Ring Pit Furnaces for Baking of high quality Anodes – an Overview

Motivation

Baking represents the most expensive step in the production of anodes for the aluminum industry.

The anode quality has the biggest variable impact on the aluminum production cost. Stringent anode quality and process control are required to improve the anode performance in the pots and hence reduce the smelter costs.

The theoretical consumption is given by the stoichiometric equation according to the Faraday law. To produce 1 ton of aluminum, 334 kg of carbon are needed, assuming a current efficiency of 100%:

![Image](2 Al₂O₃ + 3 C = 4 Al + 3 CO₂)

The electrolytic consumption takes into account the current efficiency given by the extent of the back reaction (the current efficiency is defined as the actual aluminum production divided by the theoretical aluminum production). With an assumed current efficiency of 90%, the electrolytic consumption is 371 kgC/tAl.

The net anode consumption consists of the electrolytic consumption and the so-called excess consumption that is the portion that does not contribute to the aluminum production. It is the goal of every smelter to decrease the net consumption, which means to increase the current efficiency and to decrease the excess consumption.

An anode baking furnace has to be designed and operated to achieve:

- an optimal temperature distribution in the flues and pits
- an energy consumption as low as possible
Two types of technologies are used for baking of anodes: **CLOSED Type** and **OPEN Top** ring pit furnaces.

The characteristics and particulars of both types of furnaces will be discussed and highlighted in the following paragraphs.

### The anode baking process – basics

The green anodes are stacked in the furnace in rows of three to eight layers, depending on loading arrangement. Anodes are covered by packing coke to prevent oxidation. Part of this coke is consumed during the baking process at a rate below 10 kg per ton of baked anodes in the open top furnace and below 6 kg per ton of baked anodes in the closed type (coverage required). Since more than the half of this oxidation occurs during the cooling cycle, the heat evolved retards the overall cooling process.

The anode baking process is a pyrolysis of the pitch combined with the growth of crystallites of carbon – the latter reducing the surface area. The resultant anode is a porous carbon composite with a density of 1.5 g/cm³ to 1.6 g/cm³, which corresponds to a total porosity of approximately 30%. A substantial part of the pores are closed, have diameter below 1 µm, and will not be wetted by the electrolyte.

The anode carbon can react with oxygen at temperatures above 400 °C. During the baking process, the green anode has little or no mechanical strength as it is heated up above softening point of the pitch. If the anode does not receive full mechanical support, it may deform during baking. Therefore the anodes are placed in an enclosed space (the pit) and surrounded with packing material (petrol coke, metallurgical coke, etc.), preventing oxidation and providing the required mechanical support.

The kinetics of the baking process can be represented by the following effects:

- Transport of heat from body surface towards the core
- Pyrolysis of the binder in the body with the formation of solid coke bridges and gaseous products
- Exhaust of the products of pyrolysis from the body core towards surface
The diffusion process of the pyrolysis gases (volatiles) from the body core of the anode to its surface is of major importance and very much dependant upon the physical dimension of the body, i.e. the length of the diffusion transport way.

The quality of the anodes in what respects the properties affected by the baking process, is mainly determined by the following factors of the baking curve:

- Controlled heating-up gradient
- Final baking temperature

In the temperature range of 200 °C to 600 °C (pre-heating zone) green anodes become mechanically unstable due to softening of the binder (pitch). The packing material covering the anodes prevents deformation. In the range of 250 °C to 550 °C cracking of pitch takes place with consequential release of volatiles. In the temperature range of approximately 600 °C to 900 °C the final transformation from pitch to coke occurs. During the soaking time, anode temperature reaches 1.050 °C to 1.150 °C with definition of anode properties.

An accurate draft control is necessary to guarantee that the temperature gradient remains in the desired level in the sections of the pre-heating zone. The optimization of draft level is necessary not only to guarantee anode quality and property consistency, but also to optimize energy consumption:

- reduction of fuel injection
- reduction of coke consumption
- increase the burnout of volatiles

The final temperature of the anodes loaded is reached during the soaking time. The temperature distribution, i.e. a uniform temperature level for all anodes is a relevant issue in the behavior of the anode in the reduction cell. Moreover, the duration of the soaking time can be reduced by improving the temperature homogeneity over the furnace section implying in fuel saving, what can be translated into reduction of operational costs.

