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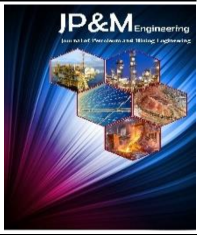

Thermal Analysis of the Baking and Start-Up Stages for Hall –Heroult Cells at Egyptalum Smelter

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Abstract

Thermal behaviour of three cells at Egyptalum smelter was investigated during baking and start-up stages by inserting twenty thermocouples in the sidewall carbon blocks and ten thermocouples in the bottom carbon blocks. The baking time, final average cathode surface temperature and the relative standard deviation for the anodic current distribution for these cells were about 71 h, 852 °C and 10 %, respectively. The heat-up rate during baking stage and the cell stability during the early operation period were improved. Temperatures in the sidewall carbon blocks at the end the baking stage in the range between 71 and 113°C and gradually increased after start-up stage to the temperatures in the range between 558 and 737 °C. The start-up time for these cells was 52 h. Valuable thermal relations were obtained between the sidewall carbon blocks and the steel shell during the baking and start-up stages. The results showed the sidewall carbon temperatures were unaffected by small voltage changes during the baking stage, but it affected by small voltage changes during the start-up stage.

Introduction

The first days of Hall Héroult cell's operation, which include baking and start-up, have strong influence on the performance and life of Hall Héroult cells [1- 3]. Electrical resistance baking with shunts-rheostats and anode flexible connectors may be considered as a preferred baking method for prebaked anode cells [1, 4-8]. The method has been applied in the Egyptalum smelter and its procedures have been illustrated elsewhere [8, 9-13]. Nickel chromium shunts were found to be more successful than stainless steel shunts, which are related to lower the applied current. Use of anode flexible connectors and increasing workers experience improved the anodic current distribution. Uniformity in cathode temperature distribution during baking stage was reflected in cell performance. Baking time, shunts-rheostats switch off, time of anode effect and cell voltage were determined during baking and start-up procedures. The required materials for these cells have been mentioned elsewhere [9].

When the cathode surface temperature during the baking stage is close to the operating temperature, the cell is started. The steps of start-up include: the molten bath is added, the current is connected to the cell and electrolysis is started, the anodes are raised in order to get a start-up anode effect, the anode effect is then quenched after about one hour and the molten metal is added, usually after about one day [4, 5].

Industrial results, with reduced cell baking time, indicated that lowering heating rates leads to cell instability in the early operating period and may lead to operational problems and / or a reduced potlife [13]. Practical research has shown that cathode baking should be done at the lowest heating rates in order to obtain the longest working potlife [3, 10, 14].

To overcome the problem of instability during the start-up period of the cell, an increase in baking time and a decrease in the heating rate were investigated in three prebaked anode cells at Egyptalum smelter. The thermal behavior of these cells was also described during the startup and baking stages.

Several factors such as the primary cell current during the baking process and the times of removal of the first and second shunts, the anode current distribution, the final distribution of the cathode surface temperatures, the baking temperature curve, and the cell voltage of the anode have been studied during the baking and start-up stages. In order to study these factors, several thermal and electrical measurements were made on these cells. The relationships between these factors are investigated in this paper.

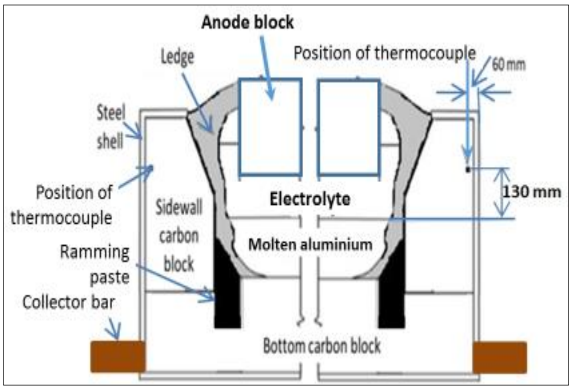
Experimental Work

Various experimental works were carried out during the baking and start-up stages on three prebaked anode (working at 210 kA) cells (numbers 617, 619 and 634) at the Egyptalum smelter. In order to find direct relation between cathode steel shell and sidewall carbon blocks, twenty thermocouples were embedded in the back sidewall carbon blocks of the cell and the corresponding temperature of steel shell were measured at the same time. Calibrated thermocouples of type K were embedded into the back sidewall carbon blocks (about 6 cm from the outer border of the steel shell) in twenty positions, as shown in Figure 1 (a, b) across each cell. These thermocouples were distributed as seven thermocouples in each longitudinal side (wide and narrow) of the cell and three thermocouples in each upstream and downstream side. Together with these measurement cells voltage was recorded. To evaluate the baking performance (checking the contact between coke bed with anode and cathode blocks) and to determine the date of cell start-up, ten thermocouples were embedded 1.5 cm into the top surface of the cathode carbon blocks as shown in Figure 1 (b). The measured temperatures of these thermocouples were recorded every hour during the baking process with the aid of a digital thermometer model: Fluke 52 [15], which was connected with the thermocouple.

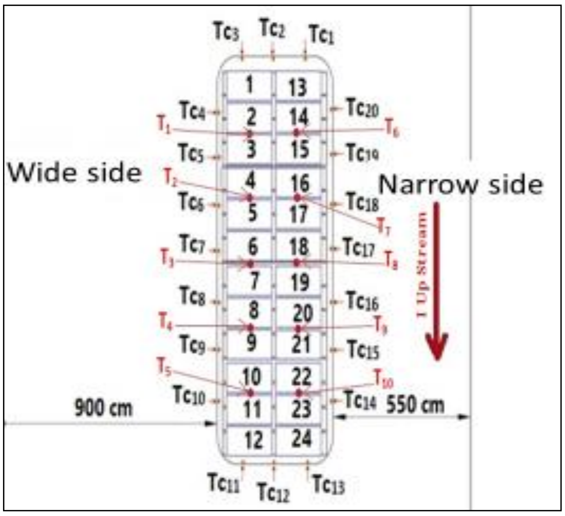
To measure high current in aluminium reduction cells, the known method is to measure the voltage drop and the resistance for a certain length, and then the Ohm's law was applied to calculate the cell current. These measurements were taken during cell baking every three h, but the first measurement was taken after one hour from the cell current connection. Voltage drop was measured with the aid of a Fluke 87V portable millimeter voltage measurement device [16] connected with double pole copper forks. This measurement was carried out on an aluminium rod between two points. The distance between the two rods of the fork was 100 mm. The anode current was then determined by dividing the current line and millivolt of each anode over the sum of the millivolts of all the anodes in the same cell.

