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MEETING THE CHALLENGE OF INCREASING ANODE BAKING FURNACE PRODUCTIVITY

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Abstract

The need to support amperage creep in smelters requires an increase in anode baking furnace productivity. The furnace operation must be adapted to provide more anodes while maintaining adequate baking performance, minimizing energy consumption and assuring anode quality. To do so, the essential factors to optimize include the firing strategy to ensure the adequate baking level for a given fire cycle, fuel combustion efficiency and adequate cooling capability even at accelerated fire cycles and high ambient temperatures. Through the operation of 28 baking furnaces of differing technologies, tools have been developed to support this process. Simulations of firing and baking as a function of the fire cycle and key furnace design parameters such as anode size, pit width and flue design; injector combustion efficiency and cooling capability are now routinely used. Industrial examples are shown from a number of sites with varying baking technology that demonstrate the gains achieved.

Introduction

Rio Tinto Alcan and its joint venture partners operate 28 anode baking furnaces of varying technologies and firing systems throughout the world producing more than 15 different anode formats. The continual increase of reduction line amperage requires increased anode mass and/or increased anode production to support the corresponding anode change cycles. This in turn requires increases in baked anode productivity (unit mass and production). Therefore anode baking furnace design and process criteria need to be optimized to ensure correct anode baking levels, baking homogeneity, optimum combustion and effective cooling. A variety of simulation tools have been developed by Rio Tinto Alcan to ensure that optimal solutions are selected to deliver the highest value in terms of investment and operating cost. These tools have been progressively enhanced during the course of their application at different operating sites with effective results. This paper describes these tools and gives examples of their utilization.

Heat transfer study

A number of different situations can lead to the need to perform a heat transfer study. Examples of challenges that can arise are listed as follows:

- What is the fastest baking cycle at which the furnace can operate? Can the production be increased further and in what conditions?
- Anode height increases are required to support reduction line amperage increases and it is necessary to enlarge the furnace pits: Can the modified furnace continue to operate with the same baking cycle as at present? Will one additional heating ramp be necessary? Will it always be possible to bake and cool different anode formats sufficiently? Would it be possible to reduce the concrete casing insulation thickness?
- As part of slowing down furnace baking cycle time what would be the adequate baking curve to maintain an anode baking level equivalent to the standard target one?
- As part of design of a new furnace, which furnace dimensions should be chosen to satisfy the customer's production requirements at minimum cost and guarantee a reliable process, bearing in mind that pit width is fixed by the size of the largest anodes and that this furnace must be able to bake different anode formats?

Thermal models have been developed to help solve these problems. These models guide customers in their choices and propose solutions to satisfy their requirements. They are applicable for all open furnace and heating equipment technologies.

Model theoretical equations

The model theoretical equations are general thermal equations:

- The equation governing thermal conduction in materials (Laplace equation):

$$\rho(T).C_p(T).\frac{\partial T}{\partial t} = \lambda.\vec{\nabla}^2 T + \left(\frac{\partial \lambda}{\partial T}\right)\left(\vec{\nabla} T\right)^2 \quad (1)$$

  Where:
    - $\rho(T)$: material density (kg/m^3)
    - $C_p(T)$: material heat capacity at constant pressure (J/kg.K)
    - T : temperature (K)
    - t : time (s)
    - λ : material thermal conductivity (W/m.K)

- The equation governing heat exchanges by convection (Newton's law) the origin of which is motion of a fluid in contact with a solid wall:

$$\varphi = h.(Tf - Ts) \quad (2)$$

  Where:
    - φ : heat flow (W/m^2)
    - h : exchange coefficient by natural and/or forced convection (W/m^2.K)
    - Tf : fluid temperature (K)
    - Ts : solid temperature (K)

- The equations governing heat exchange by radiation based on the black body radiation equation (Stefan Boltzmann law):

$$\varphi = \sigma.(T)^4 \tag{3}$$

Where:

- φ : heat flow (W/m^2)
- σ : Stefan Boltzmann's constant (=5.67.10^{-8} W/m^2.K^4)
- T : body temperature

Figure 1 shows an example of the heat transfer from fumes flowing through the flue walls to the anodes.