In summary, the following properties shall be assessed when analyzing the impact of baking process on the overall quality of the anode:

- CO2 reactivity
- Air permeability
- Thermal conductivity
- Air reactivity
- Mechanical strength

**Description of a CLOSED Type furnace design**

The baking furnace is a circular kiln with pits and can be compared with a closed chain, in which each link represents an individual section. **Figure 3** below shows a typical closed type furnace, indicating its main sub-structures:
The dimension of the furnace and the individual pits are designed according to the production requirement and the dimensions of the anode to be baked.

The whole furnace is usually built inside a concrete shell. The thermal insulation on the floor and side walls is performed through the usage of commercial refractory and insulation materials.

The flow direction of the combustion gases and air in the sections is identical to the direction of the fire advance. A typical fire group comprises 14 to 16 sections, each one composed by a certain number of covered sections. The uncovered sections are part of the cooling, maintenance, loading and unloading zone.

A section consists of 5 to 8 pits. Each pit can be typically 0.7 to 1.2 m wide and 3 to 5 m long. The combustion of the fuel takes place in independent chambers, so-called fire shafts. The temperature in the fire shaft is considerably higher because of the combustion of fuel with pre-heated air and flame radiation.

Each section has a number of pits in which the anodes loaded will be submitted to the baking process. The pit walls are made of perforated flue bricks, allowing the flow of flue gases towards the bottom of the section. The configuration of a typical section is shown in Figure 4.
Modern closed type furnaces are equipped with low weight fiber lined section covers. Each cover generally accommodates 3 thermocouples connected to an automatic control system.

A ring main surrounds the whole furnace and is under negative pressure. Its function is to transport the flue gases to the waste gas treatment unit. The combustion air is drawn into the flue walls of the first uncovered section of the fire group, passes through the sections in the cooling process and reaches the first section of the firing zone. In the sections of the firing zone, the incoming combustion air is mixed with the fuel (which is injected in counter flow to the combustion air). That combustion rises the temperature of the section up to the max. baking temperature during the entire baking process. The flue gases are passed through the subsequent sections (pre-heating zone), heating up the anodes. On the first covered section of the fire group the flue gases are then transferred to the stationary ring main via the flue gas transfer bend. A typical fire-group arrangement is shown in Figure 5:
The equipment of a fire group, which has to be moved one section forward after 28 till 36 hours, consists of:

- the exhaust manifold,
- 3 burner ramps, with individual energy supply for each flue wall,
- the cooling covers for forced cooling

After a well-defined interval (cycle or fire advance time), all the moveable equipment of the furnace is displaced by one section in the direction of the fire advance. In other words, the section right behind the first section in the pre-heating zone, the one that was just loaded with “green” product is covered and connected to the ring main via the transfer bend. The burner ramps as well as the cooling cover and the transfer bend are displaced by one section in the direction of the fire advance and the cover of the last covered section is removed.

A considerable amount of hydrocarbon volatiles released from the anodes are burned in the furnace.

The quantity of fuel required automatically is controlled by the control system based on a preset baking profile. The combustion of the fuel takes place in individual chambers, so-called fire shafts. The flue gases produced by the combustion are collected under the section cover. From that point the gases are conducted to the bottom of the next section through the perforations of the flue bricks. In that manner heat is transferred from the hot flue gases to the anodes (see Figure 2).

The anodes under baking process are heated up to a temperature between 1.050 °C and 1.150 °C. During the baking process the temperature gradient in the individual sections varies between 5 °C/h and 12 °C/h (in the critical zone), dependant upon the baking curve applied. The cooling zone comprises typically 2 sections: one in natural cooling (uncovered) and one in forced cooling. In both cases cooling process occurs via heat-exchange of air flowing throughout channels induced by suction to reduce oxidation of the packing material.
A slow rise of temperature in the pre-heating zone, a good transfer and distribution of heat in the sections in the firing zone and a smooth cool down are essential to achieve anodes with good and acceptable quality.

**Description of an OPEN Top furnace design**

A typical view of an open top furnace is schematically shown in Figure 6.

![Figure 6 - General overview of a typical Riedhammer OPEN Top anode baking furnace](image)

Similarly to the closed type furnace, the open top is also built inside a concrete shell. Principle of operation and baking process is as well comparable.

The green anodes are baked in furnace sections with a certain number of pits (max. 8 pits/section). The incoming combustion air, pushed in by the first cooling ramp is being pre-heated by passing through flue sections of adjacent flues in the cooling zone. The pits are separated by the heating flue walls. The heat generated by the combustion is transferred through these flue walls. The flue walls are kept under negative pressure to retain and drawn the fumes. The exhaust manifolds connect the outlet section to the ring main around the furnace and from there to the gas scrubbing system. The exhaust manifolds can be moved from one section to the next. Thus, the flue gases will be transported from the baking sections to the furnace outlet.