Results and Disussion

Results of the three studied cells during the baking and start-up stages are described here. As shown in Table 1, the baking time of these cells was increased from the designed value (about two days) to about three days (in the range between 70 and 71 h). The initial cell current was changed in the range between 83.9 and 98 kA. Time of removal the first and second shunts also changed. 10 ton was added to each cell for start-up stages and the cell voltage at last quantity of the added bath for these cells in the range between 10.13 and 12,25 V. On the other hand, the properties of cathode carbon blocks and ramming paste for these cells were taken from one supplier. The preheated zones of the cathode surfaces were followed up by continuous measurements and the necessary corrective actions were done [10]. During the baking stage, no hot spots were observed on the surface of cathode blocks. This result means good temperature distribution on the cathode surface block.



a) Cross section in the cell



(b) Top view in the cell

Figure 1 Locations of thermocouples inserted into the back sidewall and bottom carbon blocks.

Arrow denotes to cell current direction and numbers (1 to 24) denote to anode blocks numbers. Thermocouples (Tc_1 to Tc_{20}) inserted into back sidewall carbon blocks and thermocouples (T_1 to T_{10}) inserted into the top surface of the carbon blocks.

Table 1. Parameters of the three studied cells during the baking and start-up stages

Parameter	Cell number		
	617	619	634
Initial cell current during baking, kA	85.4	98.1	83.9
Removal of small shunt after, h/temp., ◦C/ cell current, kA	67 / 712/122.2	64 / 694/124.4	66 / 702/121.8
Removal of large shunt after, h/temp., ◦C/ cell current, kA	68:30/ 730	66:30 / 720	69:30 / 747
Time of anode blocks displacement, h/ temperature at this moment, ◦C	69:30 / 782	68:30 / 775	69:30 / 775
Baking time, h.	70:30	70	71
Voltage at last quantity of added bath, V	11.08	12.25	10.13
Time, min. / voltage , V of anode effect	60/12.2	60/13.7	58/ 11.6
Cell voltage after killing the anode effect, V	8.6	9.2	8.6
Cryolite ratio of the added bath, %	>3		

The Studied Parameters during the Baking and Start-up Stages

Baking temperature curve

The average baking temperature curve for the three studied cells (617, 619, and 634) were compared with other three cells (numbers of 515, 536 and 544) baked for 53:30 h [10] as shown in Figure 2. The baking temperature curve of the three studied cells gives nearly the same behavior as compared with the other cells. The heat-up rates were done in three steps in the three studied cells and achieved in 3 days, while it were done in two steps in the other three cells and achieved in 2 days. Increasing the baking time reduces the cell instability during the early operation period from 0.087 μΩ for the cells baked in two days to 0.064 μΩ for the cells baked in three days as shown in Figure 3. The trend of this result is agreed with data published elsewhere [17], where reducing the cell instability from 0.072 to 0.063 μΩ leads to increase in current efficiency by 2 % and decrease in energy consumption by 0.23 kwh/kg Al [17].

Study the relationship between cell voltage and current with baking time

The relationship between cell voltage and current of the three studied cells with baking time (as shown in Figure 4) illustrated that the cell voltage rapidly rose to 2.44 V during the first hour from cell current connection, then it reduced to about 2.37 V up to the next 70 h, and then increased to 3.75 V at the end the baking stage. At the same time, the initial cell current of the three studied cells was in the range between 83.9 and 98 kA (40.6 and 46.7%) of the full line current (210 kA), then it increased to the range between 122.2 and 124.2 kA (58- 59%) after shut-down the small shunts at time in the range between 64 and 67 h, and then the cell worked on full current during the last 1 to 3 h. On the other hand, this result was compared with other cells worked in the same smelter but baked for two days and used nickel chromium shunts-rheostats. The initial cell current for the other cells was started in the range between 90.3 and 100.8 kA (43 and 48 %) of the line current, and then increased to 126 kA (60%) after shut down the first shunt group, and then the cells worked at the last 3 to 6 h on the full current [9]. Figure 4 shows an increase in cell voltage during a part of the baking time. This is due to increasing the resistance of the coke layer between the anode and cathode blocks with increasing the cathode temperature. This condition takes one to two h, and then returns to normal situation with taken appropriate corrective actions.

The average cathode surface temperatures of the three cells after removal the first shunts were 712, 694, and 702 ^{o}C, respectively. Then after removal the second shunts the temperatures were 730, 720, and 747 ^{o}C, respectively. The difference in the measured temperatures between the three studied cells is due to the removal of shunts is not carried out at the same time. The effect of changing the line current of these cells will be reflected on the heat-up rate of cathode block as described below.

The electrical energy consumption

The cumulative electrical energy consumption for the baking stage is calculated based on the sum of multiplying the voltage and current (see Figure 3) measured every three hours during the baking stage. The cumulative electrical energy consumption for the three studied cells during the baking stage was 17508, 19019 and 18300 kWh, respectively, with an average of 18276 kWh. The difference between these cells are depended the initial cell current, cell voltage, and time of removal the shunts. On the other hand, the electrical energy consumption was 30000 kWh at Dubal smelter with an average baking voltage of 2.7 V and 228 kA when using 100% graphite as resistor material [18]. During baking of 175 kA cells at Hydro Rheinwerk in Germany, about 7% from energy consumption (30000 kWh) was used to increase the lining materials temperatures; the rest was lost as heat. The baking time was reduced by several hours, when the cell insulation was improved without detrimental results [12].

