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NON-INTRUSIVE FREEZE LAYER DETECTION METHOD IN AN ALUMINUM REDUCTION CELL

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Abstract

The frozen bath layer on the sidewalls of aluminum reduction cells plays a crucial role in the process of aluminum production. The stability of the freeze layer is more and more at risk with the trend of increasing line current.

We present a non-intrusive thermal based method with which the continuous monitoring of the sidewall freeze is possible. The foundation of this method is a special arrangement of thermocouples, which are embedded in the sidewalls of operating cells. The method is able to follow the thermal load of the sidewalls and feeding the measured signals into a simplified mathematical model, and an estimate of the changing thickness and shape of the freeze layer can be obtained.

We give a comparison of freeze profiles measured with traditional mechanical probing and our novel method. The continuous change of the protective freeze layer throughout specific events in the cell is also discussed.

Introduction

During normal operation, the bath in which alumina is dissolved solidifies along the sidewalls of the cells as those are intentionally less insulated. The thickness and form of the so-called freeze layer or side-ledge is a result of the thermal equilibrium between the bath and sidewall. The movement of the molten cryolite driven by the drag force exerted by the gas bubbles and the magneto-hydrodynamic forces in the molten aluminum also affect the freeze shape. The resulting freeze is bound by the sidewall and the isothermal liquid-solid interface of the bath.

The freeze has a threefold role in the aluminum reduction process. First, it provides an effective protection of the sidewalls against the corrosive bath. Without this protective layer the bath may come in direct contact with the sidewall reducing the cell lifetime. Second, the dynamic freezing and melting of the side-ledge helps to maintain the thermal stability of the cell. Finally, the freeze layer helps maintaining the optimal direction of the vertical electrical current between the anodes and the cathode by acting as an insulator on the sidewalls.

In case of steady cell operation the shape of the side-ledge in the aluminum remains stable, corresponding roughly to the isotherm of the liquidus temperature of the bath. Many transient effects occur during the normal operation an electrolysis cell. These effects can modify the side-ledge profile as a result of the system trying to regain its thermal stability. Knowing the importance of the freeze, the thickness is of special interest in aluminum production. Commonly a manual measurement method is used to probe the shape and thickness of the side-ledge. Due to its intrusive and labor-intensive nature, this method of freeze detection is only utilized 2-3 times a year [1]. There are huge efforts today to increase the production, which is mainly achieved by increasing the useful area of the cells using larger anodes. The higher production area demands higher current, increasing the internal heat generation in the cells. These developments affect the stability of the freeze layer; therefore, there is a need for methods, which provide information on the side-ledge in a continuous way. For this purpose the detection of the phase change front by means of temperature measurements can be a useful method.

It was demonstrated that a phase change front can be identified with the help of temperature measurements [2-5]. These studies are limited by their artificially generated test cases or reference values originating from well controlled experiments. We developed and tested a methodology that can detect the phase change front on the sidewall of industrial aluminum electrolysis cells. It is based on continuously monitored temperatures inside the cell walls. Our approach is adapted to electrolysis cells and able to give a first rough estimate of the freeze front based on the measured data on which an inverse identification can be based.

Methodology

The base of the methodology is to insert an array of thermocouples (TCs) in the sidewall of a cell. This can detect the thermal information when heat propagates through the walls. The information can be used to approximate the thickness and shape of the frozen bath layer with the help of inverse mathematical methods. In this section we give detailed descriptions of the experimental and computational aspects of our methodology.

Experimental work

Appropriately protected thermocouples were inserted into the sidewall blocks of an industrial point fed, prebake electrolysis cell of Rio Tinto Alcan. Before installation, all thermocouples were aged and calibrated. Measures were taken to minimize the thermal contact resistance between the tip of the thermocouples and the material of the sidewall block. Two arrays of thermocouples were formed in two sidewall blocks along the longitudinal sides of the electrolysis cell. These were located at an average of 130 mm above the bath-aluminum interface. The distance from the wall-freeze interface was about 50 mm (Figure 1) as previously described [6].

