Real Anode Temperature Measuring - From Investigations to a New Standard

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Abstract

Production of aluminum by smelting process is a highly energy-intensive task. The baking quality of carbon anodes plays a significant role in efficiency of the whole process. Underbaking or overbaking of the anodes is ongoing with substantial losses and/or troubles in the electrolysis due to unstable process conditions. Consequently, a highly controlled baking process is a guarantee for stable and good anode properties as well for the most energy efficient and environmentally friendly operation. The perfect anode baking process is mainly driven by correctly adapted baking curve with the target to reach the specified final anode temperature, smoothly. Therefore, it is important to know the final anode temperature for fine-tuning the system and adjusting the baking process. Unfortunately, a constant measuring of this temperature is not possible owed by the furnace concept, the process as such and the kind of anode handling. Prove of the final anode temperature is occasionally done by the so called "Equivalent Temperature" method that is quite complex and time-intensive, although that method is only reflecting the finally reached temperature and no temperature profile can be detected over the long baking process. It is of highest interest for a baking furnace technology provider to have a real anode temperature method available in order to optimize running facilities with the output of maximized anode quality, homogeneity and operational effectiveness, as well as design verification purposes with required feedback for the constant further system development. This paper describes the thesis at the beginning of the development that establishes a measuring procedure to receive the real anode temperature, since based on the state of the art for real anode temperature measurements in anode baking furnaces, it is known that no meaningful measurement procedure is currently available. Therefore the most common measuring procedures in this industry were researched and analyzed based on their accuracy and informative values. The investigations result in a clearly specified measuring method that has been verified in the field, and became an in-house standard as part of baking furnace performance tests, meanwhile is widely used for process analysis and consequential process optimizations.

Keywords: anode baking furnace, real anode temperature, baking curve, anode quality, furnace design.

1. Introduction

Industrial extraction of aluminium from alumina is via Hall-Héroult process. This energy-intensive process, which is known as smelting process, takes place in a molten cryolite-based electrolyte in presence of carbon anodes. Those carbon anodes are separately baked in an Anode Baking Furnace (ABF) before they be embedded in the fused-salt electrolysis. The baking quality of those carbon anodes plays a significant role in the efficiency of the whole smelting process [1,2]. Any deficiency in the baking process such as underbaking or overbaking of the anodes, off-target heat up gradient, etc. can lead to consequences as increased anode consumption, unstable electrolysis process conditions or significantly higher energy consumption [1-3].

Therefore, baking high quality anodes homogeneously is a crucial step in the aluminium production industry. A highly controlled baking process is a guarantee for stable and suitable anode properties, as well as for the most energy efficient and environmental friendly operation. An optimized anode baking process is mainly driven by correctly adapting the baking curve with the target to reach the specified baking level, in such a manner to fulfill the specified heat up gradient criteria as well. Therefore, it is important to observe the anodes temperature during the process to fine-tune the system and adjust the baking process. This in turn requires implementation of a proper real anode temperature measurement standard method.

This paper is focused on the open top ring pit Anode Baking Furnaces as the widely-used ABF technology. In an open top ABF, green anodes locate inside the pits surrounded by two hollowed cavities called Flue Wall (FW), schematically shown in Figure 1 [1]. The flue gasses flowing through the FWs are guided by the Baffles and Tie Bricks, and exchange their heat with refractories, packing cokes and anodes. In ring pit furnaces, the loaded anodes remain stationary during the baking process, and all the firing equipment move around the furnace, shifting section-by-section by connecting into the provided peepholes.