Evaluation of Baking Process

The baking process is evaluated in this study using the following factors (the final average cathode surface temperature, relative standard deviation (RSD) in the final cathode surface temperature distribution, the heat-up rate during the baking process and RSD in the anodic current distribution based on the criteria mentioned elsewhere [10].

The final average cathode surface temperature and the RSD in the final cathode surface temperature distribution

The measured temperatures of cathode surface blocks at the end the baking stage for the three studied cells were 858, 852 and 846 ◦C, respectively. The maximum temperature was in range between 871 and 887 °C, while, the minimum temperature was in the range between 825 and 827 °C. The relative standard deviations (RSD) for these cells were 3, 2 and 2%, respectively.

On the other hand, the final average cathode surface temperatures for Pechiney smelters cells were in the range between 800 and 900 °C [4, 10]. The target for this factor was usually between 800 and 950°C [19, 20]. Final cathode surface temperature distribution may be considered to be satisfactory if RSD is less than 10% at the end of the baking stage [1, 10, 12]. The obtained results mean that the baking process was very uniform and safe, and agreed with the study [5,12] that has pointed out the importance of increasing the baking temperature as close as possible up to the operating temperature. As general, the difference between these smelters illustrated that this factor is not the most important evaluating factor [5], and the difference may be related with different parameters like: modality of metal and bath penetration into the cathode blocks, type of lining materials, positions of measured temperatures, method of baking and type of used resistor bed [10].

The heat-up rate during the baking stage

The heating rate during the baking stage of the three studied cells is shown in Figure 5 and was in the range between 1 and 29 °C/h., and most of heat-up rates were in the range between 2 and 12 °C/h. These values are considered the best results if compared with the reported heating rates (in the range between 10 and 19 °C/h in other smelter) [4,10]. The difference in initial cell current of the three studied cells does not negatively effect on the heat-up rate during the baking process. It will be expected that reducing the heating rate will reflect positively on the potlife and hence reduce the thermal shocks of the cell lining. So, a preferred heat-up rate is to be low to obtain good baking results [4, 11-13]. Also, decreasing the heating rate was considered as a preferred approach until a slow thermal penetration occurs within the cathode lining and thus ensuring that no thermal shocks occur for any part of cathode lining [13].

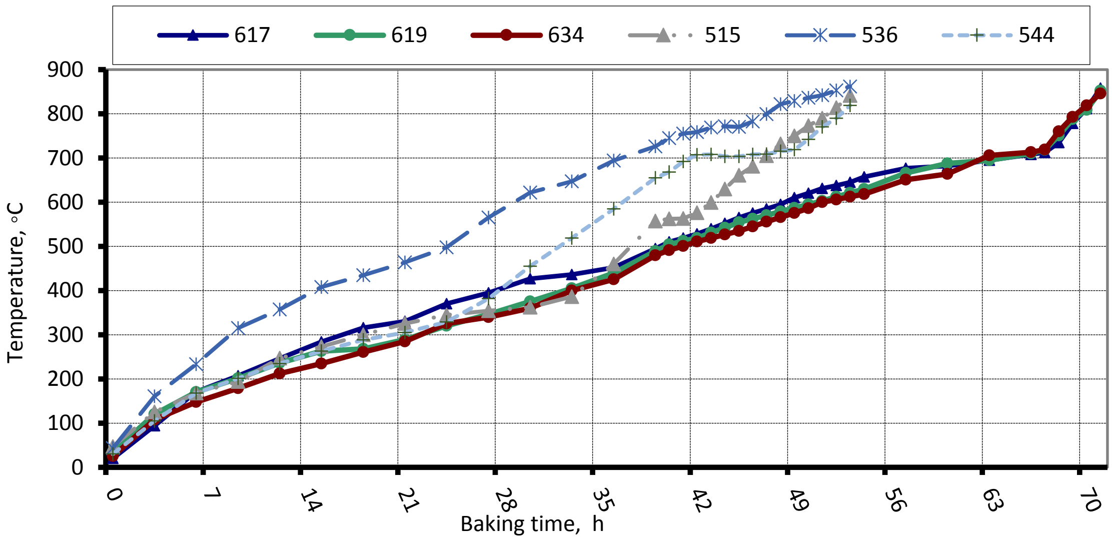


Figure 2 Average cathode surface temperature as a function of baking time for the three studied cells (617, 619, and 634), and the other three cells (515, 536 and 544).

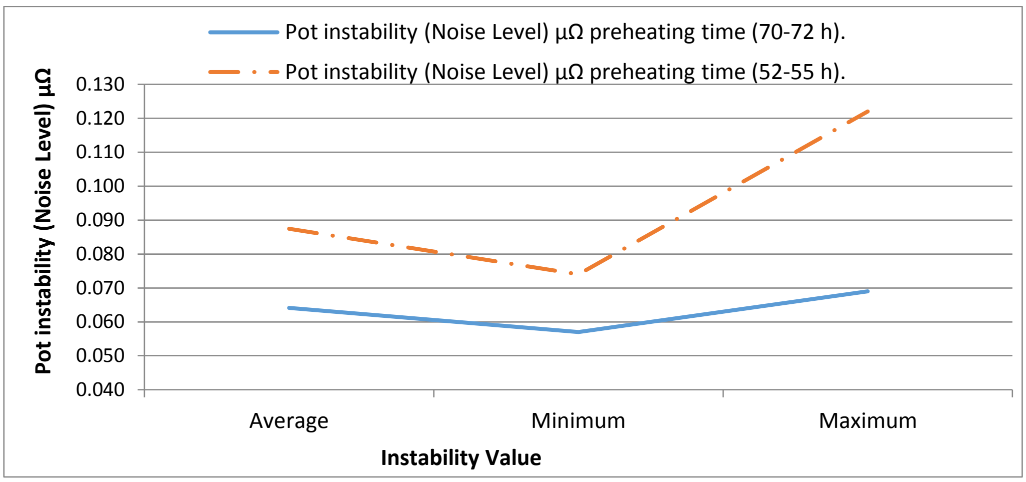


Figure 3 Comparison of instability for baked cells in two and three days.

