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AP60 CELL START-UP: THERMAL ELECTRICAL MECHANICAL QUARTER CELL MODEL

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Abstract

In the present article, a thermal electrical mechanical quarter cell model is presented. Compared to slice models, this one has the advantage of including the cell corner and of capturing longitudinal deflection. This leads to more realistic predictions, particularly for structural entities such as shell displacement and deformation. The presented model is tuned according to thermal-electrical-mechanical measurements carried out during the start-up period of an AP60 cell.
This model is useful to study different problematical issues such as lining material behaviour, current distribution heterogeneities, shell deformation during start-up and several start-up scenarios. Such a model will also be able to answer some questions regarding early infiltration risks and their potential impact on the cell lifespan.

Introduction

In August 2013, Rio Tinto Alcan started up its first AP60 smelter in Jonquiere (Quebec). This plant will serve as a platform for further AP60 Technology Development. The AP60 Technology (Figure 1) is the most cost effective and high productivity smelting technology [1].

For more than twenty years, multidisciplinary teams at Rio Tinto Alcan have worked hard to perfect the newest generation cells. Modelling teams have contributed to this success by developing thermal electrical models ensuring productivity maximization with innovative designs. They have also used magneto-hydrodynamic models to optimise cell stability [2] and electrical models to evaluate the overall electrical balance of the busbar network around cells [3]. In the last few years, thermal electrical mechanical models have been used to simulate an AP60 start-up, as this phase is considered a key element impacting the lifespan of an electrolysis cell. This critical step is achieved properly when several requirements related to the design, the used materials and the start-up operation are controlled. Numerical modelling is a quick, efficient and versatile tool capable of testing a wide range of potential ideas and concepts related to the aspects mentioned above.

This article describes a thermal electrical mechanical quarter cell model that simulates the start-up of an AP60 prototype aluminium cell. It was tuned according to the measurements taken during the start-up of an AP60 cell at LRF, Laboratoire des Fabrications (Saint Jean de Maurienne, France). Two applications are presented using this model; dry-start and heterogeneous current distribution modelling. Their respective impacts on the mechanical behaviour of cathodes are also presented.

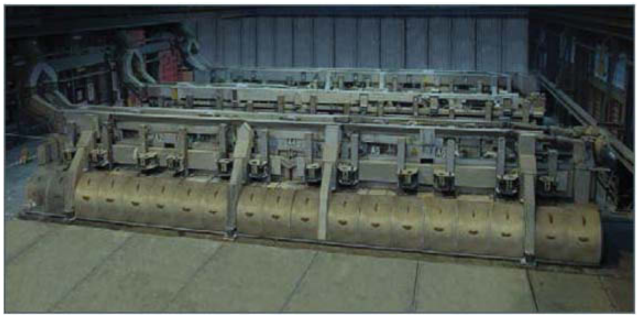


Figure 1 – General view of an AP60 cell at LRF [1]

Literature review

The use of thermal electrical models to improve aluminium cell design started more than twenty years ago. Within Rio Tinto Alcan, these steady state models are well established and are used to improve designs and to simulate normal operation situations.

During the last decade, several authors proposed multi-physical models related to aluminium cell design to consider the mechanical behaviour of the electrolysis cell. Arkhipov et al. [4-5] proposed two quarter-cell models (one of them presenting a Soderberg aluminium cell). These models are thermal electrical mechanical and include the impact of sodium expansion. Sun et al. [6-7] developed 2D and 3D thermal mechanical models applied to a Soderberg aluminium cell. These two models do not include heat generation by Joule effect. Therefore, the temperature at the top surface of the cathode is imposed rather than calculated. More recently, Dupuis [8] proposed several thermal mechanical models to design pot shells. Nevertheless, he did not include all lining materials. In 2011, Marceau et al. [9] developed a transient thermal electrical mechanical quarter-cell model. This model simulates the preheating phase of a P155 cell start-up. It uses a fully coupled approach; thermal and electrical solutions are impacted by mechanical one at each step of the convergence process. The same year, Hacini et al. presented a thermal electrical mechanical slice model that included the impact of sodium expansion on the cathodes [10]. This model was tuned according to P155 measured data and was used later on to simulate the start-up of AP4X, AP60 and APXe cells during the preheating and bath periods.