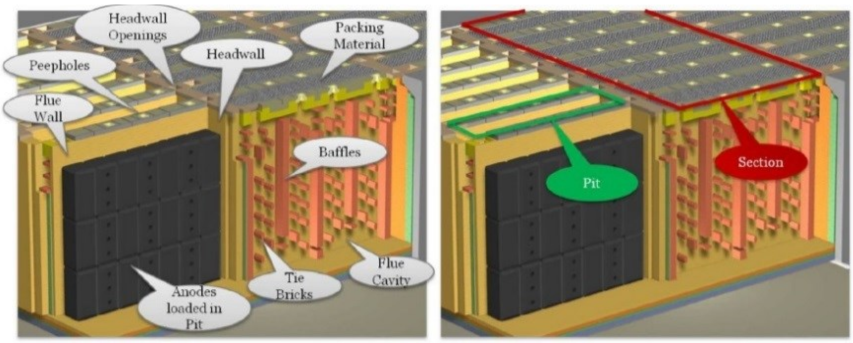

Figure 1. Schematic view and technical terms of an ABF

Considering a single pit, different anodes can experience different heat treatments during the process. The anodes close to the top and bottom of a pit are exposed to higher heat dissipations. Furthermore, different local heat distribution and flow pattern inside surrounding FWs as well as existence of occasional hot spots around burner flames and pitch burn area lead to different special heat treatment of anodes in a pit [1,2].

Due to the overall furnace concept, the baking process and the kind of anode handling, a continuous surveying of the baking level is not possible unfortunately. There are different methods as a proof to assure that the final target anode temperature is reached [1,2,4,5]. The most common method for that purpose is called "Equivalent Temperature" method in which the baking level is determined by analyzing crystalline structure characteristics of baked anodes [4,5].

As it is illustrated in Figure 2, the crystallite size of petroleum cokes, Lc, and anodes are related to their maximum reached temperature. In order to determine such relation a pre-calibration is required to link the crystallite size, Lc, with the baking level [2,4,5]. Therefore, initially small samples of petroleum coke are baked in laboratory up to 1500 °C. Concurrently, authentic samples are taken out from the baked carbon anodes with a drilling machine, small enough to keep the anodes intact for later use in the smelter [2,4].

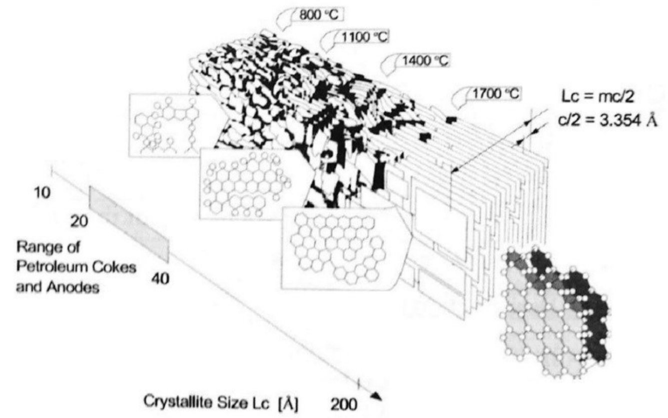

Figure 2. Crystallographic structure of cokes and anodes at different temperatures [2]

Comparing the crystallite size Lc of the reference and authentic samples, the anode baking level will be obtained. However, experience has shown that the true temperature can be up to 150 °C lower than the equivalent temperature determined with this method [1,2]. Furthermore, as other common indirect methods, it requires sampling and laboratory analysis, which are complex and time intensive. Besides, this method only reflects the maximum ever reached temperature, while no detailed information will be provided regarding the temperature profile and the heat up gradient. Those limitations have been the main motivations to establish an in-house standard for real anode temperature measurement for the process optimization as well as executing performance tests.

This paper proposes a developed standard method for anode temperature measurement which not only records the anodes baking level, but also measures the real temperature profiles during the entire process. Having such pieces of information is of great interest to a baking furnace technology provider to optimize the running facilities in terms of maximizing anode quality, homogeneity and operational effectiveness. Furthermore, the introduced procedure can be used as a standard method for performance tests and design verification as well as further development purposes.

In the course of this paper which is based on a university thesis work [1], first the feasibility, considerations, and the procedure of the proposed method will be described. Later on, the results of a performed measurement will be presented and discussed, and finally the established standard method will be compared with other available methods, and corresponding conclusions will be made. The investigations will provide a clearly specified measuring method that is verified and became an in-house standard as part of baking furnace performance tests procedure and which also provides valuable information for process optimization purposes.

2. Methodology

The feasibility of the proposed method is describable based on the heat transfer scenario in the pit, and thermal properties of packing coke and anodes, as the preliminary considerations.

