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ELECTRODE TECHNOLOGY FOR ALUMINUM PRODUCTION

Bake Furnace Design and Operation

SESSION CHAIR
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IMPROVING FUEL GAS INJECTION IN ANODE BAKING FURNACE

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Abstract

Anode baking process requires large amounts of fuel gas. Heating the refractory walls to bake the anodes is performed by direct gas injection from the top of the furnace. The resulting flame, called diffusion flame, has an impact on the anode baking performance and on pollutants formation. While combustion emissions, particularly the oxides of nitrogen (NO_x), has become a major issue in most industries consuming fossil fuels, no major studies have been published in the field of anode baking. In 2010, Fives Solios launched a program dedicated to characterizing the combustion in anode baking furnace to develop a clean and efficient injection technology. Experimental approach was preferred rather than numerical simulation. A testing unit including an actual scale refractory flue wall with experimental instrumentation was designed and commissioned in 2012. Promising results in terms of NOx abatement and thermal distribution, and implementation on an existing anode baking furnace, will be discussed.

Introduction

In the prebaked technology, green anodes are transformed to pre-graphitized carbon before being used in electrolysis cells. The transformation process that requires heating the anodes up to 1100°C consumes large amounts of fuel. Typically one tonne of baked anodes requires more than 2 Gigajoules energy in an open type furnace. This energy is supplied by combustion of injected fuel in the refractory flue walls.

Most research studies in anode baking technology focus on how to control or how to operate the furnace, but very few resources have been committed in recent years on the injection technology itself. It is although a gateway for a better understanding of the oxides of nitrogen (NO_x) formation process and of the thermal transfer mechanisms from the flame to the anodes. This paper introduces the experimental program developed by Fives Solios over the last three years to characterize and improve fuel injection in anode baking furnaces.

Injection configuration in open type furnaces

Gas fired open ring type furnace is the most representative and efficient technology installed in the aluminum industry to bake anodes. In such furnaces, natural gas is directly injected from the top of the refractory walls. The resulting energy is transferred through radiation and convection to the refractory walls and through conduction to the anodes.

The gas is injected in the combustive hot gases without premixing. The resulting flame is called "diffusion" flame because the process of mixing between oxygen and fuel occurs mainly by diffusion[1]: Combustion occurs at the interface between the fuel gas and the oxidant gas, and the burning depends more on rate of diffusion of reactants than on the rates of chemical processes involved. Diffusion flame is impacted by the gas jet configuration, the oxygen content, the fumes speed and temperature.

Figure 1 Turbulent diffusion flame inside a flue wall

Typically, each fire group is equipped with 6 injectors per flue wall line to provide the thermal energy in the forced heated sections. Depending on the position of the injector, the conditions of temperature, oxygen content and fumes flow rate will vary resulting in changes in flame profile, combustion mechanisms and thermal transfer.

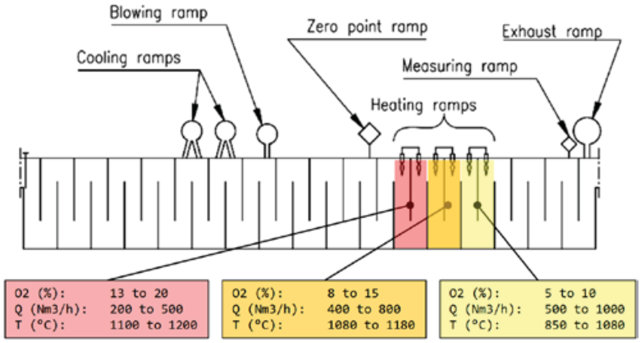

Figure 2 Typical ambient conditions per section in the heating zone

Fuel injection optimisation is a major issue for performance improvement and pollution limitation

Flame resulting from the injection of natural gas has an impact on the formation of nitrogen oxides (NOx), but also on the temperature distribution along the refractory walls that directly impacts the anode baking consistency and the refractory bricks life duration.

The nitrogen oxides have a negative impact on both humans and the environment. They represent a combination of irritating gases at the source of respiratory diseases[2]. Furthermore in contact with the atmosphere, they can form acid rain gradually. Additionally, they create a photochemical pollution, the Ground Level Ozone, formed by combination with volatile organic compounds under the presence of sunlight. The standards setting the NOx emission limits become more and more stringent in all regions of the world. In Europe, the Directive 2010/75/EU of the European Parliament on industrial emissions set the new emission limit values for NOx for gas fired combustion plants at 100 mg/Nm^3. The Directive is transposed into national legislation by Member States since January 2013.