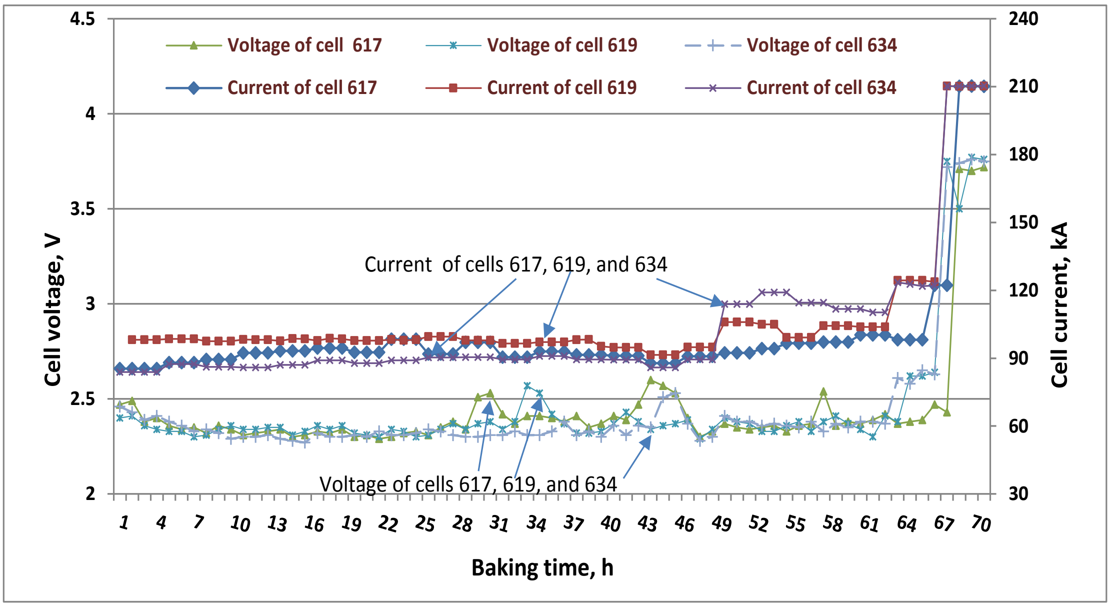


Figure 4 Current and voltage for the three studied cells during the baking process.

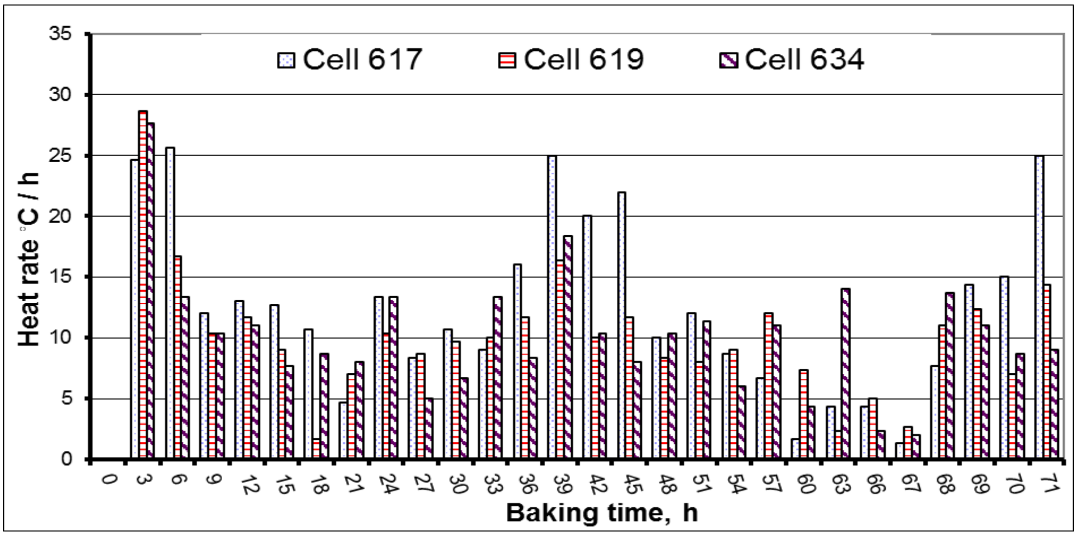


Figure 5 Heating rate of the three studied cells during the baking stage

RSD in the anodic current distribution

The anodic current distribution is a very important parameter and is used to improve the cell behavior during the baking stage [4, 10]. So, the relationship between RSD for the anodic current distribution and baking time for the three studied cells (617, 619 and 634) are compared with the other three cells (515, 536 and 545) as shown in Figure 6. The RSD for the three studied cells reached to 10% and more smooth as compared with 13% for the other cells. These improved results are due to using corrective actions during the baking process and to increase the workers' experience, which reflected on cell temperatures distribution [4, 10].

Evaluation the Start-up Procedures

The three studied cells were started with basic bath tapped from neighboring cells (all cryolite ratios for these cells were above three with bath temperatures ranged between 994 and 1007 °C with an average value of 1001 °C).

The duration of initial anode effect for these cells was 60 minutes. The average cell voltage before anode effect was 3.75 V and then increased during the anode effect period to the range between 10 and 25 V (with an average value of 14.6 V). Cell voltage during and after killing the anode effect were changed for these cells as illustrated in Table 1, and this difference is depended the cathode surface temperature and cell condition. These results were compared with the data collected from different smelters [4, 6, 20, 21], where the cell voltages for these smelters were ranged between 11 and 50 V, while the anode effect durations were ranged between 30 and 95 minutes.

Finally, ten tons of molten aluminium was added to each cell after 52 h from bath addition. The delated metal addition aims to give a chance to sodium in the bath to adequately penetrate into the carbon blocks and to give enough time for the ramming paste to expand in order to prevent any metal penetration in the cathode materials and be properly baked [20].