The heat exchange between the combustion gasses and FW surfaces takes place via convection and radiation, and then distributes through the pit via conductive heat transfer [6]. Considering this heat transfer scenario which is schematically shown in Figure 3, the anodes heat up from the sides and their center can be seen as the critical point in terms of reaching the target baking-level [1,7,8]. Therefore, the measuring method shall be able to detect the anodes core temperature. For this purpose, the thermocouples will be placed on the anodes center line, inside the available tiny gaps in their between while assuring to be in contact with the anodes.

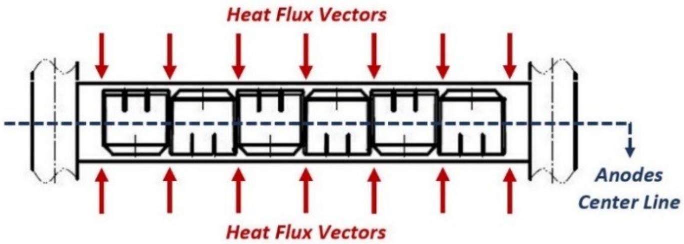

Figure 3. Heat flux vectors from flue walls towards anodes

With proper fixation of thermocouples onto the anodes, this approach not only avoids any anodes destruction, but also is able to detect the anodes temperature, accurately. The feasibility of such a procedure can be described mainly based on the thermal properties of packing coke and anodes.

Thermal diffusivity $\alpha = \frac{k}{\rho.cp}$ that is interpretable as the speed of heat transfer and temperature spread through a material, is a decisive parameter for validity of the proposed measurement method [6]. Table 1 presents the thermal properties of anode and coke as a function of temperature. Based on those values which are obtained from a laboratory analysis of the reference furnace in which the real anode measurements are performed, the ratio between thermal diffusivity of anode and coke is calculated and shown in Figure 4.

Table 11. Thermal properties of anode and packing coke

T [°C]	**Anode** (ρ=1560 kg/m³)		**Coke** (ρ=934 kg/m³)	
	k [W/m.K]	**cp [J/kg.K]**	**k [W/m.K]**	**cp [J/kg.K]**
20	3.50	800	0.40	410
200	4.40	1160	0.50	520
600	5.37	1700	0.76	810
1100	6.50	1900	1.21	1250

Figure 4 reveals that heat propagation in anodes is about 2 times faster than in the packing coke filling the tiny gaps in their between ($\alpha\_Ratio > 2$). Therefore, in our application the right measuring points to assure appropriate heat treatment of anodes should be chosen on the sides of the anodes over their center line while being properly in contact with the anodes surfaces. It can be shown that the interfacial contact temperature between the anode and coke is a strong function of the anode temperature [1,6]. Mathematically, this is describable by writing the energy equations on a control volume around the mediums interface, leading to equation (1).

$$T_s = \frac{(k.\rho.cp)_A^{0.5} T_A + (k.\rho.cp)_C^{0.5} T_C}{(k.\rho.cp)_A^{0.5} + (k.\rho.cp)_C^{0.5}} \tag{1}$$

Where k, ρ and cp respectively represent the thermal conductivity, the density and the specific heat capacity of each medium [1,6]. In equation (1), the quantity $(k.\rho.cp)^{0.5}$ is a weighting factor (w) that determines whether T_S will more closely approach T_A or T_C as the temperatures of anode and coke, respectively [1]. According to Figure 4, it can be observed that this factor is more than 3.5 times higher in the anodes than in the packing coke materials.

Another important consideration refers to the lateral gap size between anodes. Based on arrangement of anodes in the pit, the lateral gaps are much smaller than the anodes height and width, which resembles the heat transfer between plane walls. In this case, the analytical solution reveals that the temperature distribution delay in the gaps is related to the Fourier number $Fo = (k.t)/(\rho.cp.L^2)$ in the coke, which itself depends on the coke layer width [6]. Considering the physical and thermal properties of the layers, in conjunction with the heat-up gradient in the pit, the maximum temperature deviation in the lateral gaps is calculated and shown in Figure 5.