While combustion emissions, particularly the oxides of nitrogen (NO_x), has become a major research issue in most industries consuming fossil fuels, no major studies have been published in the field of anode baking for the aluminum industry.

In 2010, Fives Solios launched a program dedicated to characterizing the fuel injection in anode baking furnace in order to develop a clean and efficient injection technology. Experimental approach was preferred rather than numerical simulation because turbulent combustion is a fast and complex phenomena that depends on fluid dynamics, chemistry kinetics and heat transfer. Moreover computational simulations always require a calibration process with experimental data because of physical modeling error due to uncertainty at boundary conditions.

The study program is deployed in two phases:

A first step dedicated to characterize the today technology by determining the impact of the operating conditions, of the geometry of the injector and of the injection modes on flame configuration, temperature distribution along the refractory wall and on the concentration of the pollutants.

In a second step, the study is focusing on new technology development with the following improvement criteria:

- Allow a more homogeneous temperature distribution along the flue wall to improve baking consistency
- Adapt the injection modes to the oxygen content and temperature of the inlet fumes in order to improve combustion quality and baking efficiency.
- Limit the formation of nitrogen oxides to comply with environmental regulation.
- Avoid the formation of hot spots in the refractory wall to maximize the life time of the refractory bricks.

The first work began in 2010 with the drafting of a general technical specification to define the criteria of innovation, the measures required to characterize the injector and the flame, the combustion conditions inside a flue wall.

A testing unit dedicated to the study of fuel injection and combustion inside flue walls

From this general specification, the basic engineering of the testing unit was defined. The testing unit is designed as an actual scale refractory flue wall equipped with the measurement and control devices to ensure the following functions:

- Control the gas injection in different configurations (gas pressure, pulse frequency and duration)
- Simulate the ambient conditions of a flue wall (temperature, pressure and oxygen)
- Characterize and visualize the flame (length, temperature and radiation)
- Measuring the temperature distribution along the refractory wall
- Measure the gas composition at the inlet and at the outlet

Following basic and detailed design, the manufacturing and the assembly of the testing unit started in 2012 inside the Fives Stein combustion test station.

Figure 3 Testing unit refractory wall under assembly

Controlling the flue wall atmosphere in the ranges of temperature, oxygen content and fume flow rate applicable to the different sections of the forced heating zone was one of the major challenges to design the testing unit. The following equipments were implemented upstream of the testing flue wall in order to condition the fumes (see figure 4):

GAC: Electrical air heater. It is an independent system that is used to preheat the test cell without combustion reaction.

GRA: Reducing burner. It is able to rise up the temperature of the flue gases beyond 800°C. Theoretically, it can reach temperatures up to 1200°C with 15% oxygen content.

GGC: Fume generator. The function of the fumes generator is to reduce the oxygen content of the flue gases to a minimum of 3% for temperatures below 800 °C. Fume generation is done by heat dissipation in a radiant tube.

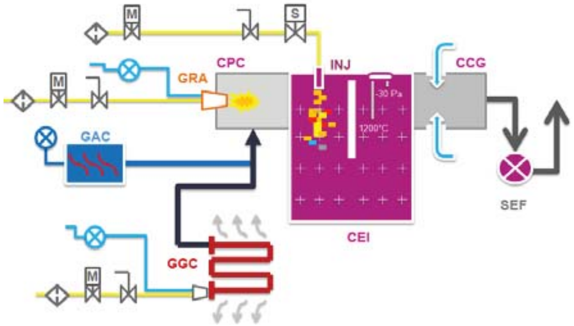

Figure 4 Schematic diagram of the testing unit

In order to characterize the flame and the temperature distribution along the flue wall, two sets of thermocouples were installed:

- 45 thermocouples sensors installed at the flue wall - anode interface to study the baking distribution
- 16 thermocouples sensors through the wall to study the flame temperature distribution along the flue gas path
- 3 three points thermocouples sensors to measure the heat transfer through the refractory wall

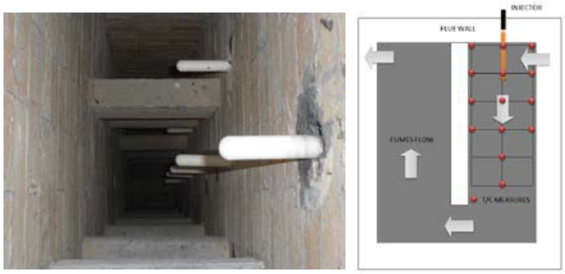

Figure 5 Temperature sensors through the refractory wall

Two extractive gas analyzers measure continuously the CO_2, O_2, CO, H_2O, NO_X contents at the inlet and at the outlet of the testing flue wall. These measurements are used to calculate the fumes enthalpies at the inlet and outlet of the test flue and to evaluate the NOx quantity produced in the flame.

