Travaux 44, Proceedings of 33rd International ICSOBA Conference, Dubai, United Arab Emirates, 29 November - 1 December 2015

Evaluation of anode cover heat loss

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Abstract

Thermal balance is a key parameter in any cell technology and has a major impact on cell operation and the resulting KPIs. The cell loses heat mainly through the potshell and anodes. The anode is typically covered with a layer of ore material to protect it from oxidation and is also utilised to maintain the required heat balance inside the cell. The desired heat loss is achieved by adjusting the height of the cover, which is one of the cell operating parameters. The impact of anode cover height on the cell thermal balance was studied using ANSYS thermoelectric models. These models predict heat loss through the anode cover, the resultant bath temperature and freeze profile. To evaluate the modeling results, the anode cover was equipped with thermocouples, allowing continuous temperature measurements throughout the anode life cycle. These thermocouples were installed at different heights to understand the variation in thermal conductivity as the cover changes from a hard layer at the bottom to a softer one at the top. In this paper, the result of these trials is presented, together with the model prediction and findings of this study.

Keywords: Anode cover; thermal conductivity; anode heat loss; modeling; cell thermal balance.

1. Introduction

Achieving good thermal balance is one of the key fundamentals for excellent KPIs in any cell technology. Understanding the pot's thermal state and the desired thermal balance of the pot enables better pot control and operation. Approximately half of the energy in a pot is lost as heat. The two major contributors are heat loss through the potshell sidewalls and heat loss from the top of the anode [1]. Understanding the heat loss through the potshell is essential for pot lining design. The lining material should provide enough thermal insulation to maintain the bath temperature on target, while providing adequate freeze on the side to protect the side lining. Another major contributor to heat loss is the top of the anode, accounting for approximately 40 % of the total pot heat loss [1]. In addition to the design of the anode and the thermal conductivity of its different components, the anode cover plays a major role in controlling the heat loss through the top. Anode cover material consists commonly of crushed bath and alumina. The anode cover serves two main purposes in the pot: to prevent anode oxidation, and to insulate the top of the pot to reduce heat loss through the top of the anode panel.

The heat loss through the anode cover depends on the composition of the cover material as well as the height of the cover. While increasing the percentage of alumina in the cover can help reduce the thermal conductivity of the cover, higher alumina content in the cover makes it more difficult for the cover to stay on top of the anode. The anode cover height is flexible and can be adjusted, if required, for heat balance when pot amperage or pot voltage changes (or any other parameter that affects the pot heat balance).

Anode cover heat loss depends on the thickness of the anode cover and its thermal conductivity. The thickness of the anode cover can be kept constant by anode redressing. The thermal conductivity depends on the composition of the cover. In this study, the cover comprised approximately 65 % crushed bath and 35 % alumina.

During the life of the anode, the cover changes continuously due to the penetration of bath vapours into the cover, which induces physical and chemical transformation of the cover, particularly in the bottom part, which becomes hard. Altough the top layer remains loose, the properties may also change because of the compaction and some penetration of bath vapours. Consequently, the thermal conductivity of the anode cover changes continuously during the anode life. This has been demonstrated by previous studies, specifically for free crust above the channels [2 - 4]. Our study involved the anode cover on the top of anodes, which covers a much larger area than the channels.

2. Modelling approach

To evaluate the heat loss from the cell, two major modelling approaches were used: quarter cell ANSYS 3D thermoelectric model, shown in Figure 1, representing the full cell by symmetry as well as separate anode and cathode models. The full model includes lining, potshell, anodes with the cover, liquid metal and bath. The model results include pot temperature distribution, freeze profile and heat loss from different parts of the pot, as well as the voltage drop in each component.

The anode slice model, Figure 2, was used for more detailed analysis of the anode cover heat loss. The results of the slice model are generalised to the whole anode panel, to obtain heat loss from the top of the pot.

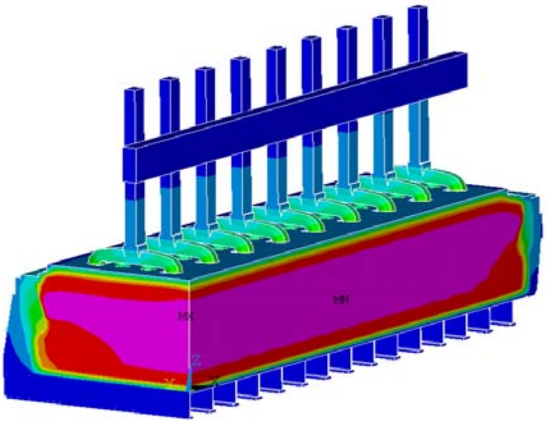

Figure 1. Full cell model.