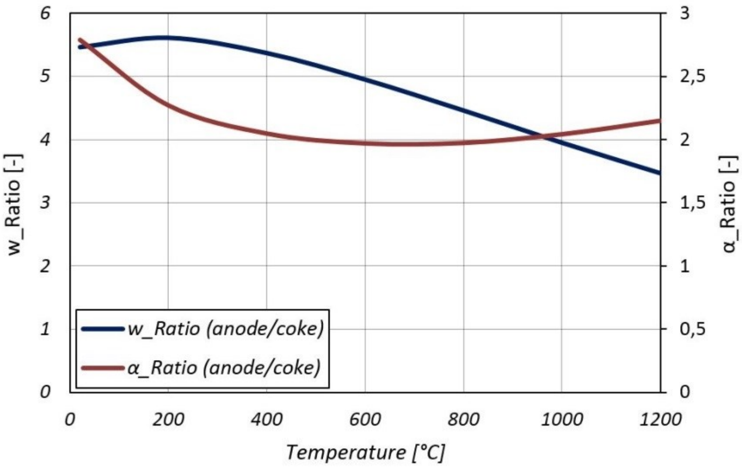

Figure 4. Comparison of thermal diffusivity α, and weighting factor w of anode and coke.

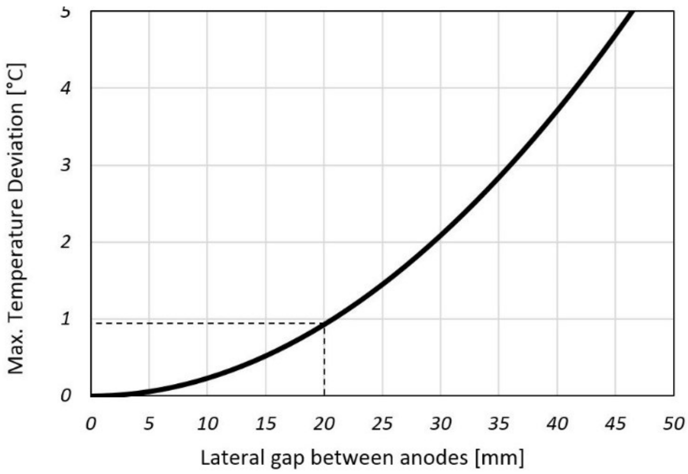

Figure 5. Maximum temperature deviation as a function of gap size between anodes.

Figure 5 reveals that the lower the gap size we have between the anodes, the lower temperature deviation we get. In the established measuring procedure, the lateral gap sizes will not exceed 20 mm which leads to less than 1 °C deviation, which is quite negligible.

As for the measuring procedure, it is recommended to consider two sections and at least one pit per section in such a way to guarantee that the test will have the necessary representativeness and reproducibility. Multiple thermocouples will be arranged at different locations per pit to get the overall temperature distribution. It is well-known from various empirical and numerical researches that there is inhomogeneity in heat treatment and the baking quality of different anodes per pit [1,2,7-10]. That is mainly because of higher heat dissipation from the pit bottom and top, flow pattern and temperature distribution inhomogeneity inside the flue walls, process discontinuities caused by crossover, hot spots around the burners, burners' capacity and pulsation rate, fire advance scheme and heat storage in refractories [1,2,7-10]. Therefore, proper arrangement of thermocouples is essential to extract sufficient data to evaluate anodes baking quality and investigate proper modifications to fine-tune the process. Figure 6, illustrates thermocouples arrangement in the reference furnace of this study.

