metal and bath speed and a well-established ledge profile, the speed-dependent heat transfer coefficient drops and less heat is conducted into the side / end pier. The reduced heat flux results in a growing ledge thickness. This mostly occurs at the centre of pot sides and ends.
   At locations with low flow velocity, e.g. sludgy zones or stagnant areas, the changed metal pad and slowed bath and metal movement can increase the heat transfer, resulting in an increased heat flux into the lining. The effect can be seen often at the pot corners.

These effects are locally restricted and not covered by the lump model. However, with a 2D+ heat-transfer model running in parallel, these effects can be quantified and incorporated into the global behaviour in the lump model.

After the heat generation and flow field have stopped, the cooling down of the bath begins. This results in a drop in bath temperature and superheat, an increased concentration of excess AlF_3 through ledge formation and, depending on total bath acidity, reduced alumina solubility, as shown in Figure 5a-c.

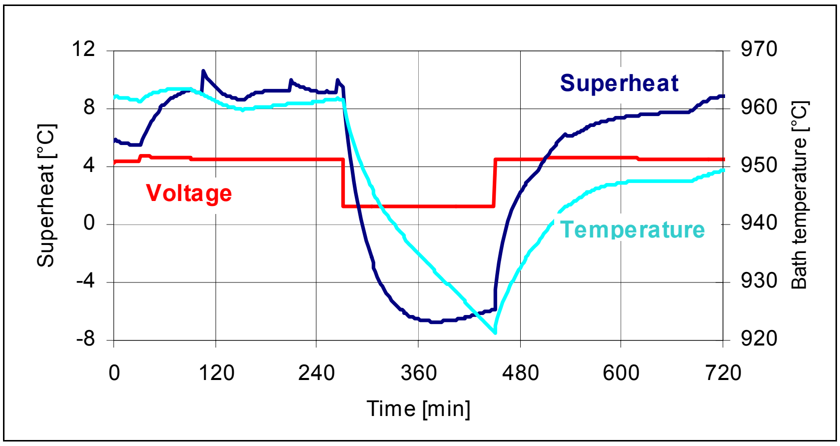

Figure 5a: Bath temperature and superheat

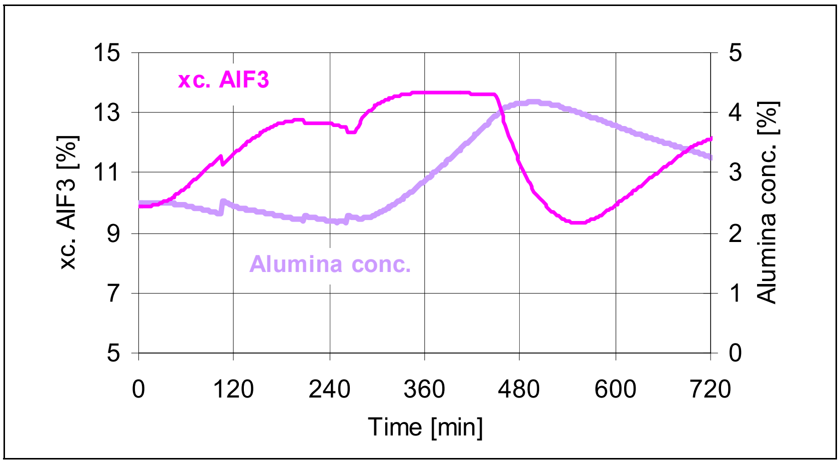

Figure 5b: Concentration of excess AlF3 and alumina

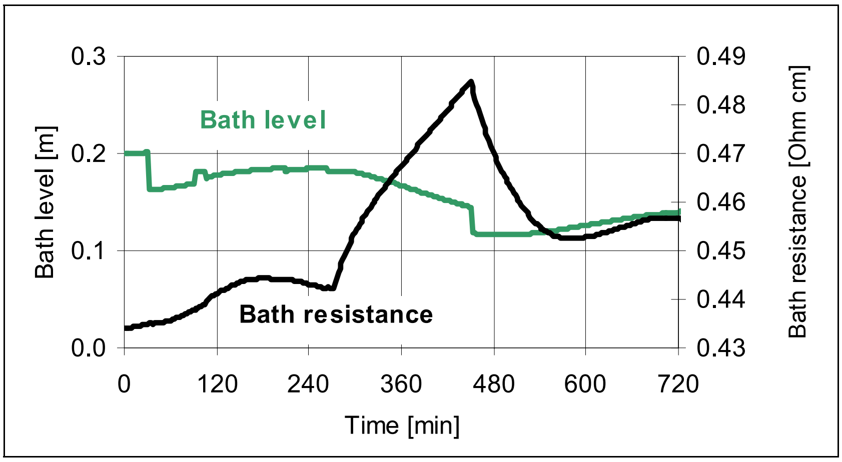

Figure 5c: Bath level and resistance

On increasing the pot voltage for additional heating, the superheat (blue line, left-hand axis) rises by 4°C until the power is shut down, Figure 5a. The voltage curve (red line) indicates the power disconnection time. The bath temperature (cyan line and right-hand axis) drops from 960 to 920°C in 3 hours, resulting in additional ledge formation and an increased concentration of excess AlF_3 (violet line) in the remaining bath, as shown in Figure 5b. The alumina concentration (magenta line) also rises by about 1% due to this separation effect, but drops back down again when the electrolysis process is restarted.

During the trial, the bath level in Figure 5c (green line) was similarly affected with a 350mV addition for preheating, increased ACD as well as the ledge formation process. On cooling, the electrical resistance of the bath increases by about 20% - see Figure 5c (black line and right-hand axis) - so that the pot control system lowers the ACD to maintain the pot voltage after power restart. This points to some measures for avoiding an anode effect during restart. With a well-validated model, different measures can therefore be evaluated to stabilize pot operation during power modulation.

Conclusions

This very condensed model validation exercise highlights both the strengths and weaknesses of mathematical modelling: a well calibrated and, hence, well validated model is able to represent the complex dynamic behaviour of a Hall-Héroult aluminium electrolysis cell accurately: Such a model can help to plan and execute strategies for power modulation, reduce specific power costs and ensure stable pot operation and extended pot life.

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