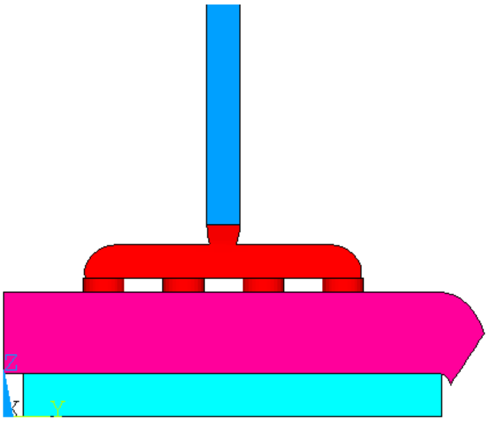

Figure 2. Anode slice model.

3. Measurement setup

To validate the anode model results, the temperature distribution through the thickness of the cover material was measured. This was done by installing a vertical stack of five equidistant thermocouples at different levels from the top of the carbon and fixing them on the anode yoke to secure them in the same position for the whole anode life cycle. The thermocouples were connected to a data logger, which recorded the temperature every 15 minutes. Figure 3 shows an anode with the thermocouples installed before anode setting. One of the thermocouples was fixed onto the top surface of the carbon and the rest were placed at 3 cm, 6 cm, 9 cm and 12 cm above the top of carbon surface. The thickness of the anode cover was 13 cm. For this study, five anodes were measured. The anodes in this study were DX+ anodes with four stubs and the location chosen for thermocouple installation was between the first and second stub from the side of the pot. With respect to the anode width, the thermocouples were installed 3 cm away from the side of the yoke.

Figure 3. Thermocouples above the anode, fixed to the yoke.

The heat flux through the cover was not measured, which would otherwise provide valuable insight into the change in heat flux through the life of the anode. For model validation, the rod temperature near the clamp was measured as was the air temperature inside the hood. Additionally, the anode cover height was measured at different ages of the anode.

4. Results and analysis

4.1. Anode cover thickness

The cover thickness was measured for two anodes during the trial, together with the height of hard cover material and loose cover material as shown in Figure 4. The height of the loose cover was measured directly while the height of the hard cover, since the hard material is difficult to break, was calculated with reference to the vertical distance to the bottom of the yoke. Figure 4 shows the evolution of hard cover over the anode life. The formation of the hard cover occurs over the first 10 days after which it settles to about 40 % of the total cover.

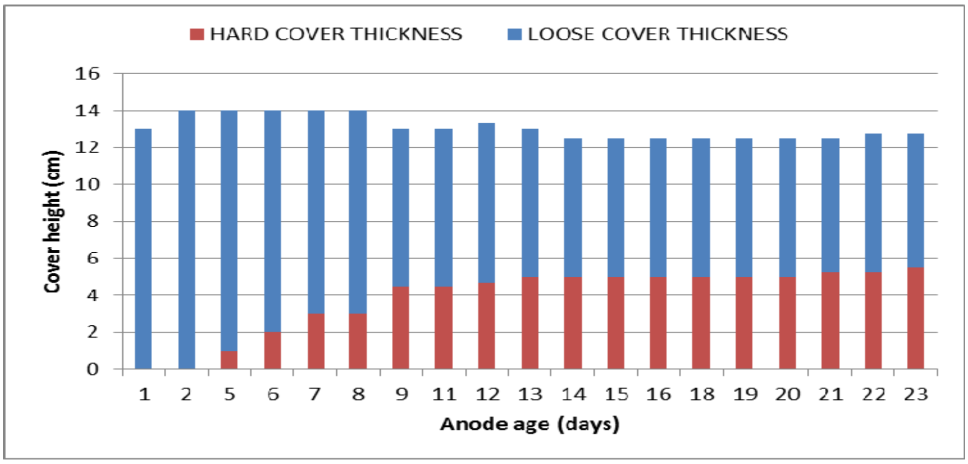

Figure 4. Measured thickness of hard and loose cover over the anode life cycle.

4.2. Heat loss for midlife anode

A midlife anode is usually considered for design and modeling purposes; and is assumed to represent the average parameters of the anodes from setting to removal. The anode life cycle for the pot chosen for this trial was 25 days, so the average temperature between days 10 and 15 was considered for midlife evaluation. Figure 5 shows the average measured temperature at different heights in the cover for the five anodes.