In 2012, Dupuis et al. proposed a simplified thermal electrical mechanical quarter cell model dedicated to the cooling down of cells after a power interruption. The authors pointed out that only quarter cell models are able to produce reliable stress prediction in the long direction of the cell [11].

In 2013, Zaraoui et al. [12] presented several numerical tools for cell design. For thermal mechanical aspects, they used a simplified ''empty shell'' model. This model was tuned using an adjustment factor to match the measured deformation, which is a limitation to its predictive capacities.

Model presentation and structure

The structure of this model is identical to the P155 start-up model presented by Hacini et al. [10]. The model uses a sequential coupling approach; a thermal-electrical (TE) analysis is run first. This analysis gives the temperature profile during the preheating and bath periods. This part is calibrated by tuning the cell voltage curve according to the real curve measured during the start-up of an AP60 cell at the LRF. Once the thermal-electrical analysis is completed, temperature profiles are loaded into the thermal mechanical part of the model as external loads.

The present model was developed using the ANSYS® Workbench 14.5 software. The model geometry is presented in Figure 2. It was created using DesignModeler and is completely parametric.

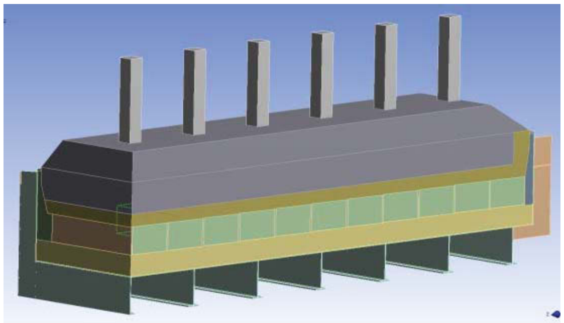


Figure 2 – General view of the AP60 quarter cell model.

Because they have no mechanical role, all materials above the cathodes are not represented in the TM analysis (bath, metal, anode assembly). However, their weight on the cathode plane is applied. The superstructure weight is also considered and is applied at the shell ends. Numerical contacts are defined on all interfaces and are controlled using thermal and electrical contact conductances.

Thermal Electrical (TE) Analysis

Thermal electrical (TE) analysis simulates heat generation by Joule effect due to the passage of current through the cell and gives the temperature profile variations during the preheating and bath periods.

The model geometry is adapted for two different configurations; during preheating, there is no cover/crust, no bath and no metal. Anodes and cathodes are only separated by preheating bedding. For bath period simulation, the preheating bedding is replaced by bath. The temperature profile within the model at the moment of the bath introduction results from calculations during the preheating stage, except for the volume representing liquid bath, to which an initial temperature of 970°C is applied to represent bath pouring in the cell. As the model geometry is fixed during simulation, material affectations are modified to represent both preheating and bath periods.

The current model is transient and represents different steps of the AP60 cell start-up; therefore, material properties vary in function of temperature and time.

Electrical boundary conditions are identical for both preheating and bath periods; the current enters from the top of the anode rods and exits through the aluminum flexibles where the voltage is set as the reference. For thermal boundary conditions, natural convection and radiation are applied to all external surfaces, with variable bulk temperatures to consider the differences between the top and the bottom of the cell.

Thermal Mechanical (TM) Analysis

The thermal mechanical (TM) analysis is run using the temperature profiles obtained with the TE analysis. The ramming paste behaviour is very complex to characterize. At low temperatures, the green paste is soft; it has no or very low rigidity. Progressively during baking, it hardens and its density decreases due to volatile emission. Once baked, its behaviour could be considered as elastic. All these facts make the modelling of the paste behaviour difficult. A simplified approach is used to consider the abrupt change of behaviour from soft to hard. Mechanical properties as a function of temperature are inspired from Tremblay et al. [13].

Model tuning

Temperature Predictions

The model predictions were compared to the measurements taken during the start-up of an AP60 Cell at the LRF. Several thermocouples were installed inside the cell lining and temperature rise has been registered throughout all the start-up period. Time values are intentionally left adimensional. Here are some comparisons with these measurements.

As the model represents only quarter of a true cell, and is tuned according to data coming from a full instrumented cell, each prediction of the model for a given position is compared to several sensors located at symmetric positions of the cell. Example: for cell corners, there are four cell corners instrumented which gives four curves labeled ''Measured (Cell Corners 1 to 4)''. For the shell bottom temperature, all thermocouples near the cell centre were considered.