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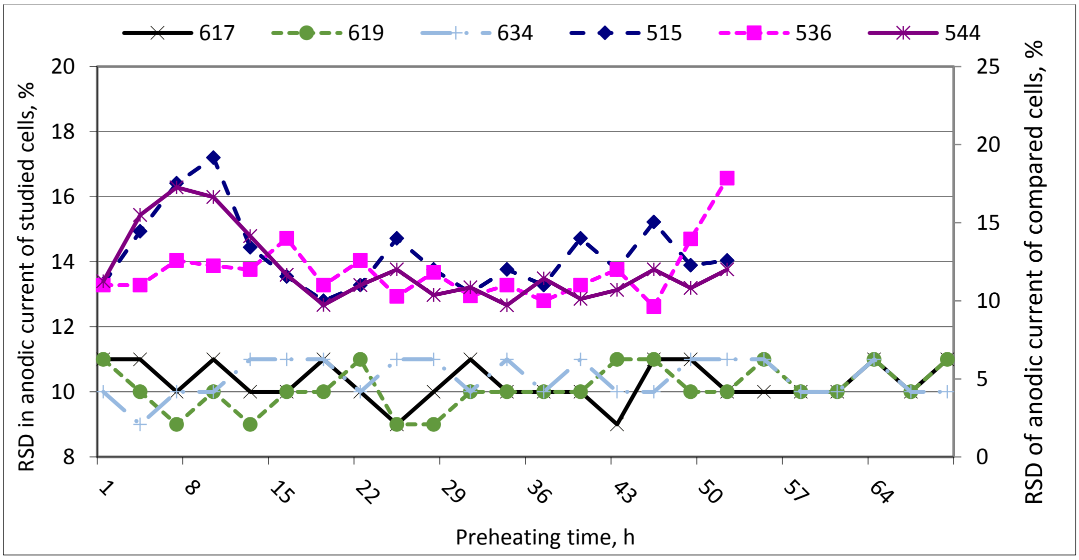


Figure 6 RSD in the anodic current distribution for both the three studied cells (617, 619 and 634), and other three compared cells (515, 536 and 545)

Thermal History of Sidewall Blocks during the Baking and Start-up Stages

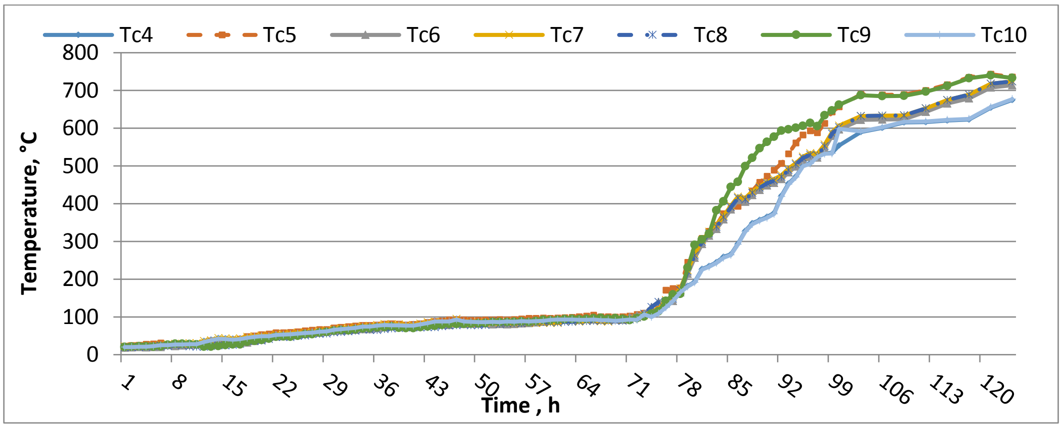
The measured temperatures in the back sidewall carbon blocks during the baking and start-up stages (the period from electrolyte addition to metal addition) for cell 617 are shown in Figure 7 (a, b) and 8 (a, b). At the end of the baking stage, the temperature in these locations was in the range between 71 and 113°C and gradually increased after the end of the start-up stage to the temperatures in the range between 558 and 737 °C.

During the baking stage, temperatures of the wide longitudinal side were higher than those of the narrow longitudinal side, with a little difference that doesn't exceed 3 ºC. Also, the same difference was observed in the temperatures between the upstream and downstream sides. These results don't give a clear picture. This is because the temperature of the sidewall lining doesn't reach to a stable temperature during the baking stage. Also, the average heating rates during the baking stage in the longitudinal sides were 1, 1.03 and 0.9 ºC/h, and in the transverse sides were 1.22, 1.02 and 0.95 for cells 617, 619 and 634, respectively.

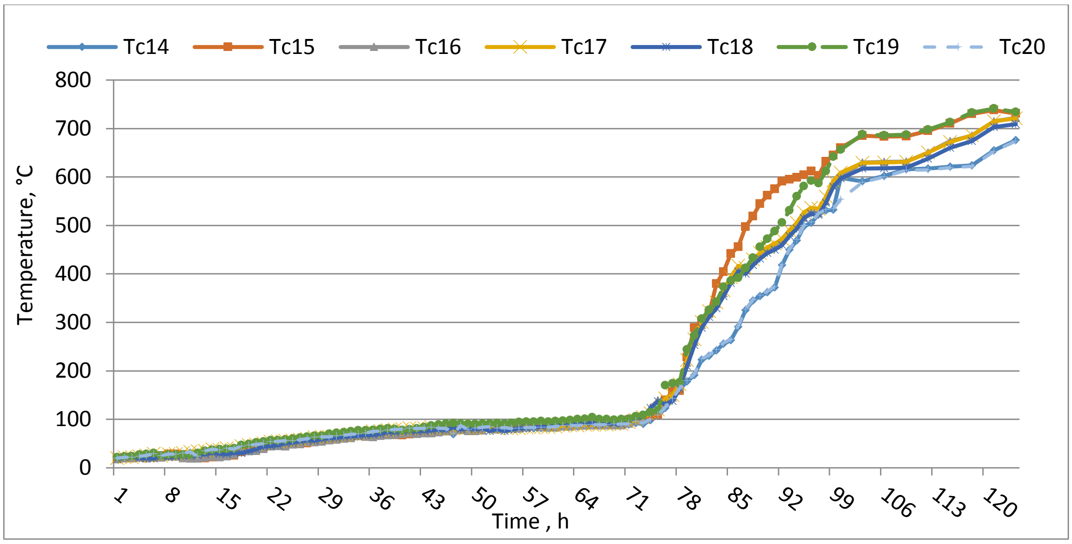
After adding molten metal, the average temperatures in the wide longitudinal side were higher than those of the narrow longitudinal side, with a maximum difference don't exceed 3 ºC in cells 617 and 619, and reached to 50 ºC in cell 634. On the other hand, a little difference in temperatures between upstream and downstream current sides and the maximum difference doesn't exceed 4 ºC. Average temperatures of the wide and narrow longitudinal sides at the end of the start-up stage were more than the temperatures of the upstream and downstream sides with the values of 131, 134 and 88 ºC for cells 617, 619 and 634, respectively. These results showed that something happened in cell 634 and this difference in temperatures may be related to the difference in bath temperatures.