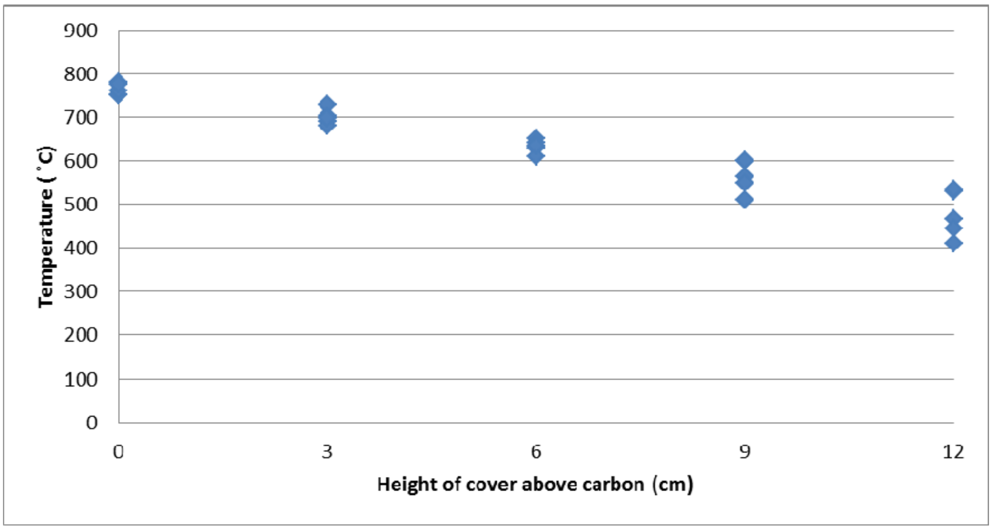

Figure 5. Five days average midlife temperature at different heights in the anode cover for each anode.

To reproduce the measured temperatures using the model, different functions and values were used for the thermal conductivity of the cover material in the model. One of the representations of thermal conductivity uses two layers, with different thermal conductivity for hard cover (commonly called crust) than for the loose cover. The transition between the two is modeled as a straight line from 600 °C to 700 °C. For the loose cover below 600 °C, thermal conductivity for cover with high fine fraction of crushed bath from Taylor was used [5]. The thermal conductivity of the cover was adjusted for the alumina percentage. The thermal conductivity for the hard crust above 700 °C was approximately 2.6 W/m²°C before adjustments were made according to temperature profiles in the crust, obtained by our measurements. The temperatures calculated by the model using these properties are shown in Figure 6 under the name Model 1. The temperatures in the model were lower than measured at different heights, indicating higher thermal conductivity in the model than actual.

To improve the results from Model 1, so that temperatures closer to the measured values were obtained, the thermal conductivity for hard and loose cover was multiplied by different factors. Figure 6 shows results from Model 2, which reduces the difference between the model and actual measurements.

Another representation of thermal conductivity is to use a simple linear correlation between temperature and thermal conductivity for the range from 400 ˚C to 850 ˚C instead of the stepwise transition explained above. The results of this approach are labelled Model 3 in Figure 6.

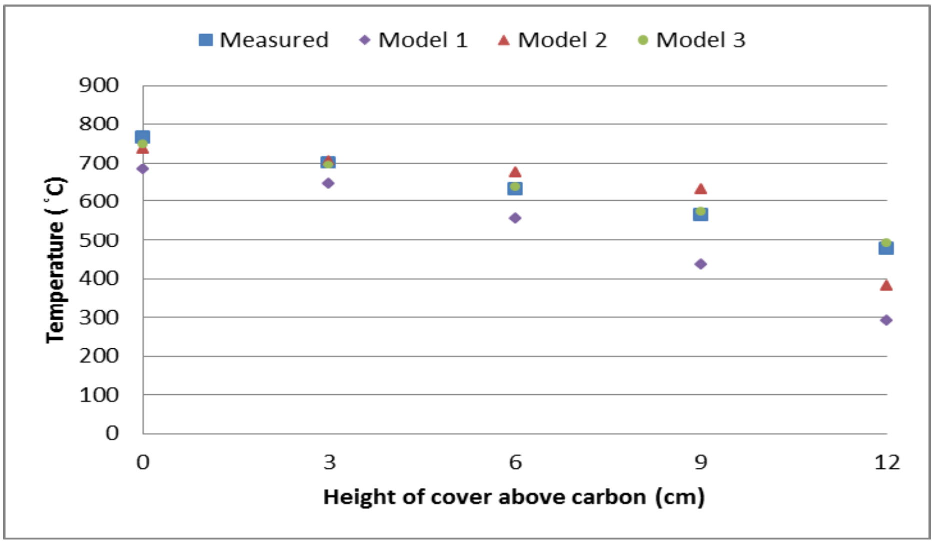

Figure 6. Average measured vs. model temperatures at different heights in anode cover at midlife.