Figure 3 presents the cathode plane temperature at different locations of the cell during the preheating period. Obviously, all cathode surface thermocouples are lost when the bath is poured in the cell. The model is able to correctly predict the temperature increase during the preheating. Both model and measurements show that the temperature is higher in the central channel than in the lateral channel. The temperature difference is more important between the corners and the center of the cell. These results clearly show the interest of having a quarter cell model rather than a slice one since, in the latter, no information is given about the cell ends and corners.

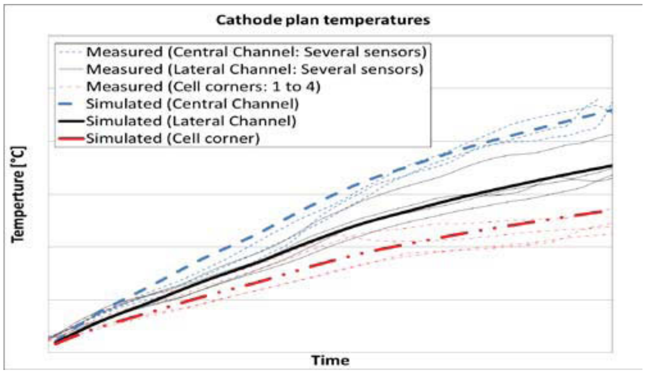


Figure 3 – Cathode plane temperature (central channel)

For the shell bottom temperature, the model correctly predicts the temperature rise for the centre of the cell (Figure 4). The model slightly deviates twice compared to the measurements due to the influence of the ambient temperature, which varies during the day while it is kept fixed in the model. Such deviation should not have an important impact on the model structural predictions.

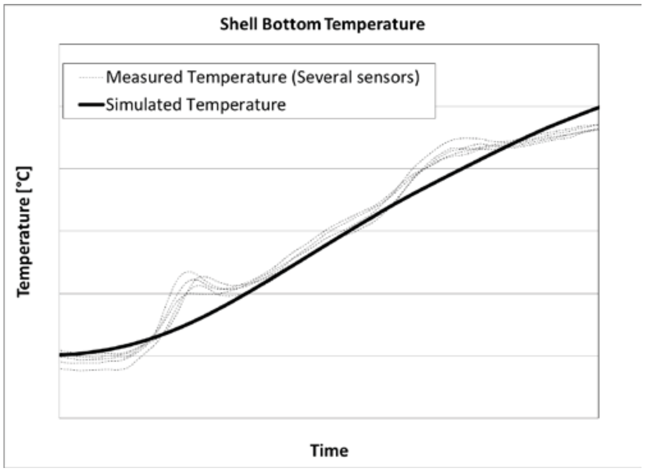


Figure 4 – Shell bottom temperature (cell centre)

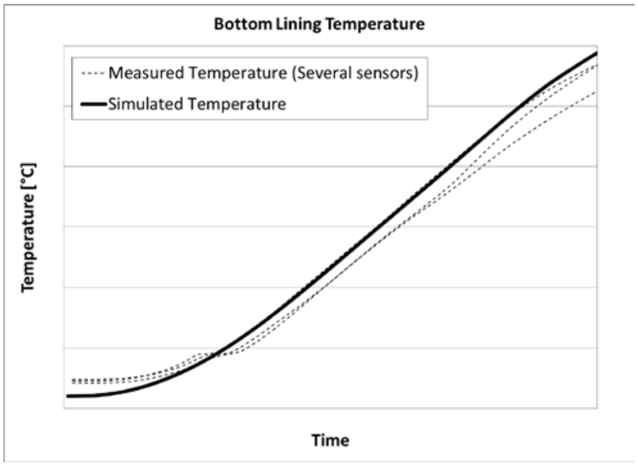


Figure 5 – Bottom lining temperature (cell ends)

The same observations are made regarding the model predictions at the shell side and in the bottom lining: no significant deviations are noted between the model prediction and the measurements (Figures 5 to 6).

Globally, the model correctly predicts the temperature profiles in different zones of the cell. Minor differences should not affect much the thermal mechanical analysis or the model predictions.