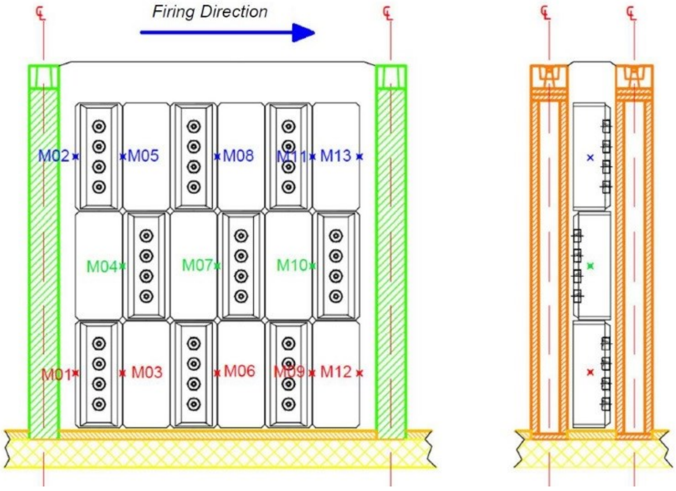

Figure 6. Thermocouples arrangement in the pit

Proper type of thermocouples should be employed so that to withstand the pit's physical and chemical conditions. They will be placed in the determined measuring points through protection pipes. The gas-tight protection pipes are principally responsible to enhance the thermocouples endurance versus the exposed harsh reducing and oxidizing environment, as well as protecting them against physical damages during loading process [1,11].

In order to precisely guide the thermocouples into the already defined measuring points, according to the established in-house standard, the overall length of the required protection pipes L_{pp} should be determined based on equation 2 [1]:

$$L_{pp} = h_{jut} + h_{top} + 0.5\,.\,h_{Anode} + \left(N_{layer} - 1\right).\left(h_{Anode} + h_{mid}\right) \qquad (2)$$

Where h_{jut} stands for the portion of the protection pipe jutting out from the pit, h_{top} is the height of the cokes top layer, h_{Anode} is the anodes height, h_{mid} is the thickness of the packing material between anode layers, and N_{layer} is the layer number of the target anode (counting from top).

The measurement setup has to be already prepared, and then thoroughly implemented during loading process. The protection pipes are made of multiple parts, and each part will be fixed in position, after loading each anode layer subsequently. Following the safety measures to complete the loading process and filling the pit with the packing coke, the thermocouples will be inserted into the corresponding pipes, as shown in Figure 7 [1].

Figure 7. Procedure of imbedding thermocouples and protection pipes [1]

After the loading process, the thermocouples will be connected via proper compensation cables into data-loggers which record the thermocouples' measured values. To protect the compensation cables against heat, they will be guided over a constructed cable bridge in such a manner to avoid any interruption in normal operation of the firing equipment. The data archiving encompasses the whole process and provides detailed information recorded in every second minute.

To evaluate the error range of the measured temperatures, the accuracy of the instruments, and the deviations rooted from the established procedure should both be taken into the account, simultaneously. Figure 8, depicts the error range analysis of the utilized thermocouples provided by their supplier. According to the range of temperatures in our application, thermocouples error will be within 0.3% of the recorded values resulting in ±4 °C deviation [1]. It should also be noted that the response time caused by of the type of the thermocouples and protection pipes' material and thickness are absolutely negligible compared to the process-related temporal variations.

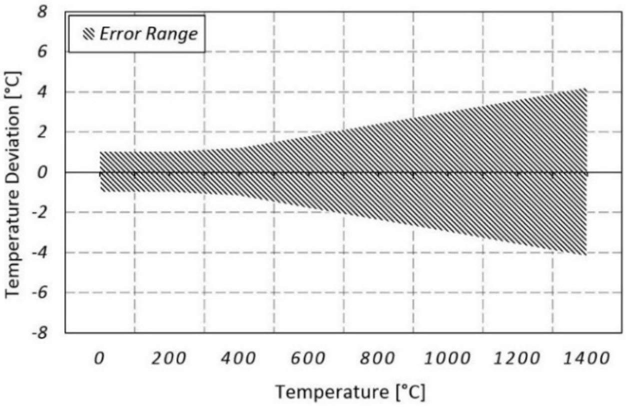

Figure 8. Error range of the thermocouples

In addition to the equipment-based errors, the deviation of the recorded values due to the established procedure are less than 1°C, as already discussed and depicted in Figure 5. Therefore, the maximum total error of the presented anode measuring standard method is less than ±5°C which is considerably lower than the other available methods [1,2,4].

3. Results and Discussion

In this section, the results of the performed measurement in a reference furnace with 3 preheating, 3 firing and 6 cooling sections with the fire advance cycle of 24 hours are presented and discussed. As explained in section 2, the measurements are performed in two different pits, each with 13 imbedded thermocouples. The recorded values provide precious information about the furnace operation including temperature distribution in the pit, anodes baking-level, heat-up gradient and possibilities for process optimization from different perspectives, as discussed in the followings.