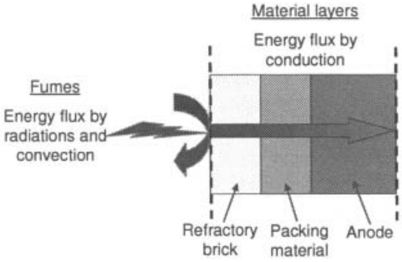

Figure 1: Schematic of heat transfer from fume through to anode during heating

Furnace design: pit enlargement case study

The following is an example relating to increasing anode size at Aluminium Dunkerque. The feasibility of increasing pit width by reducing the bake furnace concrete casing insulation thickness was studied. The main issue was whether or not furnace insulation would need to be replaced. Insulation samples were taken and sent for analysis to measure the thermal characteristics of the worn material. The resulting values along with the material thickness and a defined gas temperature curve were then used in a thermal model to ensure that relatively low temperatures were maintained at the interface between the insulation and civil works to avoid concrete deterioration.

Figure 2 shows the good agreement between the measurements taken at the insulation/concrete interface and the results of the model. It was then possible to reduce insulation thickness in the model to assess the potential savings in terms of pit width, and thus prove the feasibility of increasing furnace capacity without reconstructing the concrete casing or fully restoring the insulation. The design change has been incorporated into the upcoming major furnace rebuild. This has provided the potential for Aluminium Dunkerque to increase the baked anode production by 4.2%.

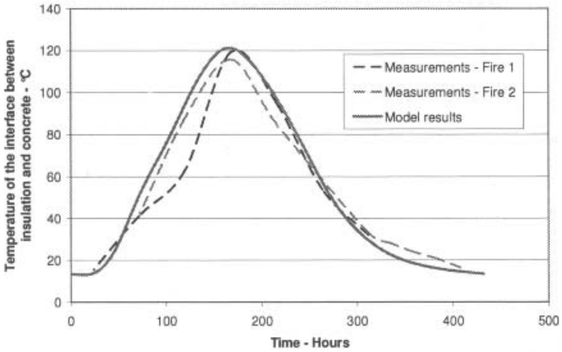

Figure 2: Insulation - civil works interface temperature simulation

Increase of production needs through firing cycle optimization

The following study was completed for Sohar Aluminium when the baking cycle was accelerated from 26 hours to 24 hours. The 24 hour cycle operation was studied by modelling to confirm and optimize the process and operating parameters. As the Sohar furnace has a relatively high cooling capacity, the only point to be checked was whether the furnace can effectively maintain an adequate anode baking level with at a 24h cycle.

Knowledge of process characteristics at a 26 hour fire cycle allows the simulation of the 24 hour case. The capacity to burn pitch volatile matter was also considered in the study. Model inputs included flue wall, pit and anode dimensions and a gas temperature curve based on the process target temperature curves. The model then calculated the resulting anode temperature. Figure 3 shows the baking simulation results at 26 and 24 hour cycles for the same furnace. Final anode temperature corresponds to the temperatures measured on the site.

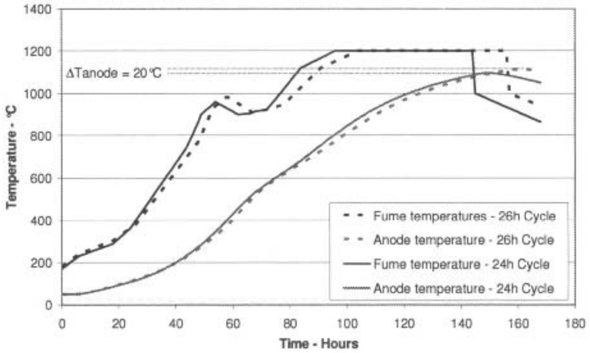

Figure 3: Simulation of anode baking in the Sohar furnace for 24h and 26h cycles

For a peak firing temperature of 1200°C, final anode temperature dropped by 20°C when the cycle was accelerated. To increase final anode temperature by 20°C with at a 24h cycle, either the peak firing temperature can be increased, or an additional heating ramp can be added to prolong peak firing, provided that exhaust capacity is sufficient.