An injector gas line is implemented in order to condition and supply gas at the inlet of the injector in accordance with safety regulation EN-746-2.

Two controllers were implemented to ensure the remote control of gas injection and fume conditioning equipment. One controller is dedicated to the safety interlocks. The measurement data are collected via a data processing unit and treated through LabVIEW software. All the information is displayed in real time through a PC interface.

A complete Hazard and operability study (Hazop) was performed in order to ensure safety compliance with standards and prevent any explosion risks during combustion tests.

The testing unit was completed in May 2012. The drying of the refractory wall was performed in July 2012 at the first temperature rise. In the continuity of the drying phase, the first gas injection tests were conducted in order to adjust the flows, calibrate and validate the measurement acquisition systems.

First trials and promising results in NOx abatement

A first test campaign was held in November 2012 in order to characterize the actual injector technology. All gas fired furnaces are equipped with pulse pause firing systems. In most of technology supplied, the opening time of the injector is fixed and the closing time is calculated as a function of the thermal power. This injection mode provides stable flame profile whatever the thermal power is. Typically the opening time is in the range 0.3 seconds to several seconds. The gas pressure is typically 100 kPa at the inlet of the heating ramp gas circuit. It can range from 50 to 150 kPa depending on the aluminum producer.

Figure 6 Overview of the combustion testing unit

The injector is basically a tube from 5 mm to one inch diameter. In some cases a calibrated restriction is required to adjust the nominal flow rate and an outer tube surrounds the injection tube to ensure thermal protection and to promote induced air.

In the first trials, we have tested 3 injectors A, B and C with different shapes but equivalent nominal flow rates to study the influence of gas jet configuration on flame profile and NOx formation. Injector A is based on existing technology while injectors B and C propose alternative designs.

The gas pressure was set to 100 kPa. The inlet fumes conditions were fixed at the following values:

- fumes flow =500 Nm^3/h,
- fumes temperature = 1080°C,
- Oxygen content from 10% to 20%.

Flames temperature profiles measured through the refractory wall were recorded after stabilization. These measures represent the temperatures of the alumina sheathed thermocouples inserted in the flame hot gases.

The records show main differences in the temperature range and distribution. The injector "A" flame is getting the highest peak temperature with less homogeneity. Injector "C" flame has a better distribution with lower peak flame temperature.

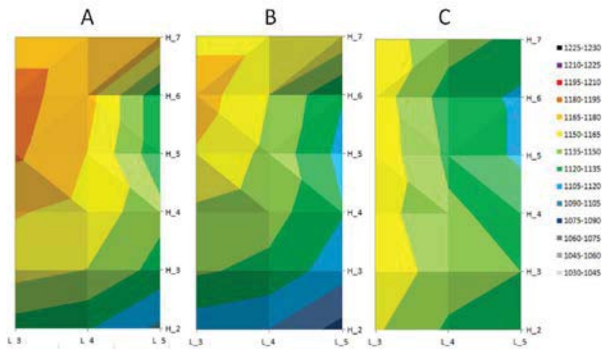

Figure 7 Flame gases temperature records

The observation on flame temperatures (Figure 7) is in relation with the mixing rate of gas jet with combustive flow.

Injector "A" gas jet is characterized by very high speed, high mixing rate with low scale turbulence (intimately mixing). High mixing rate generates very fast combustion reactions with high energy release in a small volume. It explains why flame is less homogenous with a higher peak temperature.

Injector "C" gas residence time, defined as the amount of time the fuel mixture remains in the combustion area, is increased due to lower jet velocity. We can observe larger scale turbulences due to a lower mixing rate compared with injector "A" (Figure 8). Flame is distributed over a larger volume and is more homogenous.

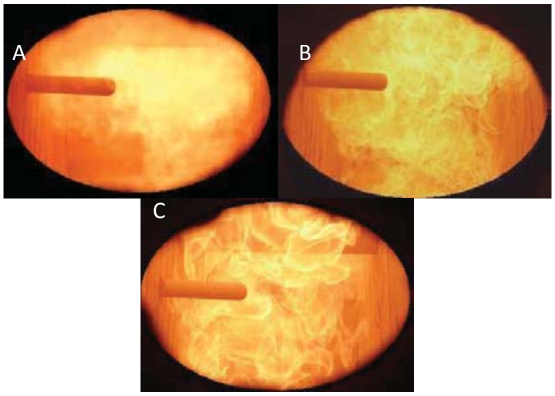

Figure 8 Flame photography

The influence of flame profile on the thermal distribution is studied thanks to the implementation of 3 points thermocouple probes inserted inside the refractory wall.