To shed light upon the matter, the obtained results from three representative thermocouples located at the left (TC5), center (TC7) and right (TC11) side of a pit are shown in Figure 9. The Thermocouple TC5, TC7 and TC11, are respectively located in measuring points M05, M07 and M11 as depicted in Figure 6.

Considering Figure 9, it can be observed that the lowest recorded temperature in the preheating sections belongs to TC11 and the highest values are measured by TC5. This refers to the heat distribution in those surrounding FWs. The hot combustion gasses coming out from the firing zone flow through the preheating sections, and lose their temperature as they get closer to the end of the section. This leads to lower heat transfer rate into the end of the pit at the preheating sections where TC11 is located, and higher rate around TC5. On the other hand, in the cooling zone the flow temperature is lower at the beginning of each FW, and having comparable heat transfer coefficients, the highest heat dissipation occurs where the temperature different between the flow and refractories is higher. A pronounced illustration of this effect can be seen in the sudden temperature drop measured by TC5 at the beginning of the 7th day when the refractories are still hot and expose to the cooling flow at the beginning of the section.

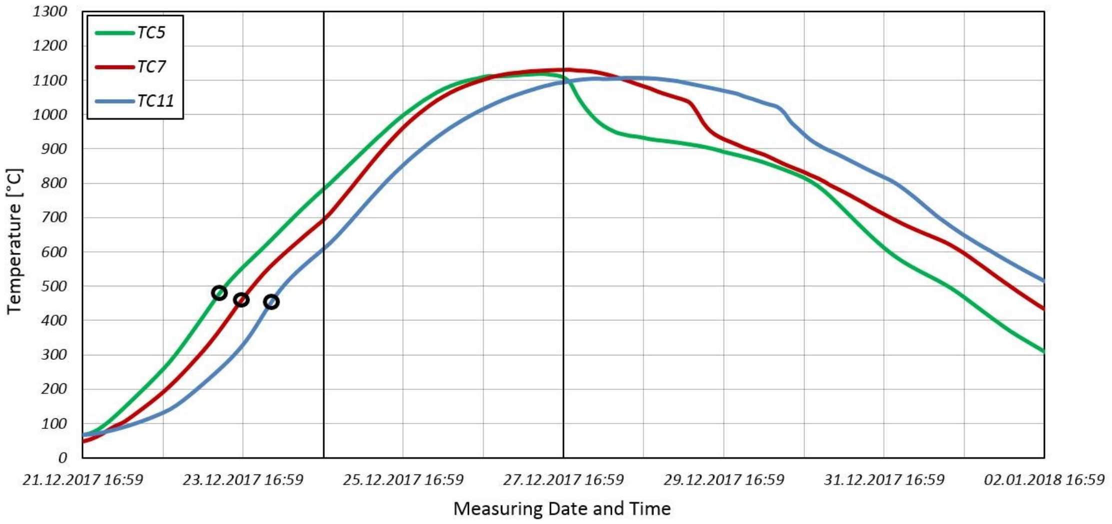

Figure 9. Measured real anode temperatures for TC5, TC7 and TC11

The pitch burn is another important factor in preheating zone which locally increases the flue temperature and the local heat transfer rate, subsequently [1]. As it is observable in Figure 9, the anodes experience their highest heat-up gradient around the second and third preheating sections, which stems from combustion of their released volatiles, known as the pitch burn [12]. Those maximum values for TC5, TC7 and TC11 which are marked with a black circle in Figure 9, are respectively equal to 13.9, 13.6 and 15.0°C/h. Those maximum heat-up gradients, and the right timing of the pitch burn are among important process parameters in terms of baked anodes quality and fuel consumption.