Table 1 shows the results of different simulations. In order to maintain an adequate baking level, the peak firing temperature needed to be increased from 1200°C to 1225°C, or the peak firing time needed to be extended by 8 hours at 1200°C with an additional heating ramp. The extended fire solution was used as it exerts less stress on the refractory materials and ensures greater flexibility for the process.

Cycle	Peak fire time	Peak fire temperature	Final anode temperature
26h	52h	1200°C	1115°C
24h	48h	1200°C	1096°C
24h	48h	1225°C	1115°C
24h	56h	1200°C	1115°C

Table I: Final anode temperature simulation results

The simulations determined the parameters required to ensure optimized operation at a 24 hour cycle and the solution has since been implemented [1].

Impact of reducing fluewall brick thickness

In another case study the impact of fluewall brick thickness on anode temperature was investigated for Tomago Aluminium Company. Reduction of the fluewall brick thickness by 10 mm was considered to allow final baking temperature to be achieved at faster fire cycles. The furnace was limited in achieving the peak fire temperature at the required soaking time. The site did not have the space to add a 4th burner ramp. The resulting increased pit width also allowed for potential future increases in anode size within the existing furnace footprint. There was also an added benefit of reducing energy consumption. Modeling was used to calculate an optimal heating curve to enable an equivalent final anode temperature to be reached during the baking cycle,

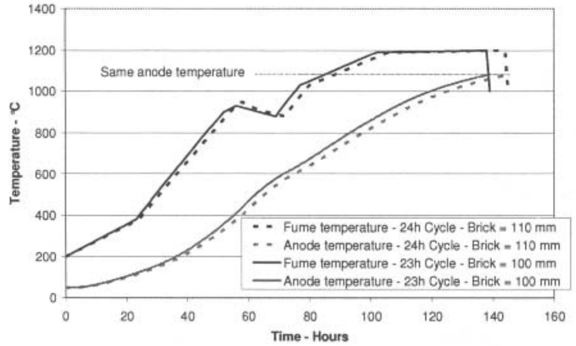

Figure 4: Calculated temperatures for reduced fluewall brick thickness.

Such a solution would allow for a production increase of around 4%. However these gains would need to be weighed up against the potential risk of reduced refractory life due to the narrower bricks.

Cooling Optimization

Increased furnace production is possible either by accelerating the baking cycle and/or increasing anode mass per pit for an equivalent baking cycle. The capacity of the furnace to cool the anodes adequately before unloading must also be determined. To assist in determining the cooling behavior for a given furnace an anode cooling model was developed.

Alma works requested a study on the anode cooling phase to enable the acceleration of the baking cycle from 27h to 26h, which had led to an increase in anode unloading temperature of between 20°C to 40°C.

Initially, the cooling model was validated by comparing the simulation and site measurements results in the initial cooling configuration. Figure 5 shows the correlation between the model results and the measurements. The anode cooling zone covers the upstream furnace sections from the heating ramps to the anode unloading zone.

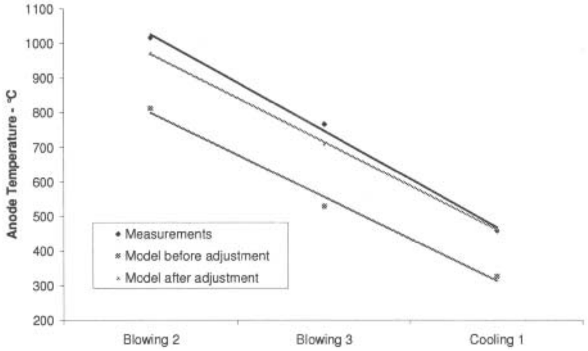

Figure 5: Cooling model anode temperature validation

The simulation and field measurements show good agreement. The model was then used to investigate improved cooling configurations to deliver the best outcome for the client. Parameters such as ramp position, peephole opening/closing configuration, peephole dimension, ramp blowing power and flue wall brick thickness were studied. This in turn allowed a pre-selection of the most promising cases, thus considerably limiting the tests to be conducted on the site.