The sections of a furnace are arranged in two rows side by side, connected on each extremity by the crossover. The flow direction in the flues and the fire advance direction are identical. A typical fire group comprises 3 preheating sections, 3 sections with fuel injection, 6 cooling sections, 1 discharging section, 1 or 2 sections for maintenance and 1 † 2 loading sections, i.e. a total of 16 / 17 sections. The fire advance moves step by step from one section to the next in 24 hours to 30 hours. The entire firing process takes typically between 390 hours and 480 hours. The usual preheating time ranges from 78 hours to 96 hours, which defines the heating-up rate.
The equipment of a fire group, which has to be moved one section forward after 26 till 32 hours, consists of:

- the exhaust manifold,
- a draught measurement ramp,
- 3 burner ramps, with individual energy supply for each flue wall,
- the cooling ramps for forced cooling
- port plates of each flue wall. These port plates are located in the head wall openings to minimize air leakage to the exhaust manifolds.

The anodes in the open top ring type furnace need 156 h till 192 h for cooling. Forced cooling is accomplished in the last three or four cooling sections. Normally fans blow ambient air into the flue walls of this forced cooling area. It cools the brick work and thus cools the packing material and finally the anodes. The forced cooling area is situated after the natural cooling area. The natural cooling area consists of 2 sections. A typical baking curve for baking of anodes in an open top furnace is shown in **Figure 8**.
The cooling air flows through the flue walls of the cooling zone and reaches the firing zone. 3 firing ramps are usually positioned in this area, each equipped with 2 burners for each individually controlled flue wall. The burners inject fuel only. The combustion gases pass inside the flue walls from section to section in the direction to the preheating area, exchanging the heat with the anodes. The flame profile should be kept long and slim in order to obtain optimal heat transfer and protection of the flue wall (extended lifetime).

In the preheating sections the volatiles are exhausted by the under pressure through open joints of the flue walls. They will be mixed with hot flue gases, which still contain sufficient oxygen to burn them to a large extent. The target is to burn as much volatiles as possible between the first and the third section to avoid accumulation of tar in the ducts and thereof minimize the risk of fire.

The temperatures of the exhaust gases vary between 250 °C and 320 °C just before the fire-move. After the fire-move the temperature decreases to 100 °C and 130 °C.

**Summarized comparison between CLOSED Type and OPEN Top Furnaces**

In Figure 9 below, the main aspects related to both technologies and typical values are highlighted for quick comparison:
The construction

Both furnaces are comprised by a large number of pits. Usually 5 to 8 parallel pits, separated by flues, defining a section. The flues consist of refractory bricks, through which the cooling air and the combustion heat are transmitted.

Sections are built parallel in 2 rows with crossovers between the rows at each end, thereby forming a ring. The flow direction of the combustion gases and air in the sections is identical to the direction of the fire advance. In most of the furnaces the fire group moves in clockwise direction.

The furnaces will be heated from the top. The burners are installed on burner ramps each positioned on one section of the firing zone.

The exhaust manifolds connect the outlet section to the ring main around the furnace and from there to the gas scrubbing system.

Flues

The flues in a closed type furnace consist of hollow refractory bricks forming a vertical passage for the cooling air and the flue gases from the top to the bottom. These bricks are of special shape and quality determine lifetime of the furnace. During loading and unloading all the openings of flue bricks must be closed preventing packing material to fall in blocking the channels underneath the pit floor.

The flues in an open top furnace are a hollow construction of refractory bricks forming a horizontal passage for the cooling air and for the combustion gases over the whole length of a fire group. These flues are equipped with baffles and tie bricks to direct the flow and to give sufficient mechanical stability to the flues. The flues contain gaps to exhaust the volatiles.
**Fire shaft**

Only closed type furnaces have fire shafts. The quantity of fire shafts corresponds to the number of pits in the sections. The width of the fire shaft is almost identical to the width of the pit itself. These fire shafts have the advantage of providing sufficient space for the flame and thereby preventing the overheating of the refractory material. A good mixture of fuel and air is guaranteed, because both flows go in the opposite direction.

Flue walls of open top furnaces are made of refractory material of higher quality because combustion (fuel injection) takes place inside those structures directly.

**Section Covers**

Only closed type furnaces have section covers. In modern furnaces the steel covers are lined with fiber materials ensuring better thermal insulation and reducing mechanical stress over the furnace walls. The improved geometry enhances flow distribution leading to a better temperature homogeneity.