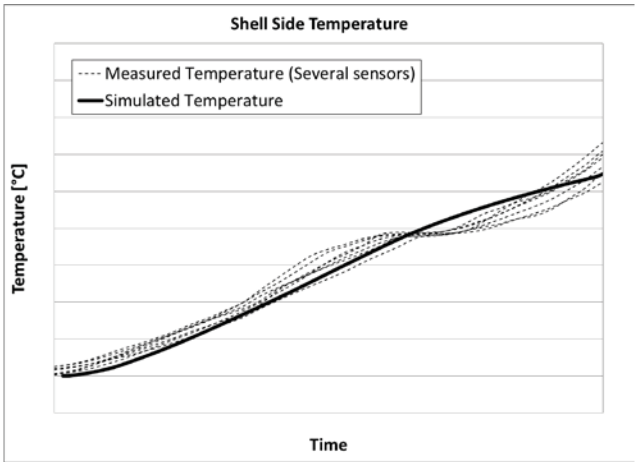


Figure 6 – Shell side temperature

Displacement Results

As for temperature, the model predictions were compared to the displacement measurements taken during the start-up of an AP60 cell at the LRF. Displacement sensors were installed outside the cell to measure its three main displacements: the shell bottom rise, the side and end openings. Time values are intentionally left adimensional and the same scale is used for all figures.

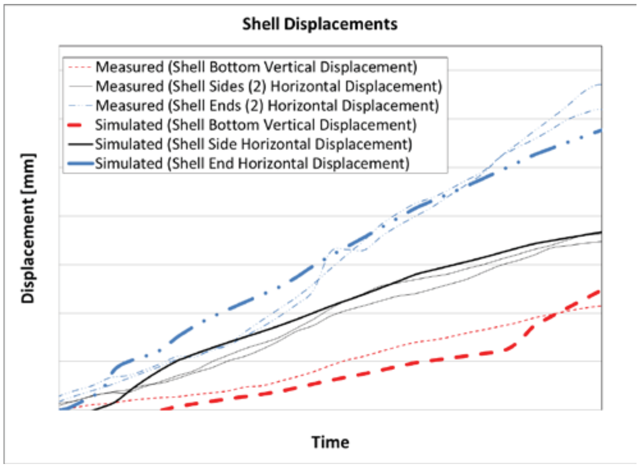


Figure 7 – Shell bottom vertical displacement

Figure 7 shows the displacements predicted by the model for the preheating period. The model slightly underestimates the displacement of the shell bottom and overestimates the horizontal side and end displacements. The deviation remains acceptable.

One should keep in mind that the vertical displacement of the shell bottom is an indicator of the cathode plan rise (central cathodes versus those at the ends). The greater the vertical displacement of the shell bottom, the higher the rise of the cathode plane. This parameter has a direct impact on the cell operation during the first hours of its start-up as it influences the anode cathode distance before metal pouring.

Model application

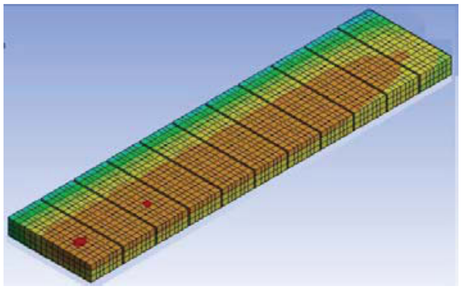
This model is dedicated to start-up modelling. It could be useful to study different problematical issues such as the global behaviour of lining materials, shell and cradle deformations during start-up and several start-up scenarios. Such a model is also a good tool to study early infiltrations and cathode cracking. Two applications are presented in this article.

First application: dry-start modelling

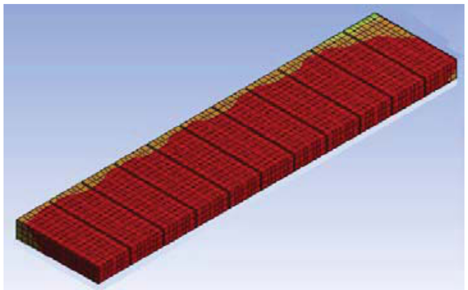
Dry-start start-up is a critical step to start the first cells of a greenfield smelter. As the crushed bath is introduced in the cell before its energizing, additional power is needed to melt down this solid bath.