An example of the Alma furnace cooling simulation is shown in Figure 6. It shows the calculated anode temperature profiles through the different zones for the initial case of a 27 hour fire cycle.

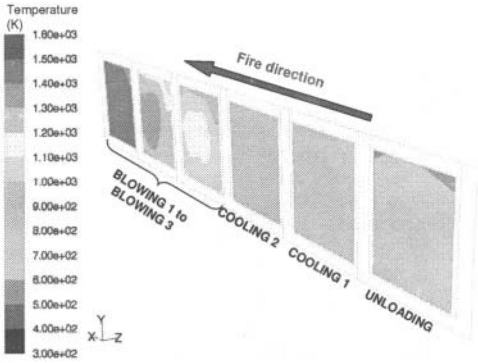

Figure 6: Simulated anode temperature for the initial case

Table II shows the results of different simulations at other fire cycles and cooling configurations on anode unloading temperature. The simulation suggested that a 30% increase of the blower flow would reduce anode unloading temperature by 30°C without impacting downstream process control. This solution was tested on site and validated by site measurements confirming an anode unloading temperature reduction of 25°C. As a result Alma was able to increase production of its furnace by 4%.

Cycle	Cooling configuration	Calculated anode unloading temperature
27h	Initial	390°C
26h	Initial	420°C
26h	30% increase of blowing flow	390°C

Table II: Cooling simulation results summary

In another case study for Tomago Aluminium Company, the cooling efficiency of one of the baking furnaces was studied to determine if sustained operation at very short fire cycles could be achieved. Of particular interest was the impact of different ambient air temperatures (summer versus winter) on cooling efficiency. Modelling was used to develop optimum cooling configurations including ramp and peephole positions. A number of the modelled cooling configurations were trialled while operating on a 21 hour fire cycle. Configurations included 1 or 2 cooling ramps and different numbers of cooling and unloading sections. Measurements conducted during the trials were used to further develop and validate the cooling model.

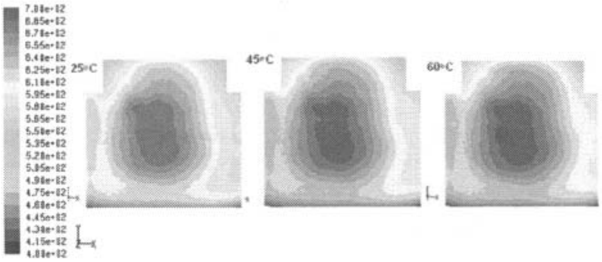

Figure 7: Anode temperature at varying ambient air temperatures.

The modelling indicated that increase in anode temperature would have a corresponding increase in packing coke temperature. The maximum manageable packing coke temperature for the bake furnace crane would be exceeded during summer conditions. Therefore, with the current cooling ramp capability sustained operation of the furnace at 21 hour fire cycle is not feasible during summer conditions, Figure 7.

Additional modeling was performed to investigate options for improving cooling efficiency, these included additional cooling ramps and increasing cooling flow. The results suggested that sustained operation at short fire cycles would be possible if the blowing and cooling systems were upgraded.

Fluid flow and combustion studies

Internal flow characteristics of the furnace flue walls are important parameters to take into account as they have a significant impact on baking homogeneity and combustion quality. Pressure drop is also critical as there needs to be sufficient suction in the flue wall lines to ensure proper transfer of volatile matter. However, it must not be too high to cause unwanted air infiltration into the furnace.