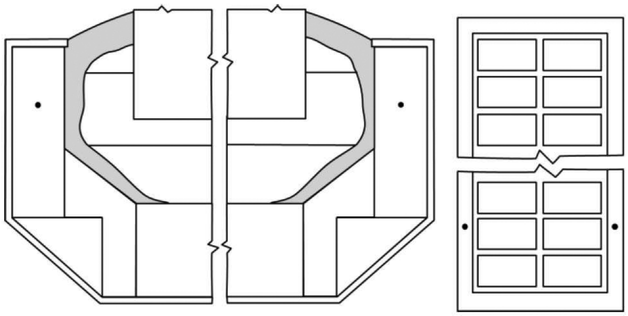

Figure 1. Approximate position of the thermocouples arrays in the electrolysis cell marked with dots

The thermocouples in the arrays were arranged so that the local temperature gradients and second order derivatives (excluding the mixed derivatives) could be estimated. We registered one thermocouple signal in each array as the reference temperature; all other thermocouple signals were recorded as differences to this reference. The temperature signals were recorded with a sampling interval of one minute using the data acquisition system of the plant.

For comparison, during the measurement period the freeze shape was measured several times by means of mechanical probing. The probing involves the removal of the anode where the freeze is measured with an extended time of operation without it. Additionally, the pot cover is partially removed for an extended period of time to gain access with the equipment.

Freeze shape identification

We use an inverse method for the freeze thickness and shape identification. Inverse methods are based on matching measured values with calculated quantities derived from a parameterized mathematical model of the problem. The mathematical model is referred to as the direct problem, which is then embedded into an optimization procedure. This procedure, the inverse algorithm than changes the parameters of the model systematically matching the calculated values with the corresponding measured values. The criteria of match vary accordingly to the problem at hand and it is represented by the cost function of the optimization.

Direct problem

We developed a simplified, two-dimensional, steady model of the sidewall and the side-ledge in ANSYS Release 14. With this we could achieve a low computational cost direct model suitable for an inverse algorithm. The assumption of steadiness was verified with the measured gradients and second order derivatives, which showed well-established temperature distributions in the sidewall. The measured thermal gradients also showed that the longitudinal heat flow is zero or sufficiently small to model the problem in only two dimensions. The overall scheme of the direct model is given in Figure 2.

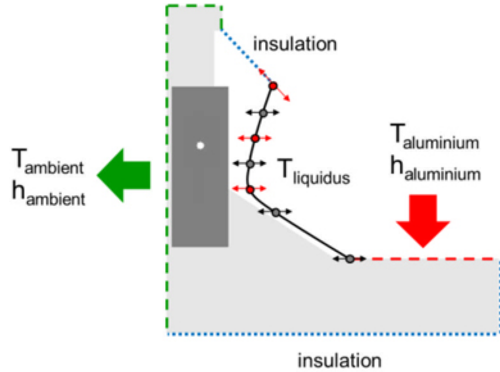

Figure 2: Scheme of the numerical model of the sidewall and the freeze

We modeled the influence of the liquid aluminium with a heat transfer coefficient on the cathode surface. Similarly, the heat loss on the external surface of the sidewall was modeled with the ambient temperature and a combined heat transfer coefficient. The isothermal phase change surface is defined by seven control points along its contour. The locations of these points (the thickness of the freeze layer) are the optimised parameters of the inverse algorithm. All other boundaries were considered adiabatic. The positions of the bounding adiabatic surfaces were chosen so that they do not influence the temperature at the location of the measurements. The truncated surface of the freeze profile at the top of the model is set as a 45° line through the corner point of the side block edge and a point on the ledge profile at the electrolytic bath upper level, an approach adopted from Dupuis [7].

Inverse algorithm

We used the ANSYS parametric design language (APDL) to implement the inverse algorithm of the freeze shape identification. The developed algorithm consists of three main steps, each of which gives an estimate of the freeze thickness and profile. The subsequent steps are created so that they increase the accuracy of the result of the previous step.

The first step of our algorithm directly gives a rough guess based on the measured data. In this we apply a second order extrapolation using the Taylor series to directly estimate the freeze layer thickness and shape locally. This direct estimation provides an initial guess for the identification. In the second stage we select three control points (solid red points in Figure 2) on the top half of the freeze that have stronger influence on the temperature field in the region of the thermocouple array. The positions of these points are optimized while we apply a linear interpolation between them to calculate the values of the unused, passive control points. The bottom part of the freeze is set to a constant thickness equal to the thickness at the lowest active control point in this step. Finally, in the last step we include all control points in the optimization loop to refine the solution of the second step.