The average heat-up rates during the start-up stage in the longitudinal side were 11.6, 11.4 and 10.6 ºC/h, and in the transverse side were 8.8, 8.9 and 8.7 for cells 617, 619 and 634, respectively.

The increase of both all sides temperatures and heat-up rates from the baking stage up to the start-up stage are related with the higher difference in the heat transfer between the packed sodium carbonate and cryolite (insulation materials) to the sidewall carbon blocks during the baking stage and also between the molten bath and aluminium (conductive materials) to the sidewall carbon blocks during the start-up stage.

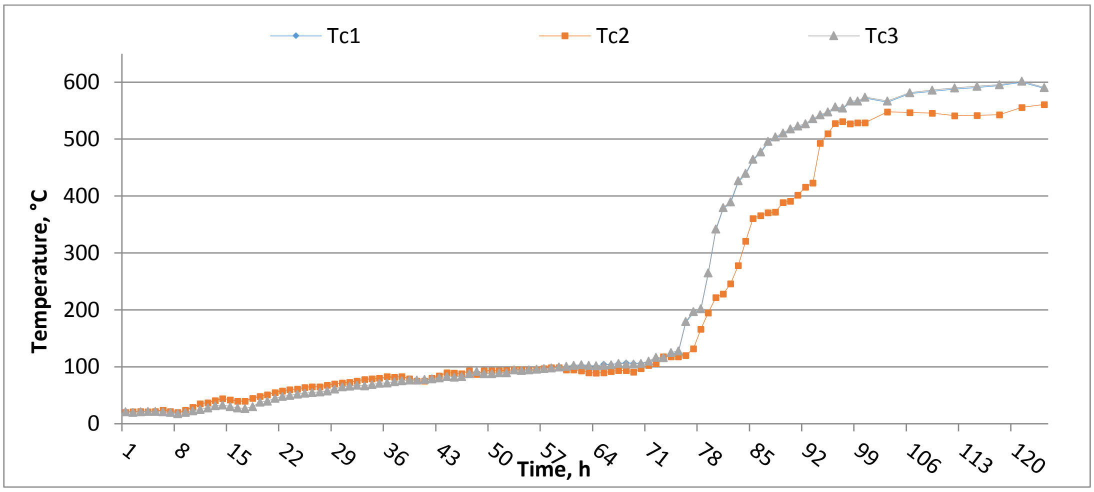


(a) Wide longitudinal side

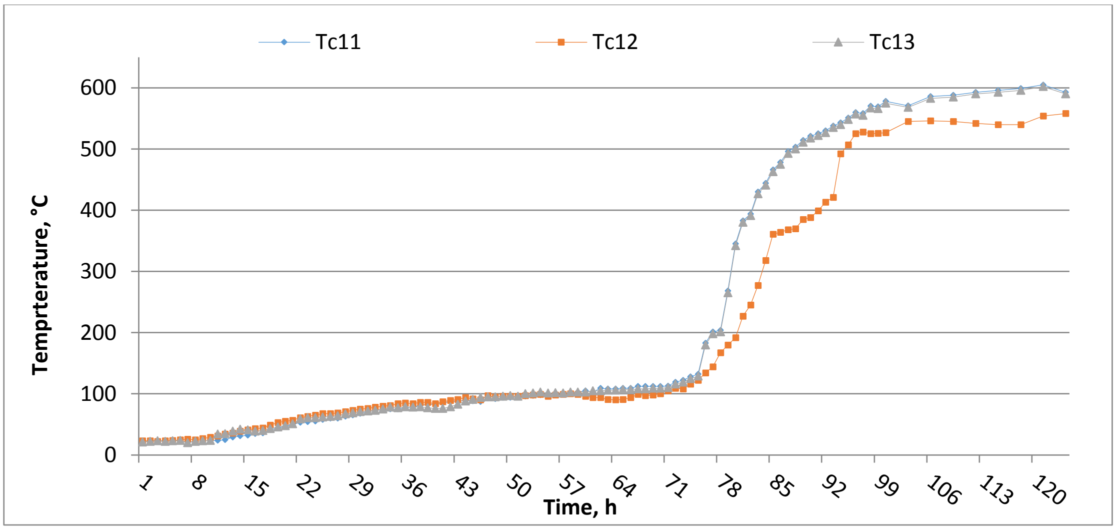


(b) Narrow longitudinal side

Figure 7 Temperatures of the back sidewall blocks in both a) wide and b) narrow longitudinal sides for cell 617 during the baking and start-up stages.



(a) Upstream side



(b) Downstream side

Figure 8 Temperatures of the back sidewall blocks in both a) upstream and b) downstream sides for cell 617 during the baking and start-up stages.

Average measured temperatures for the twenty thermocouples of cell 617 and the corresponding cell voltage during the baking process are shown in Figure 9. As shown from this figure that the increase in the temperature of back sidewall carbon was unaffected by small voltage variations. This result is agreed with data published elsewhere [2].