The absolute differences between the average measured temperatures and the model are shown in Figure 7. Model 1 shows differences in the range of 50 ˚C to 185 ˚C. Model 3 shows a better fit to the data and less difference against the average measured temperature compared to the other two models.

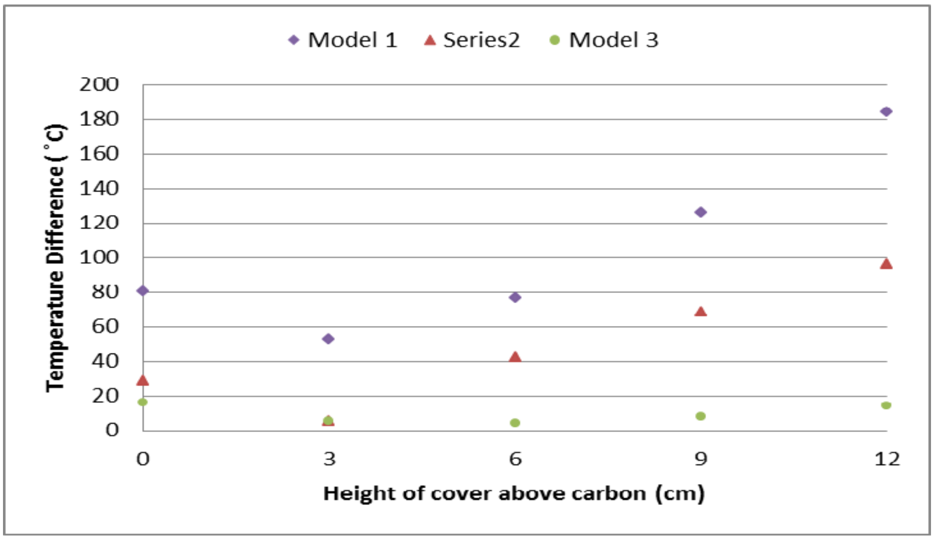

Figure 7. Difference between average measured temperature and model temperature at difference anode cover heights.

To evaluate the impact of cover properties represented in the model, the heat loss from the three models was compared. Using the same model assumptions, and limiting the change to the thermal conductivity of anode cover material as discussed above, the total anode heat loss was 62 kW higher in Model 1 compared to Model 2; and 13 kW higher in Model 2 compared to Model 3. Thus, Model 1 was considered unsuitable for representation of the cover material in these pots and could lead to erroneous conclusions on the thermal balance. Model 3 gave the best agreement between the measured and modeled temperature profile.

Model 3 was further used to analyse the impact of cover height on heat loss. Table 1 shows the change in heat loss per cm cover height in the range of 6 cm to 18 cm. The impact on heat loss per cm of anode cover is higher at smaller cover heights (8.7 kW per cm at 6 cm to 8 cm) than at higher cover thicknesses (4.4 kW per cm at 16 cm to 18 cm).

Table 1. Model 3 heat loss vs. anode cover height.

Change in cover height (cm)	Difference in anode heat loss using Model 3 (kW/cm of anode cover)
6 to 8	-8.7
8 to 10	-7.3
10 to 12	-6.2
12 to 14	-5.4
14 to 16	-4.8
16 to 18	-4.4

4.3. Heat loss throughout anode life cycle

The temperature at different levels in the cover for one anode was monitored and is plotted in Figure 8. These temperatures are shown for the whole anode life, which is about 25 days, and is shown for one anode as an example. The temperature in the cover goes through different stages. For about two days after anode setting, the temperature increases rapidly, starting from the time of anode dressing when the cover material is added on the top surface of the anode. The second stage shows almost constant temperature at each level in the cover and continues until the anode age of 10 to 15 days. In the third stage, the temperature starts increasing again. This increase is slower near the top of the carbon than higher up in the cover. The average temperature increase at the top of the carbon is 50 ˚C while the increase at 12 cm is 170 ˚C. The temperature flattens out at 24 to 25 days, undoubtedly because the thermal conductivity of the cover has settled to its final values. The temperature evolution during the anode life does not seem to correlate with the evolution of the hard cover as seen in Figure 4.