The inverse identification was driven by the built-in APDL gradient based optimisation; a least square cost function was used with uneven weights of the temperature and temperature difference agreement, the latter having a stronger influence on the results. The basic idea behind this lies in the nature of thermocouple accuracy, namely, the temperature readings are significantly less accurate than the differential signals between the thermocouples. Also, due to the high temperature level, the difference between the calculated and measured temperatures gives a much higher numerical value than the difference between the calculated and measured temperature differences. Additionally, a second order regularisation [8] was used to obtain smooth freeze profiles by prohibiting instabilities arising from the ill-posed nature of the inverse problems [9].

Sensitivity study

To identify the uncertainties related to our simplified model, we carried out a sensitivity study on the parameters affecting the resulting side-ledge profiles. These parameters included the freeze thermal conductivity, the liquid aluminium and the ambient temperatures, the heat transfer coefficients and the liquidus temperature. The model was found to be most responsive to the changes of the freeze thermal conductivity and the ambient heat transfer coefficient (Figure 3).

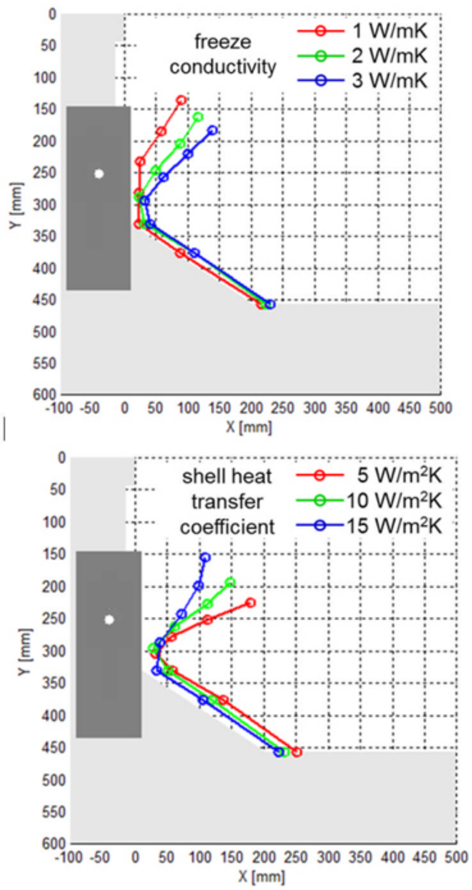

Figure 3: Main findings of the profile sensitivity study: the two most significantly influencing parameters are the freeze conductivity (top) and the ambient heat transfer coefficient on the shell (bottom)

We found that with these parameters the positions of the freeze control points have a near to unity sensitivity coefficient. The only exception is the thinnest part of the freeze considered as the critical section, which shows a significantly lower sensitivity in a wide range of parameter variations. These results of the sensitivity study point to the importance of model parameters, but at the same time they also show that the inverse estimation is safely approximating the minimal thickness of the freeze.

Comparison of calculated and measured results

We compared the estimated profiles based on temperature measurements and the results by mechanical probing in two cases. Both of these profiles are located in front of the array in the positive sidewall of the cell during a one-month follow-up interval. For the inverse identification we selected the temperature right before the thermal perturbation of the anode change appeared on the signals. The resulting freeze profiles along the sidewall compared with the corresponding freeze profile by mechanical probing are given in Figure 4.

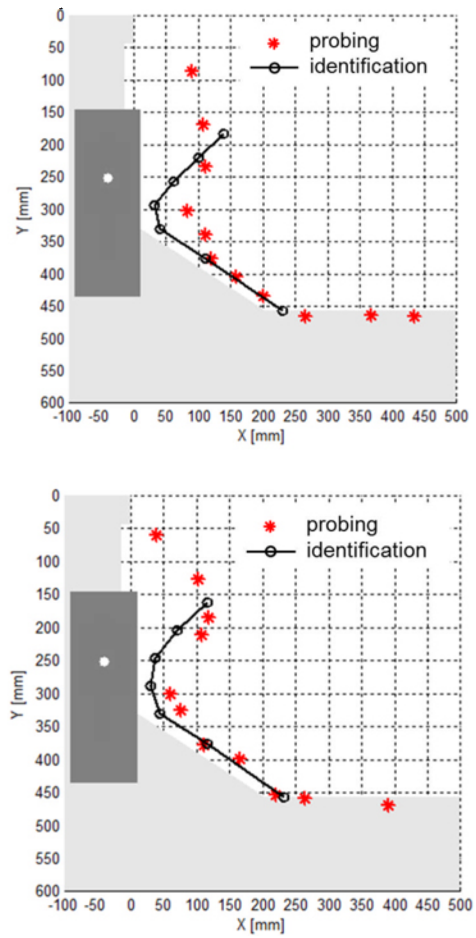

Figure 4: Identifications based on measured temperatures compared with mechanical probing data