**Head walls**

In closed type furnaces the fire shafts are part of the head walls. The mechanical structure of the head and side walls is designed to support the weight of the section covers. The exhaust manifold are placed over the fire shafts in the first section of each fire group.

In open top furnaces channels in the upper part of the head walls establish the physical connection of two subsequent flues, leading the flue gases in the fire advance direction. There are also openings on the top for connection of the exhaust and cooling manifolds. If not in use, these openings are covered with insulating covers.

**Flow and Heat Transfer**

In the preheating and in the firing zone the heat transfer is accomplished by convection and radiation from the flue gases to the flue wall, then by conduction through the flue wall and through the packing material and finally into the anodes. In the cooling sections this process is vice-versa. It is an indirect heat transfer process, depending on temperature and velocity of the flue gases, on heat conductivity, specific heat and density of each material and on exposure time.

In closed type furnaces the heat transfer is not only performed through the flues but additionally via the top and bottom surfaces also exposed to flue gases. A uniform mass flow of flue gases through the flue wall channels ensures balanced and homogeneous heat transfer and in consequence enhanced temperature distribution.

The section cover conforms the link between 2 subsequent sections. Underneath the vault of the section cover, flue gas flow of different fire shafts is mixed and temperature and pressure balance takes place.

In the cooling zone the flow of the cooling air under the cover intensifies the burning reaction of the packing material. This reaction prolongs the cooling time and increases the consumption of the packing material.

In open top furnaces the adjustment of the draft is accomplished easily and separately in each flue. With increasing draft level the mass flow of the flue gases will be increased correspondingly. An ideal draft is necessary to achieve an optimum and more uniform heat transfer. In such furnaces the pressure drop is higher and the draft is measured over the whole length of the fire group. As a consequence, the mass flow of flue gases is higher. Strategically posi-
tioned baffles and tie bricks lead to uniform heat transfer, although the heat transfer surface is smaller than in closed type furnaces.

**Volatile**

The majority of the volatiles are released between 200 °C ≥ 600 °C. More than 40 volatilised hydrocarbons are released from the carbon products during this heat treatment. Condensation of volatiles inside the transfer bend as well as ring main and downstream shall be avoided. In general it can be reduced maintaining the furnace outlet temperature over the dew point of the VOC’s.

Another factor to be considered is the ignition of the volatiles in the furnace. The increasing temperature might influence the temperature gradient in the carbon products and accelerate the diffusion process, which can lead to cracks in the product.

![Figure 10: tar volatile kinetics (Source: Denedde, Charette, Bourgeois, Castonguay “Kinetic Phenomena of Volatiles in Ring Furnaces”, TMS 1986)](image)

In closed type furnaces the channels of flues do not have the small gaps and therefore hot spots cannot occur. However, volatiles are released vertically, i.e. throughout the packing material up to the vault underneath the section covers, implying in an extended time required and changing considerable the kinetic phenomena. The mass flow of each flue channel is smaller and the temperature gradient between product and flue gas is lower, therefore less volatiles can be burned. The exhaust gas temperature at the transfer bend is adjusted in the range 80 °C to 180 °C in order to protect the system against tar condensation and preventing ignition of volatiles. The resulting exhaust gases can carry between 500 ≥ 1,000 mg of tar per Nm³.

In open top furnaces the flues are designed with lateral gaps to exhaust released volatiles. The negative pressure inside the flue walls creates necessary suction effect to drain the volatiles
throughout the flue wall laterals into the flue wall channel. Inside the flue wall channels, volatiles react with temperature and oxygen and combustion occurs. Alkali volatiles (coming from recycled butts), especially Na, can react with the refractory material. Hot spots caused by excessive and localized combustion at inner wall of flue wall channels and alkalis present in the volatiles can reduce the lifetime of the flues. The objective is to burn the volatiles completely between the first and the third pre-heating section to avoid the risk of fire and the pitching of the exhaust gases and to reduce energy consumption. Volatiles burning closer to the exhaust manifold increase the temperature of the off gases and must be cooled down before entering certain exhaust gas scrubbing systems. Exhaust gases carry between 100 to 300 mg of tar per Nm³.

**Baking Curve**

In the pre-heating zone, in the critical range of 200 °C to 550 °C, a maximum temperature slope of 14 °C/h should be respected. Too high heating-up gradients could generate cracks due to too fast release of volatiles.