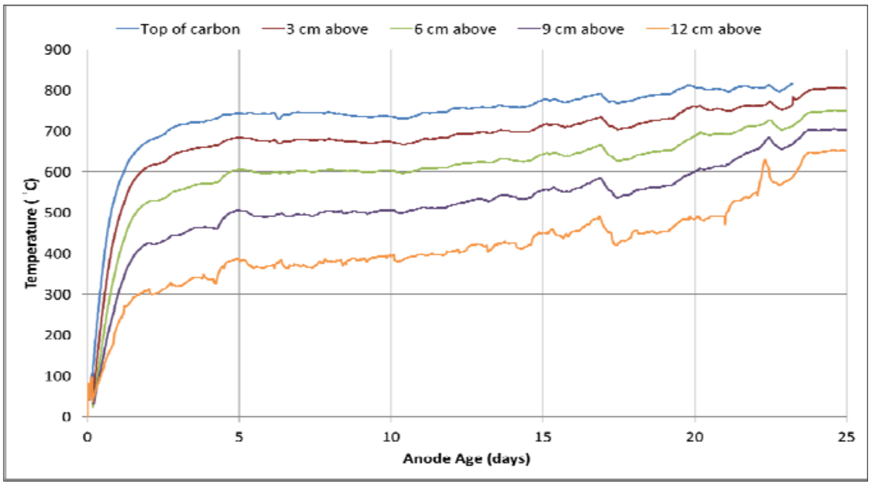

Figure 8. Temperatures at different levels in the anode cover throughout an anode life cycle for one anode.

For further considerations about how thermal conductivity changes over time and through the thickness of the anode cover, the temperature differences between two successive layers were calculated and are shown in Figure 9. Heat loss through the anode cover is governed by Equation (1):

$$q = k_i \frac{\Delta T_i}{d} \tag{1}$$

where: q Heat flux, W/m^2,
k_i Thermal conductivity in the layer i, W/m°C,
ΔT_i Temperature difference between two successive probe positions, °C,
d Distance between two thermocouples, equal for all thermocouples, m.

Since the heat flux is the same through all the layers, the temperature differences indicate that the thermal conductivity decreases in a vertical direction and changes over time. A large temperature difference indicates low thermal conductivity and conversely small temperature differences indicate large thermal conductivity. The thermal conductivity is greater by approximately a factor of two in the bottom layer of the anode cover than in the top layer. The temperature difference remains nearly constant between the age of 5 and 19 days in the bottom two layers of the cover, but gradually decreases in the top layers because of continuing increase in thermal conductivity. At 19 days, the top layer probably got some fresh loose cover by redressing and the thermal conductivity decreased for a few days. Finally, after the age of 22 days, the thermal conductivity increased rapidly in all layers, indicating the presence of bath near the top of the anode and more rapid penetration of bath components into the cover. The same behavior was seen in other trials. Further investigation, which should include the measurement of heat flux, is needed to determine the thermal conductivity in each layer.

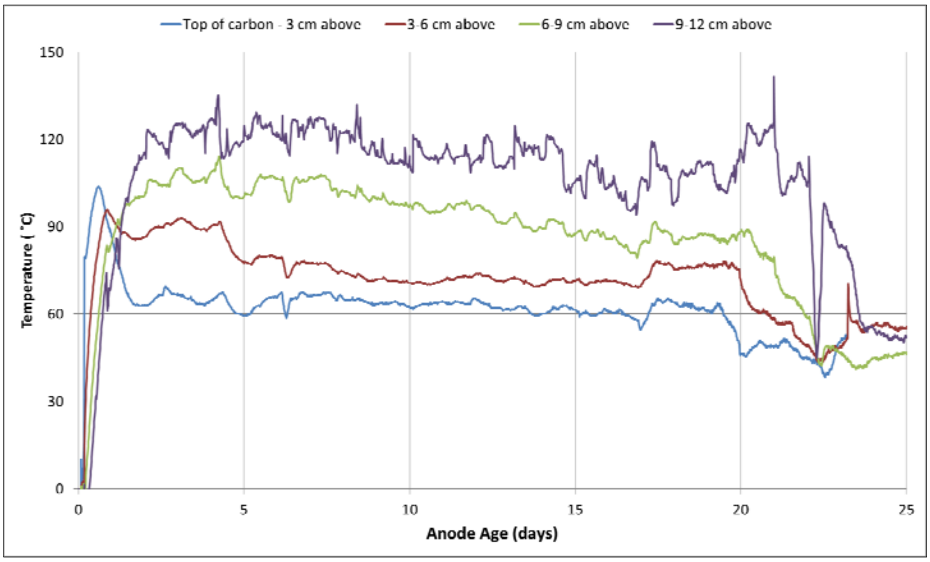

Figure 9. Temperature difference between different levels in the same anode shown in Figure 8.