Models have been developed to ensure proper understanding of the related phenomena and resulting furnace optimization. These models allow definition of flue wall designs with optimized flows and gas injector performance. They are applicable for all open furnace and heating equipment technologies.

Flue wall design: Optimization of homogeneity and pressure drop

The model that used was described in a previous study [2]. Figure 8 shows a comparison of initial and optimized flow characteristics for the Saint-Jean-de-Maurienne furnace fluewall.

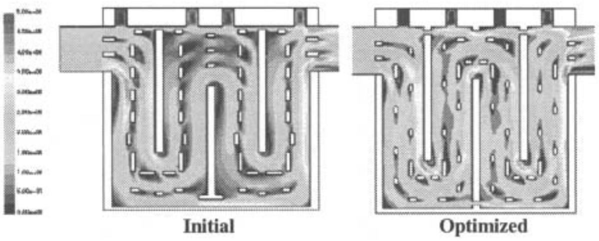

Figure 8: Velocity field flow simulation

After optimization, velocities were homogenized in the flue wall by the addition of tie-bricks which also enhanced mechanical strength. Flow is globally better distributed in the fluewall zones and fewer dead spots remain. Normally addition of the extra tie-bricks would have led to a 30% increase in pressure drop but optimization of the position of these bricks made it possible to maintain an equivalent pressure drop to that of the original design. Enhanced flow in this flue wall has improved heating homogeneity and combustion, thus increasing process flexibility.

Combustion: optimization of injector design

An example from a study conducted for the Aluchemie site is shown in Figure 9. Simulations of the initial and optimized cases of continuous natural gas injection show the volumetric concentration of methane in air, which is the image of the mixture between methane and air.

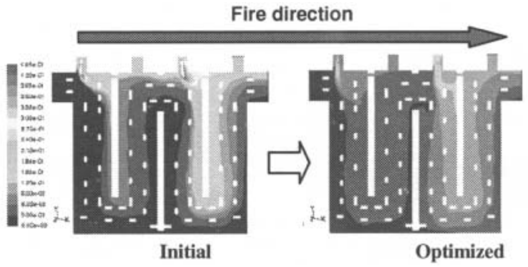

Figure 9: Gas injection simulations

The initial case shows a poor gas / air mixture resulting in large areas of poor combustion at the top of the flue wall. The gas is not burnt in optimum manner and homogeneous heating of the flue wall is not achieved. In reality this results in the formation of incomplete combustion products and excessive energy consumption. The optimized injector design markedly improved the air / gas mixture; the methane is better dispersed in the injection zone and no poor combustion zones are present.

These simulations were followed by tests of the injector on site. Figure 10 shows a pit profile of anode crystalline length (L_c) in nm of the original and optimized injectors.

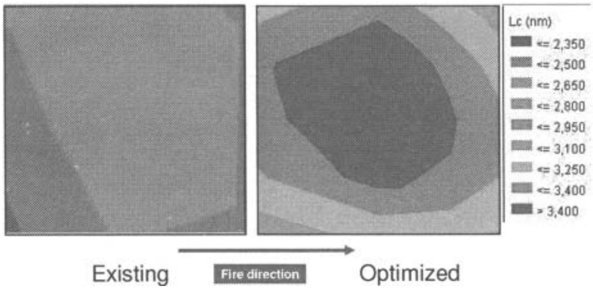

Figure 10: Results of optimized burners at Aluchemie

For equivalent natural gas consumption levels the mean baking level increased from 2.54 nm to 3.27 nm. The site has implemented the optimized injectors on all furnaces confirmed the results which in turn have allowed acceleration of furnace baking cycles.

A similar study was conducted for the Alma site following the identification of similar problems. The model was used to recommend changes to the burner dimensions and operating pressures. Trial burners were tested and the results are demonstrated in Figure 11 which shows a pit profile of anode crystalline length (L_c) in nm of the original and optimized injectors. As seen in the figure there is a significant improvement in the baking level for an equivalent quantity of gas injected due to improved combustion and resulting heat transfer.