In the firing zone, the heat-up rate is lower for TC5 and TC11 compared to TC7, as they are exposed to higher heat dissipations caused by heat storage into the headwall refractories, and losses from the furnace top. The final baking-level measured by TC5, TC7 and TC11 are respectively reached at the middle-end of 6th day, beginning of 7th day and the end of 7th day, as shown in Figure 9. It is essential to note that the anodes heat-up continues even in the cooling zone. The heat transfer delay between the flue gas and anodes is due to heat storage in refractories and utilized packing cokes, and can be up-to around one day, depending on furnace parameters.
Another important measured value is the achieved baking-level of the anodes with respect to their loading position inside the pit, as represented in Table 2. As it can be observed, the final temperature of all the anodes in this reference furnace have reached the target value of 1100 °C. In the center anode this value even hits 1131 °C. As explained before, due to the less heat dissipations, the baking-levels in the middle anode layer are higher than those at the top and bottom layers. Moreover, considering the differences in the horizontal direction, the achieved temperatures at the left and center of the pit which are more influenced by the back burners operation are in the same range, while higher than the ones at the right side of the pit [10]. This behavior can also be detected from the representative baking curves plotted in Figure 9.

Table 12. Anodes baking-level distribution in the pit.

TCs Position		*Position in Pit*			*Color Range*
		Left	*Center*	*Right*	> 1125
Anode Layer	*Top*	1121	1119	1111	1120-1125
	Middle	1127	1131	1114	1115-1120
	Bottom	1117	1118	1110	1110-1115

As described in section 1, in addition to evaluating the performance parameters such as anodes baking-level and heat-up gradients, the proposed standard method provides vital information for fine-tuning the whole process. For instance, the measured baking-level distribution represented in Table 2, together with the timings of reaching the target values which are detectable in Figure 9, imply the necessity of adjusting the burners capacities per firing section. To this extent, it is strongly recommended to adjust the ratio between back burner and front burner by reducing back burner and increasing front burner capacities respectively. [1,10]. Furthermore, the target flue temperature of the firing system can also be fine-tuned which in case of the reference furnace is recognized to be 1165 °C [1]. Such modifications are of great importance as they not only will enhance the homogeneity and quality of the baked anodes, but also lower down the overall fuel consumption, reduce furnace emissions, minimize hot spots over refractory bricks and prolong the refractories lifetime.

4. Conclusion and Outlooks

This paper has proposed a verified standard method for real anode temperature measurement, which has been accepted and used as part of the performance test of anode baking furnaces, as well as being widely used for process analysis and optimization purposes.

The established standard method not only is capable to accurately measure the anodes baking-level, but despite other available methods does also provide detailed information about anodes temperature history during the entire process. Those pieces of information are of great importance to an anode baking furnace technology provider to optimize the running facilities in terms of maximizing anodes quality, homogeneity and operational effectiveness.

The feasibility and error analysis of the proposed standard method have been investigated based on the heat transfer considerations, laboratory-based thermal properties of packing coke and anodes, as well as employed instruments error range. The performed investigations have shown that the maximum overall temperature measuring deviation via this method is within the range of ±5 °C which is quite negligible compared to the other methods and that is equivalent of less than 1% accuracy of the real final anode temperature.

The results of an executed measurement were presented and discussed in section 3. Based on the measured values of multiple thermocouples embedded in the pit, detailed information about temperature distribution, achieved anodes baking-level homogeneity, location of pitch burn, anodes heat-up gradient and heat transfer delay due to heat storage effect in different layers were obtained, and subsequent conclusions were made. In addition to evaluating the performance parameters, the investigations revealed the necessity of adjusting some process parameters such as the ratio of front and back burner capacities and target flue temperature of firing system.

The process optimization measures are of great importance as they not only will enhance the homogeneity and quality of the baked anodes, but also lower down the overall fuel consumption, reduce furnace emissions, minimize hot spots over refractories thus prolonging their lifetime, and reduce maintenance related costs. Considering the heavy-duty nature of the anode baking furnaces, it is strongly recommended to perform the standard real anode temperature measuring in regular intervals, respectively after process and/or green anode recipe adaptation in order to sustain the optimum performance of the furnace.

To conclude, the proposed standard method for real anode temperature measuring is more accurate than other available methods and provide precious detailed information regarding the entire process which are crucial to fine-tune and optimize the process parameters. The developed method has been verified and became an in-house standard which is in-use both, as part of performance tests and process optimization purposes. Furthermore, in addition to open top anode baking furnaces, all those verified advantages have been a motive to develop a new standard method for real electrode temperature measuring in closed type furnaces, as an outlook for future researches.

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