4.4. Impact of spike on anode heat loss

One of the anodes equipped with thermocouples for continuous temperature tracking in the cover was found by anode current distribution measurement to have high anode current compared to other anodes in the pot. This anode was suspected to have a spike and was removed for checking. Figure 10 shows the spike that was found. The spike was removed and the anode was then set back into the pot.

For this anode, the temperature at different levels in the anode cover is plotted in Figure 11. The data for the thermocouple at the top of the carbon was lost after anode removal. The temperature increased by an average of 125 ˚C at all levels in the cover during the two days before spike removal. The fact that the temperature increased approximately by the same amount for the different levels shows that there is no abrupt transition in property of the cover in the range of 500 – 850 ˚C.

Since the temperature difference between levels in the cover stayed about the same, the change in heat loss is equivalent to the ratio of thermal conductivity at the spike temperature to the thermal conductivity at normal temperature at each height. Based on this assumption, the increase in heat loss is approximately 37 % from the top of the spiked anode. This extra heat is locally generated in this anode because of the spike, which takes more current than average and could be short-circuiting to the metal.

Figure 10. An anode with spike.

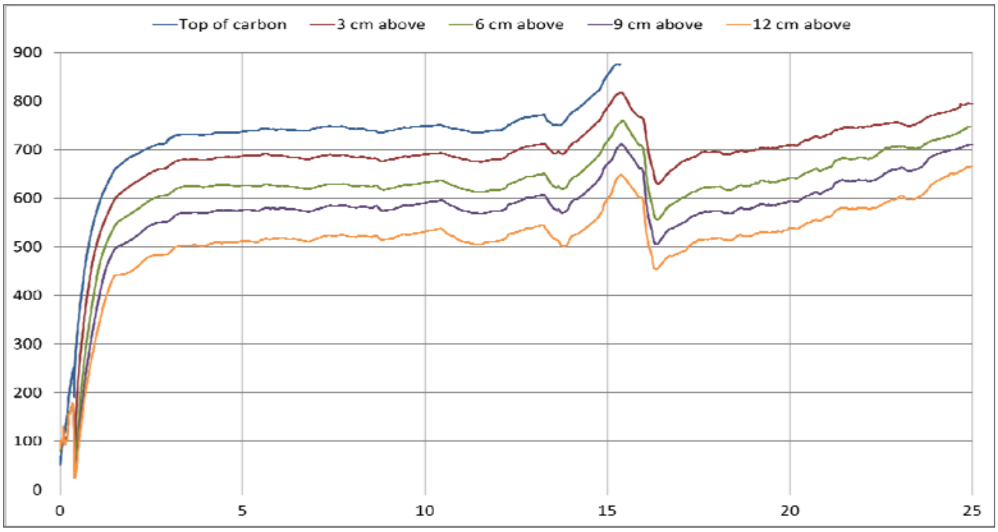

Figure 11. Temperatures at different levels in the anode cover for an anode with spike.

5. Conclusions and way forward

Continuous temperature recording at different levels inside the cover material can give insight to the thermal behavior of this material throughout the anode life cycle. Using these measured temperatures, together with mathematical modelling, it is possible to estimate thermal conductivity variation of the cover in space and time. Measurements show that part of the cover becomes hard during the anode life. The anode cover consists of 40 % hard cover from the 10th day onward while the remaining cover is loose. This change in the cover hardness does not have direct impact on the cover thermal conductivity. In the trials conducted, it was found that a linear correlation between thermal conductivity and temperature can be used in the range from 400 to 850 ˚C to evaluate the anode heat loss. In addition, the change in heat loss from the anode as the cover height changes can be calculated and used to establish cell thermal balance when the cell internal heat changes. Temperature evolution through the anode life cycle shows that time has an impact on the thermal conductivity of the anode cover.

It is important to note that these results are specific to the cover material used at the time of trial, as composition and granulometry of the cover material can impact the results. Further studies and investigations are required to establish a more comprehensive understanding of the anode cover heat loss. The impact of changing cover height on heat loss should be determined experimentally by conducting more trials using different cover heights and comparing the results to the model.

6. References

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