Although the mechanical probing as well as the inverse identification contains significant uncertainties, the profiles in general show reasonable agreement. It can be observed that the identified profiles underestimate the thickness in the upper half of the freeze but reconstruct the bottom half accurately. Despite of the deviations in the estimated thickness, in a real monitoring situation this identification improves the security of cell operation during control.

Continuous change of the freeze profile

We applied the presented freeze identification to typical events in the operation of an electrolysis cell to give an estimation of the continuous evolution throughout these events. We studied an anode change close to the sampling location and an anode effect of the electrolysis cell. Furthermore, we identified the profiles throughout a freeze probing session to see the profile changes due to the intrusive measurement technique used in the industry.

Anode change

The change of an anode is known to bring significant thermal disturbance in the cell and therefore, to the sidewall freeze. To remove an anode the crust, together with the top of the freeze, is broken around the anode to facilitate its removal. Once the anode is removed, the bath is directly exposed to the environment, losing heat mostly by radiation. The new anode acts as a thermal sink in the system with its significant thermal mass. Additionally, the bath solidifies first on the surface of the new anode isolating it both electrically and thermally preventing the heat generation by the Joule effect. The sample signal during an anode change near the detection point and the resulting freeze estimations are given in Figure 5.

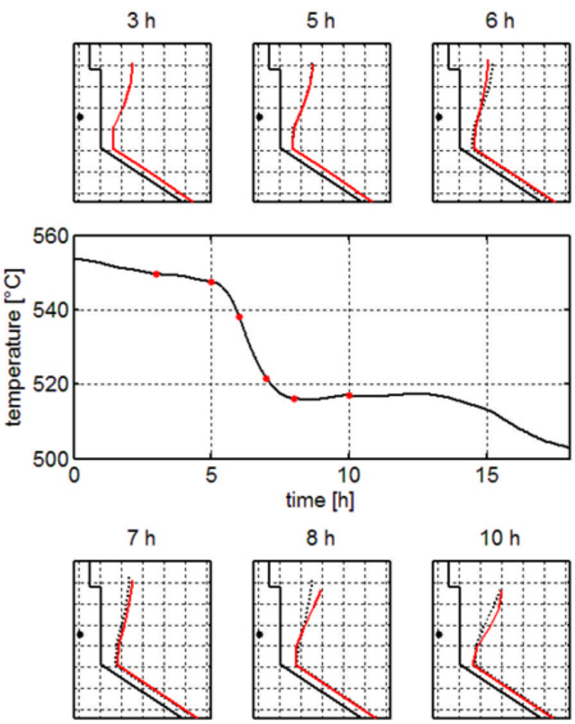

Figure 5. Evolution of the freeze profile in case of an anode change near the thermocouple array on the positive side of the cell

To help evaluate the profile evolution in Figure 5 the freeze estimations are plotted with a continuous line along with the preceding calculated profile represented by a dashed line. Although there is a slight decrease in the temperature, we find no changes in the freeze profiles in Figure 5 prior to the 5th hour of the sample signal. After the thermal effect of the anode change reaches the sensor, in the 6th hour we detect the thickening of the middle, thinnest part and thinning of the top portion of the freeze. Both of these changes correspond well to the expected effects of the anode change. The thickening middle portion can be a result of the decreased heat production in the vicinity of the studied portion. The thinner upper freeze is the consequence of the process of an anode removal resulting in the crushed crust and upper freeze portion.

As time advances the top freeze gradually thickens as demonstrated by the identifications in the 7th and 8th hour. As the anode warms up the heat production results in the decrease of the freeze thickness in the most critical middle region as seen in the 10th hour of the signal.

Anode effect

The locally poor alumina concentration may lead to an anode effect resulting in rapidly increased heat production [10]. Figure 6 shows the effect of this violent thermal event on the positive sidewall temperature of the reduction cell.