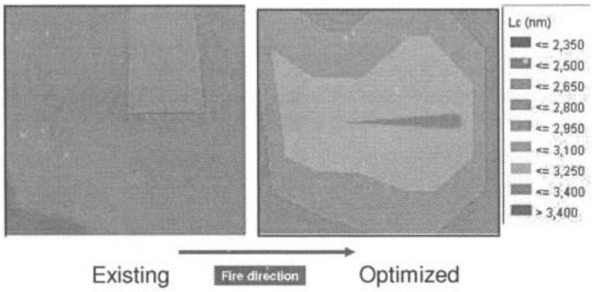

Figure 11: Results of optimized burners at Alma

Firing system tuning– Alma works example

Since the start up of the Alma plant in 2000 the reduction line amperage has continued to increase requiring larger and denser anodes in larger quantities. However in the baking furnace area the process control system and anode baking performance was not adapted in parallel to ensure stable and optimum operation. Over time these factors plus some others led to a deterioration of furnace condition and performance, a number of duct fires, loss of production and limits to furnace production output which led to a need to externally purchase anodes.

Since 2008 a number of actions, including those already outlined earlier in the paper, have been implemented to turn this situation around with the result of increased furnace productivity, improved baking quality and reduced fire risk. This turnaround has eliminated the need for anode purchase and has set Alma up with sufficient baked anode production to sustain upcoming amperage increases with minimal investment. The following section of the paper outlines a number of process tuning initiatives that have contributed to this outcome.

Burner injection cycle optimisation

Using a flue gas analysis system the combustion quality within the fluewall was measured downstream from the first burner ramp for different gas impulsion cycles. Figure 12 shows the comparison a pulse cycle of 30 seconds compared to that of a pulse cycle of 15 seconds for an equivalent burner power. The measurements showed that the long injections resulted in higher amplitudes of oxygen concentration with a higher risk of insufficient oxygen being available for gas and volatile matter combustion while the shorter pulse reduces the amplitude and ensures that there is always sufficient oxygen available for combustion of the natural gas and the downstream volatile matter. The shorter pulse has since been implemented.

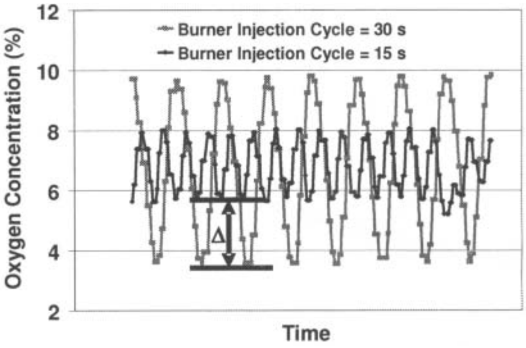

Figure 12: Pulse length impact on oxygen concentration

Burner ramp temperature target optimization

Further combustion measurements at different times during the fire cycle showed that at the start of the cycle following fire change the oxygen concentration remained low (0-2%) when compared to the middle or the end of the cycle (5-10%). In addition to this the first burner ramp struggled to follow the temperature target. Finally the corresponding gas injection rates were very high on burner ramps 2 and 3. All of these items resulted in excessive injection of natural gas, incomplete combustion, excessive energy consumption, process instability and increased fire and explosion risks.

To address the problems the firing curves were tuned to reduce gas injection of burner ramps 2 and 3 following fire change so that burner ramp 1 were supplied with more oxygen. This resulted in a much better combustion performance and better conformance to the temperature target as shown in Figure 13 while still achieving target final anode temperatures.

Preheating temperature target changes

Historically fluewall temperatures achieved in the natural preheating zones remained too cold for the full length of the cycles. This in turn resulted in a late pitch burn with a significant amount of partially combusted material and high levels of opacity.