The present model was used to simulate an AP60 cell using a dry-start strategy. The model takes into account:

- Preheating bedding configuration and property variations with temperature.
- Current intensity variation during start-up,
- Phase transformation that occurs during the crushed bath melting.



a) At the end of preheating for the classical liquid start-up



b) Equivalent instant for the dry start

Figure 8 – Cathode Temperatures

The injected energy is higher for the dry start-up than for the liquid one. This leads to a greater increase of temperature in different parts of the cell, particularly in the cathode plane (Figure 8). The first question that comes to mind is whether this increase is harmful to the cell or not. Thanks to the thermal mechanical quarter cell model, it is possible to evaluate the stresses on each cathode. These stresses include the effect of thermal loading but also force reactions of other materials surrounding the cathodes. Figure 9 shows minimal and maximal principal stresses within the cathodes. It is clear that the increase in temperature leads to a more important confinement, which results in greater compressive stresses. For tensile stresses (maximum principal stress), no significant impact is observed.

The overall increase in temperature in the cathode plane increases the stress level in the cathodes. These are mainly compressive stresses. The level of stress is below the critical limit of the material. This increase in temperature should not cause cracking into the cathode blocks.

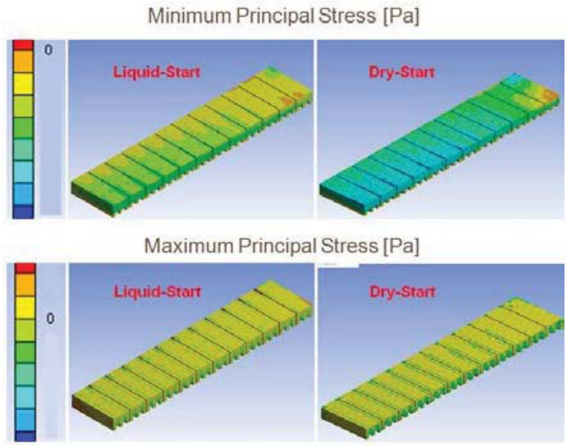


Figure 9 – Principal stresses on the cathode plan

Second application: heterogeneous current distribution modelling

Heterogeneities of current distribution could appear during the start-up, precisely when the cell is preheated. This is mainly caused by heterogeneous contact quality between anodes and preheating bedding.

Thanks to the model flexibility, it is possible to impose and control the current distribution: its location, duration and intensity. In the present work, a major heterogeneity was introduced in the model:

- I2/I1>3 for a long period (> 24 hours).
- Preheating bedding resistivity was decreased under anodes 2 and 5 to control the current flow (Figure 10).

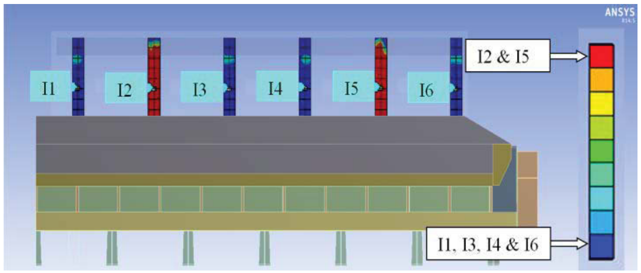
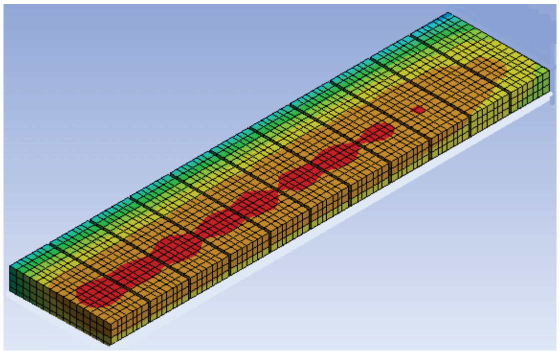
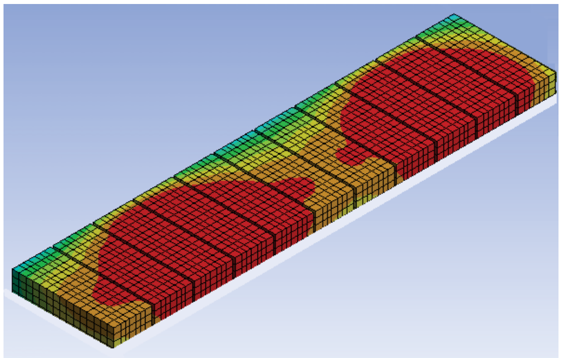