In order to find thermal relationship between the back sidewall carbon and the corresponding steel shell during the baking stage, temperature was measured on steel shell on the locations shown in Figure 1 for the three studied cells. Based on these measurements, the obtained results for these cells are shown in Figure 10. The results show that the average back sidewall carbon temperature during the baking stage (T_{ASWCB}) is polynomial correlated with the average steel shell temperature (T_{ASSB}). Regression analysis indicates that the correlation for T_{ASWCB} with T_{ASSB} as shown in equation (1) and has a coefficient of determination, R^2, of 0.998.

$$T_{ASWCB} = 1E\text{-}05T_{ASSB}^4 - 0.002T_{ASSB}^3 + 0.11T_{ASSB}^2 - 0.25T_{ASSB} + 27.43 \quad (1)$$

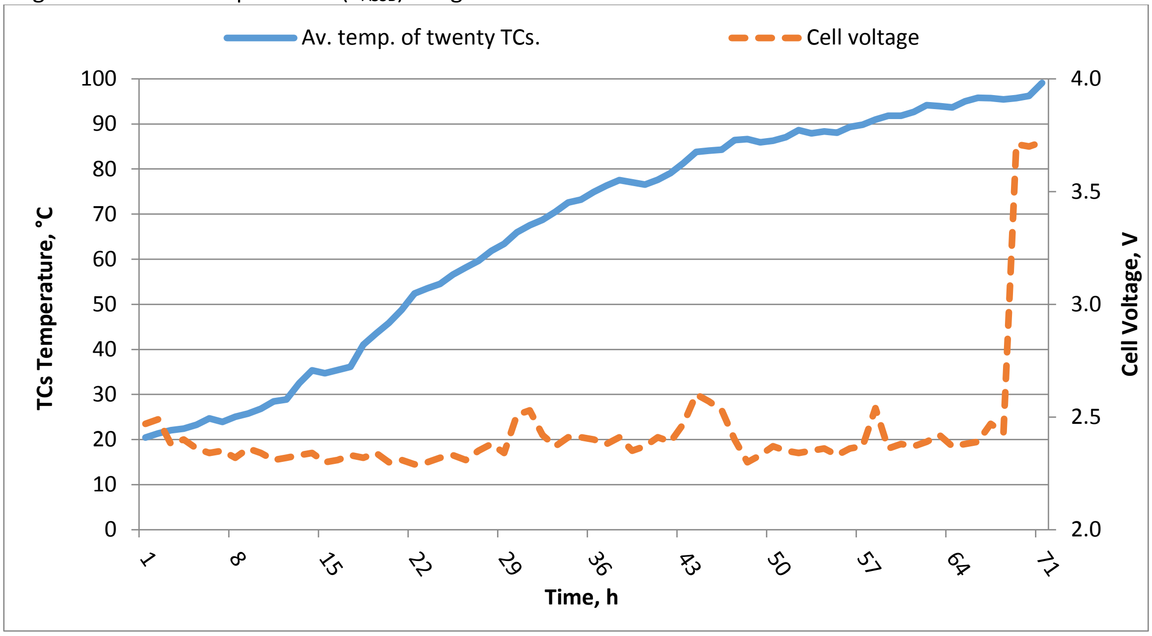


Figure 9 Relation between cell voltage and T_{ASWCB} with baking time for cell 617.

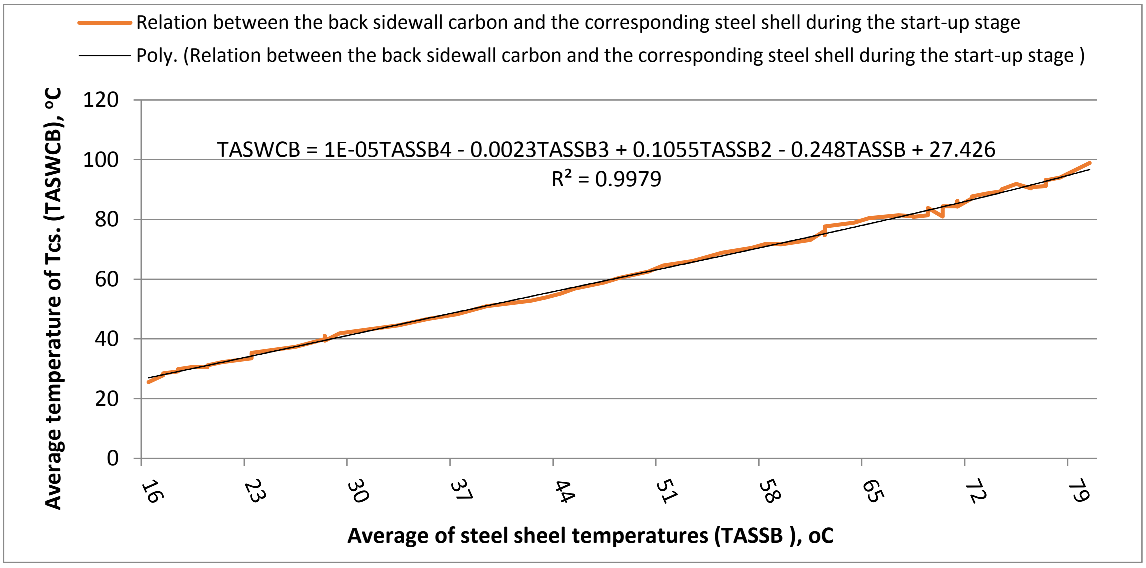


Figure 10 Relation between T_{ASSP} and T_{ASWCP} during the baking stage

Average temperature of the twenty thermocouples for cell 617 and the corresponding cell voltage during the start-up stage are shown in Figure 11. The recorded results show that the increase in the temperature of the sidewall carbon block is affected by small voltage changes during this period.

Also, thermal relationship between steel shell and back sidewall carbon during the start-up stage as illustrated in Figure 12. The average temperature of the twenty thermocouples during the start-up stage (T_{ASWCSS}) is polynomial correlated with the average steel shell temperature (T_{ASSSS}). Regression analysis indicates that the correlation for the T_{ASWCSS} with the T_{ASSSS} as shown in equation (2) has a coefficient of determination, R^2, of 0.997.