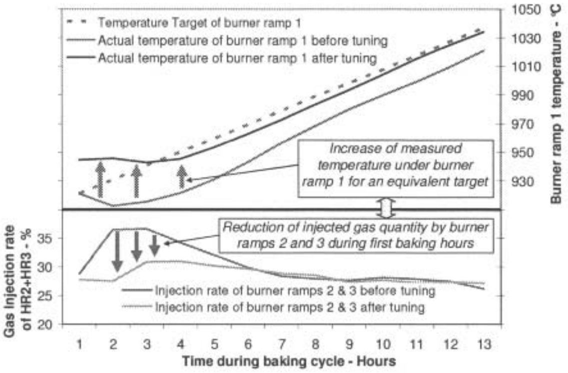

Figure 13: Natural gas distribution and temperature behavior

Again this was a factor increasing the risk of fires as well as higher energy consumption and a limiting factor for the maximum furnace production level by limiting the firing cycle. The preheating targets have been tuned to rectify this situation and ensure an early, hotter pitch burn. The target curves are shown in Figure 14.

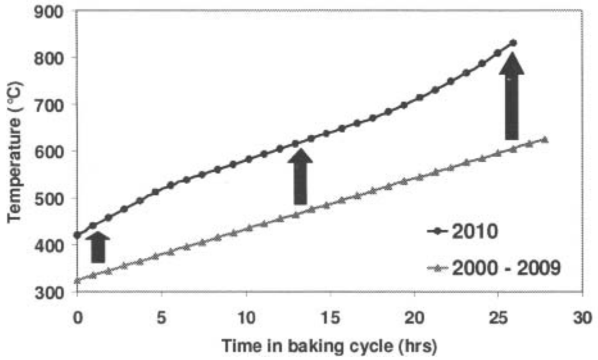

Figure 14: Natural preheating changes to improve pitch burn

The change to this curve in combination with the other initiatives mentioned earlier in the paper now ensure more complete combustion in the natural preheating section. This is essential due to the fact that along with sufficient oxygen availability, the higher preheat temperatures ensure that the ignition temperatures within the fluewall are always above the lower limit of around 600°C require to ensure the volatile matter will completely burn.

Benefits have included no partially combusted material carry over and reduced fire risk. Energy consumption has improved due to the significantly higher anode temperature prior to the forced heating section of the furnace. The concept has been pushed even further by the implementation of an innovative process control methodology developed in collaboration with Sohar Aluminium [3] that will further allow improvement in productivity. The methodology has been successfully tested at a 25 hour fire cycle. Combined with the other initiatives detailed in this paper this will safely allow the overall furnace productivity to improve by 7%. In addition to the productivity increases, all these improvements have resulted in improved baking level and reduced energy consumption levels as shown in Figure 15 and duct fires have been eliminated.

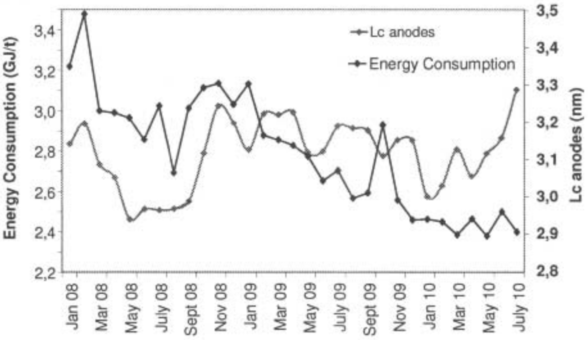

Figure 15: Energy consumption and baking level results

Conclusions

To support the ongoing amperage increase initiatives at a number of sites, a series of models have been developed and validated to allow anode baking furnace productivity to improve. These models have been validated and used to predict the process and design impact of test cases for heat transfer, fluewall flow characteristics, gas injection combustion and anode cooling. In addition to the models, process tuning exercises have also been successful in unlocking extra capability.

Implementation of initiatives coming from different studies have resulted in concrete productivity improvements at a number of Rio Tinto Alcan sites and in many cases have had the added benefits of reducing fire and explosion risks, improving energy consumption and anode baking levels.

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[3] APR patent (will be published for the 11th of November)