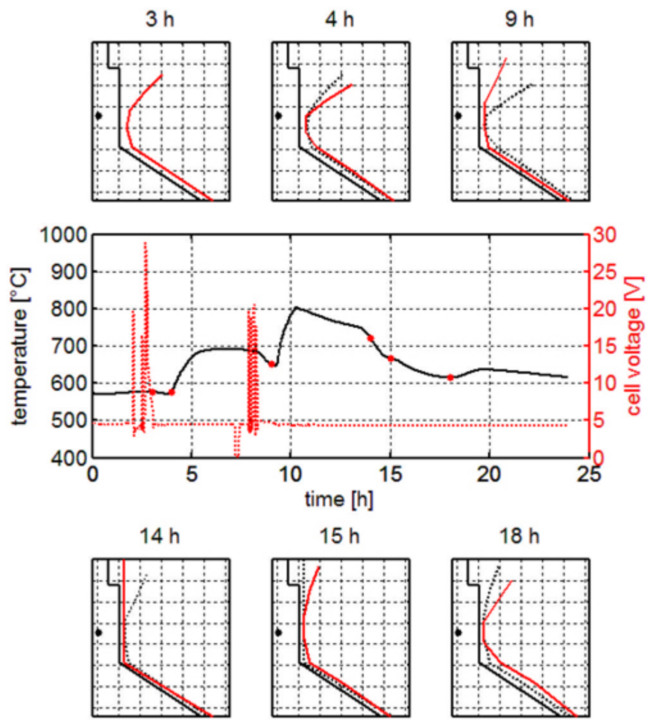

Figure 6. Evolution of the freeze profile in case of an anode effect in the electrolysis cell

We can see on the temperature evolution in the sample signal that two anode effects rapidly increased the sidewall temperature by about 100°C each. This increase resulted in a maximum temperature of 800°C in the wall. The profile estimations show a reasonably thick frozen bath layer before the thermal effects of the events. A significant change is already detected at the beginning of the thermal changes (3rd to 4th hour of the sample signal). Our method was unable to detect a stable freeze layer till the next presented profile in the 9th hour. This is probably the result of a partially or completely disappearing freeze layer which cannot be represented in our current model. This is confirmed by the estimated profile in the 9th hour, where one can observe that the thickness of the frozen layer has been reduced in general. The next possible identification is shown in the 14th hour where our method detects a thin freeze layer along the wall. It has to be noted that the identification converged with a high value of the cost function. This indicates that the forced constraints of the freeze profile parameters dominate the result. We suspect a disintegrated frozen layer at this period of the sample signal. The freeze starts to thicken in an hour and in the following hours our method estimates the further thickening of the frozen bath layer (see 15th and 18th hour in Figure 6). Based on these estimations we suspect that in this particular case the sidewall was exposed to the bath for periods of 3 to 5 hours.

Mechanical probing of the freeze shape

The mechanical probing of the freeze shape is a highly intrusive procedure with significant thermal effects on the cell. The manipulations promote increased heat loss in the area of interest during a relatively long period. We used the measured signal to estimate the changes of the freeze shape during and following a probing of the freeze in front of the sensor. In Figure 7 the evolution of the reference temperature signal is plotted along with the estimated profiles at characteristic instants.

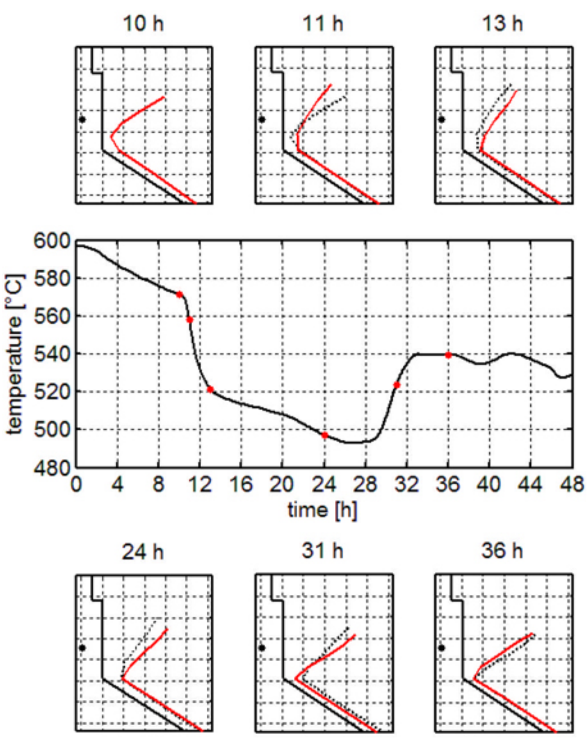

Figure 7. Evolution of the freeze profile in case of a mechanical freeze probing session near the sensor