Figure 10 – Heterogeneous current distribution

Obviously, when the current distribution is homogeneous, the temperature profile of cathodes in the central part of the cell is nearly uniform (Figure 11.a). In the presence of heterogeneity (imposed on the preheating bedding in this case, as in Figure 10), the temperature is higher under the anodes drawing more current (Figures 11.b). A thermal mechanical analysis will be needed to evaluate if the imposed heterogeneity leads to an important temperature gradient on cathodes.



a) Homogeneous current distribution



b) Heterogeneous current distribution

Figure 11 – Cathode Temperature

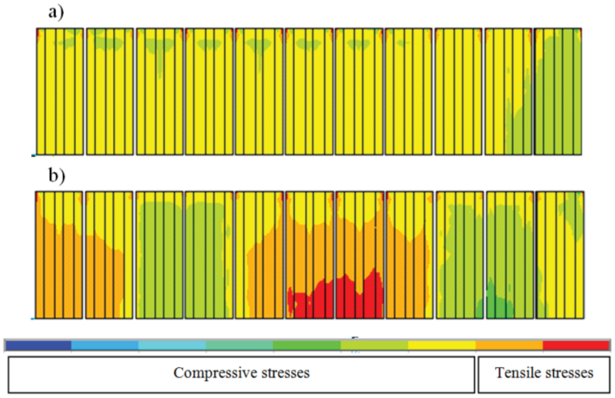


Figure 12 – Longitudinal stresses in cathodes:
a) Homogeneous current distribution, b) Heterogeneous current distribution

Figure 12 shows stress profiles given by the TM quarter cell model for both homogeneous and heterogeneous current distributions. In the first case (Figure 12.a), no or few tensile stresses are observed, which means that the cathode cracking risk is low. However, in the presence of heterogeneity (Figure 12.b), tensile stresses appear. These stresses are longitudinal to the cathode length and could cause failure by cracking.

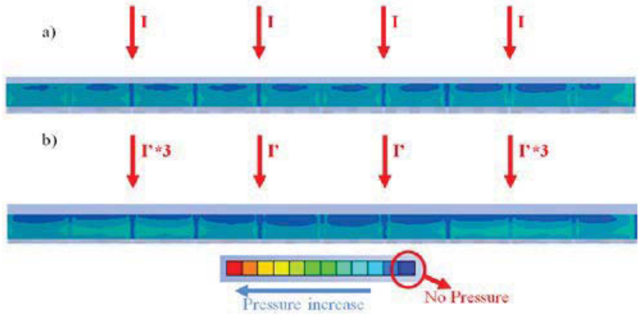


Figure 13 – Contact pressure between ramming paste big joint and cathodes:
a) Homogeneous current distribution, b) Heterogeneous current distribution

Moreover, heterogeneities can also raise the risk of infiltration. Figure 13 compares the contact pressure at the cathodes/ramming paste interface at the block end in the case of homogeneous and heterogeneous current distributions. It can be observed that contact pressure increases under the anodes drawing more current as the temperature in the corresponding cathodes rise by Joule effect. The contact pressure is reduced under those drawing less current. A reduction of contact pressure at the interface is an indicator of an increase of the infiltration risk.

Conclusions

This article presents an AP60 thermal electrical mechanical quarter cell model. This model simulates the cell start-up, i.e. preheating and bath periods. The model is tuned according to data from an AP60 start-up at LRF. Overall, this work shows that:

1. The current model correctly predicts temperature variations during start-up in different zones of the cell.
2. The model gives good predictions for displacements during start-up.

The quarter cell model is a powerful tool compared to the slice model as it gives predictions on cell ends and corners. It is used to simulate different start-up scenarios, such as testing different preheating durations or configurations. It is also used to test the impact of design and material grade changes on the behaviour of the cell. Two examples of application were presented:

Dry-start modelling:

- The consequences of a significant and uniform increase of temperature in the cathode plan should not have a major impact on the cracking risk of cathodes as the stress level in the cathode remains very low.

Heterogeneous current distribution modelling:

- Heterogeneity of the current distribution changes the temperature map in the cathode plane.

- If this heterogeneity is strong in terms of intensity and duration, an important temperature gradient appears in cathodes. In this case, tensile stresses are generated and could cause cathode failure by cracking if higher than the critical limits of the cathode material.
- Heterogeneities could also have a negative impact on the risk of infiltration as they are able to modify contact pressure between cathodes and ramming paste big joint.

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