The higher coefficient R^2 mean a better goodness of fit for the result. The obtained relations can be used to evaluate the sidewall materials status during the baking and start-up stages, and assists the smelter workers to take a corrective action during these stages.

$$T_{ASWCSS} = -0.0075T_{ASSSS}^3 + 0.2165T_{ASSSS}^2 + 18.129T_{ASSSS} + 61.533 \quad (2)$$

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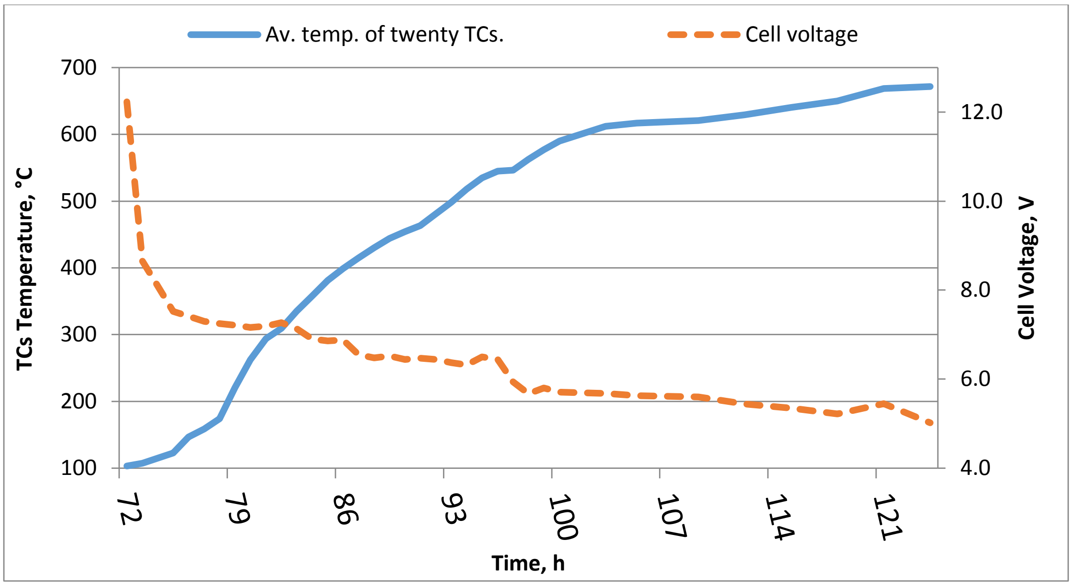

Figure 11 Relation between cell voltage and T_{ASWCEM} with time during the start-up stage of cell 617.

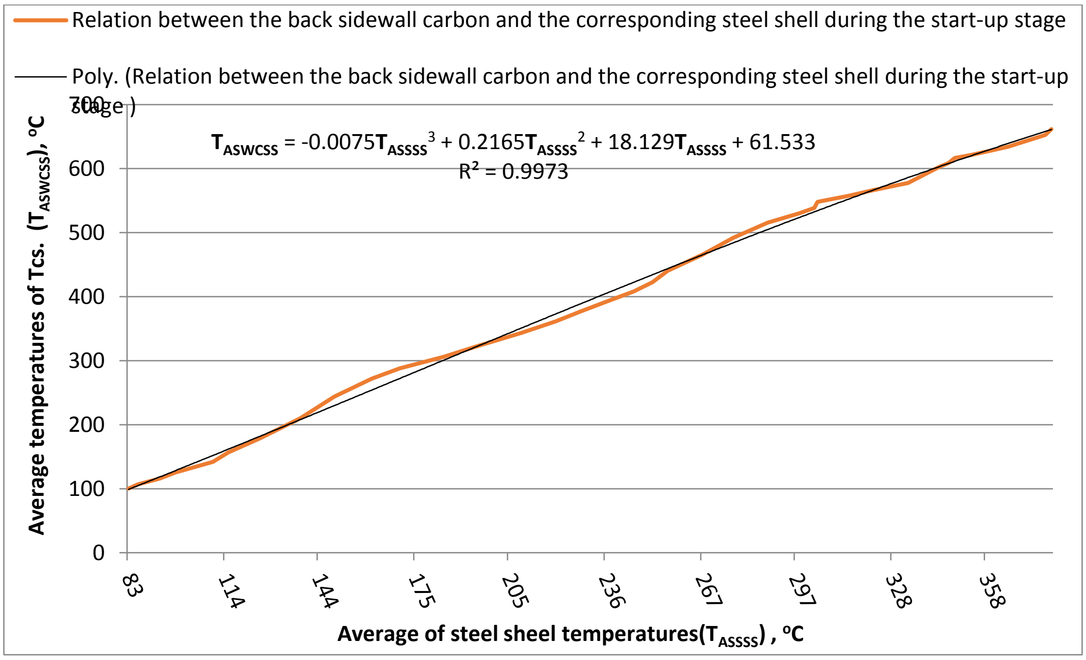

Figure 12 Relation between T_{ASSSS} and T_{ASWCSS} during the start-up stage.

Conclusions

Baking and start-up stages were investigated for three cells baked for three days. The following results can be concluded:

- Increase the baking time from two days to three days decreases the cell instability during the early operation period from 0.087 to 0.064 µΩ, respectively, and will be reflected on cell performance.
- The temperatures of cathode surface and RSD of cathode surface temperature distribution at end the baking stage were 858°C, 852°C, 846 °C, 3%, 2%, and 2%, respectively for these cells.
- The average RSD for the anodic current distribution during the baking stage was constant (10 %) for these cells.
- The heat-up rates obtained in the range between 2 and 12 °C/h will be positively reflected on potlife.
- The sidewall blocks temperatures increase from the range between 71 and 113°C at end the baking stage to the temperatures in the range between 558 and 737 °C after end the start-up stage.
- Increase the average heat-up rate in the longitudinal and transverse sides from about 1.02 °C/h during the baking stage to 10 °C/h at end the start-up stage.
- Difference behaviour of the sidewall carbon temperatures due to voltage changes during the baking, and start-up stages.
- The relations between sidewall blocks and steel shell of the cell can be useful in evaluating the sidewall blocks status during the baking and start-up stages, and assisting the smelter workers to take a corrective actions.

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Conflicts of interest

There are no conflicts to declare.

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