The estimated profiles demonstrate a similar tendency than in case of an anode change. The effects of thickening the middle and thinning the top sections are more pronounced in this case due to the longer intervention in the area of interest. The temperature signal allows us to estimate the anode removal, which gives access for the freeze probing equipment, around the 10th hour of the presented period. As a result of the removed anode the identification predicts a significant increase of thickness of about 50% at the thinnest, middle section of the freeze. In the following hours the identification captures simultaneous thickening of the thinnest and top parts of the freeze. As the reference temperature starts to increase in the 29th hour, during the heat-up of the new anode, the freeze starts to thin in the critical section. The bottom part of the freeze is also thinning slightly.

Discussion

The drive in the aluminum smelting industry to increase production represents a risk to cell lifetime. The longer cell lifetime is important not only from an economical point of view but also influences the ecological footprint of the production. High cell thermal loads due to increased production surfaces endanger the stable existence of the frozen bath layer protecting the cell sidewalls. While the erosion of the sidewalls is one of the leading causes of a cell failure [11], there are only occasional checkups during the operation to evaluate the state of the freeze and the thermal loads of the sidewall.

We previously proposed a method to continuously follow the thermal loads of the sidelining by means of temperature measurements inside the cell walls [6]. In the present work we extend the sidelining diagnostics to determine the state of the protective freeze layer on the sidewall section instrumented with a thermocouple array. Although it was previously proposed by other groups to use several thermocouples along the wall for similar purposes [4, 5], in this work we strategically select the arrangement of the thermocouples instead of simply lining them up. With a specific arrangement we measure not only individual temperatures but temperature derivatives.

Our approach allows a fast, rough estimation of the freeze thickness and shape based on the measured temperature derivatives. This instant estimation is gradually improved with an optimization procedure based on the particularities of our temperature measurement method. Namely, we emphasize the importance of temperature differences compared to absolute values in the calculation. The sensitivity study of our mathematical model demonstrates the uncertainty of the results with changing key parameters. The freeze thermal conductivity and external steel shell heat transfer coefficient proves to be the critical parameters. These parameters need to be determined experimentally to the highest possible accuracy to have an accurate model. The sensitivity study results also assure that our method is capable of providing safe freeze estimation in its current state in the broad range of the uncertain parameters. The estimation of the most critical, thinnest part of the freeze changes only slightly with significant parameter variations.

In spite to these uncertainties, we found a reasonable agreement between our estimation and the mechanical freeze probing results. One of the greatest sources of deviation in our view is the intrusive nature of the currently accepted freeze probing technique. As it was found in the continuous profile identification study the freeze have a tendency to thicken up in the middle section and get thinner on the top portion during a probing session, This is exactly the difference that we can see comparing the estimated and probed profiles.

With the help of the calculation method based on the continuous temperature measurement we could follow the main tendencies throughout specific events in the electrolysis cell. This would clearly not be possible with mechanical freeze probing. The changes correspond well to what one expects knowing the thermal impacts of the different events. Our method provides a tangible measure and a record of the changes.

Although the presented frozen layer estimations method corresponds well to both mechanical probing results and expectations based on thermal effects, it has its limitations caused by a number of factors. The steady approach of the modelling might be erroneous in fast thermal changes such as in case of an anode effect. Additionally, the change of the composition of the sidelining is inevitable due to sodium penetration and erosion which is currently completely neglected. Similarly, the freeze material properties are complex and inhomogeneous, while our method assumes a single constant thermal conductivity.

Conclusion

We successfully demonstrated the feasibility of estimating the freeze thickness and shape based on temperature measurements in a working aluminum electrolysis cell's sidewall. The simplified model of the sidelining and freeze is capable of providing safe estimates of the protective frozen bath layer. The method is able to continuously follow tendencies of the sideledge evolution throughout specific events of the operation that would not be possible with traditional methods.

The presented approach can provide a continuous history of the freeze state, which could be an aid for a better planning of cell operation in order to maximize its lifetime. With long term freeze monitoring the design developments aimed at increased production rate could be aided using the proposed method.

Acknowledgements

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