In **closed type furnaces** the heating-up rate is usually lower: between 8 °C/h and 10 °C/h. Soaking time also depends on setting weight of pits and varies in the range of 60 to 80 h. Natural cooling starts with 500 °C for 28 h to 32 h, followed by a forced cooling period of 28 h to 64 h. In both cases, anode unloading temperature is usually below 300 °C.

**Open top furnaces** operate generally at faster firing cycles. Heating-up rates of 14 °C/h can be reached. Soaking time is generally in the range 60 to 80 hours, depending on the setting weight of the pits. Cooling period varies between 144 to 180 h.

**Control**

The basic function is to maintain prescribed flue gas time/temperature curves. A bake furnace is an extremely 'slow' system. Anode temperatures reach the flue gas temperature with a delay of many hours or even 1 to 2 days. It is therefore not feasible to use the anode temperature as an input signal for the bake furnace process control system. The desired anode baking curve has to be translated into a 'Flue gas temperature target curve'. Optimum shape of this curve is a function of the bake furnace design and is used as the input control signal for the control system.

There are basically two variables on the furnace to be controlled to obtain the temperature profile according to the pre-defined baking curve (set-point):

- **Fuel quantity** – injected through the nozzles of the burner ramps, positioned in the sections belonging to the fire zone;
- **Furnace draft** – adjusted by the opening of the valve of the flue gas transfer bend, located in the first section of the fire group.

To measure temperature, thermocouples are used. They are installed either directly in the flues or underneath the section covers. In the exhaust manifold thermocouples control the exhaust gas temperature as described above. The draft is measured in a pre-determined section in the pre-heating zone and controlled by dampers installed in the transfer bend.

In **closed type furnaces** the temperature underneath the covers of the sections in the fire zone is controlled directly by the volume of fuel injected by the burner nozzles of each burner ramp. The temperature underneath the section cover vault is measured by means of 3 fixed mounted thermocouples. This measurement is fed back to the control system that electronically and automatically regulates the fuel amount (rising or lowering the fuel volume injected).
The temperature in the pre-heating zone is controlled adjusting the opening of the flap of the transfer bend. Opening the valve implies in a higher amount of flue gases being transported from the fire zone to the ring main through the pre-heating zone, meaning a higher heat transfer to these sections. By closing the flap, a lower transfer of heat takes place.

Another consequence of changing the level of suction is the cooling profile. A higher draft means that more cold air is drawn through the last section of the fire group, accelerating the induced cooling process of this zone. On the other hand, reducing the draught implies in a lower cooling efficiency.

The control system allows the operator to select any of the pre-heating sections for the temperature reference of the transfer bend. In order to ensure an efficient temperature control in this zone, the section chosen should neither be the first one, due to air turbulence and a very low temperature range nor one of the sections effected by the combustion of the volatiles, due to uncontrolled temperature variations.

In open top furnaces the actual flue temperature is measured at different locations in regular intervals and compared to the target temperature. The energy input to the furnace is provided by burners on three bridges per fire, as well as by the combustion of pitch volatile matters released from the anodes.

The fuel control is performed by start - stop operation of the burners. Slide gates in the exhaust manifold perform the draught control. The actual draught level is monitored continuously in every flue. The temperature is measured in every flue at five locations. With this information, the furnace behavior is analyzed continuously for every section in heat-up or baking.

Draft and fuel regulation is integrated for optimum regulation characteristics. For regulation purposes the ‘active’ sections, i.e. the sections between exhaust manifold and the last burner bridge are divided in five ‘zones’. In a fire arrangement with six active sections, one zone consists of two sections.

Final words
The main benefits obtained from the optimization of the baking furnace as well as baking process, translated into initial investment (CAPEX) as well as operational costs (OPEX), are listed below:

- Baking furnaces with optimized number of sections in a fire group resulting in lower initial investment;
- Improved baking profiles resulting in higher production rates;
- The optimization of the baking profile also reduces residual tar, saves energy and improves environmental aspects;
- Development of the furnace brickwork, geometry, insulation and auto firing equipment provides outstanding temperature homogeneity in each section, allowing the production of high quality anodes and thus reducing aluminum productions costs;
- The optimizations carried out on the baking furnace also positively influence the whole design and investment cost of the complete anode baking facility as well as the operational and maintenance aspects (extended lifetime).
Authors:

Mr Dipl. Ing. Friedherz Becker - Head of Riedhammer Application Center (ZAC)
Mr Eng. Frank Goede – Sales Manager - Carbon Division Riedhammer GmbH

This article was published in the September - Aluminium Essen 2006 fair - issue of the Aluminium International Journal.