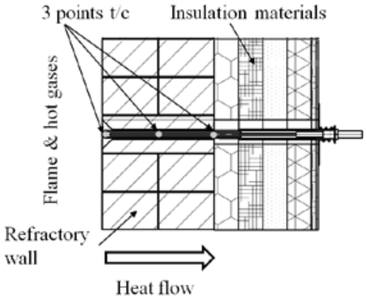

Figure 9 Three points t/c probe inside refractory wall

The heat transfer is deducted from the calculation of the energy transferred by conduction through the refractory wall. From the simplified Fourier equation $d\varphi = -\lambda$ Grad T, we deduct the heat flow density $\phi/S = -\lambda\ \Delta T/L$ where

- ϕ/S: Heat flow density (w/m²)
- λ: Thermal conductivity of the refractory (W/m°C)
- L: distance between t/c points
- ΔT: Temperature difference between t/c points

The heat flow is calculated from 3 positions inside the flue wall in order to determine the distribution (HF1 located in the flame area, HF2 in the flue wall bottom area and HF3 in the top area at the flue wall outlet). The calculation results are given for flame A and C in the figure 10. The average heat dissipation is stable between flame A and C (1489 against 1500 W/m²) but we observe a more uniform distribution of heat release along the flue wall with flame C. It is correlated with flame temperature distribution observed.

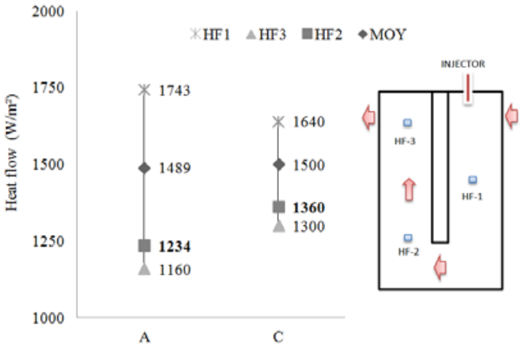

Figure 10 Heat flow distribution

The influence of flame profile on NOx formation was studied with an oxygen content ranging from 10 to 20%. It is remarkable that in the same operating conditions, with an equivalent thermal power injected, the quantity of NOx produced is varying a lot with the injector shape.

At 17% oxygen content injector B is producing 3 times less NOx than injector A, while injector C produces almost 20 times less NOx than injector A. It is also important to note that NOx formation occurs mainly above 15% oxygen content. It means that in an anode baking furnace, most of NOx is produced in the second and third heated sections.

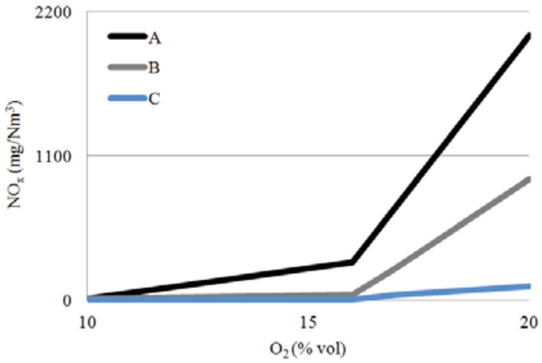

Figure 11 NOx formation versus oxygen content

The gas jet configuration has a major impact on NOx formation because it influences the local mixing rate of fuel and oxygen that impact directly the flame temperature.

NOx formation during the combustion process occurs mainly through the oxidation of nitrogen in the combustion air by a mechanism known as "thermal NOx". The rate of thermal NOx formation is directly affected by the combustion zone temperature and the oxygen concentration. Thermal NOx can be reduced by decreasing the flame temperature or limiting the oxygen concentration.

The thermal distribution along the refractory wall was recorded in the same operating conditions for flame A and flame C after 5 hours injection at a fixed thermal power. The records are representative of the temperature at the interface of refractory bricks and anodes. The results are presented in figure 12. There is no remarkable difference between the two injectors despite a slight homogeneity improvement at the flue wall top area for injector C. The mean temperature deviation along the flue wall increases with injector A from 42°C to 46°C after 5 hours and remain stable for injector C at 45°C. The thermal efficiency is also slightly improved for injector C with an average temperature increase of 37°C against 31°C for injector A at equivalent thermal power and flue wall conditions.

The influence of flame temperature homogeneity on the product temperature is not obvious in this test. A six hours test may be too short to observe significant temperature differences at the interface between flue wall and anode.

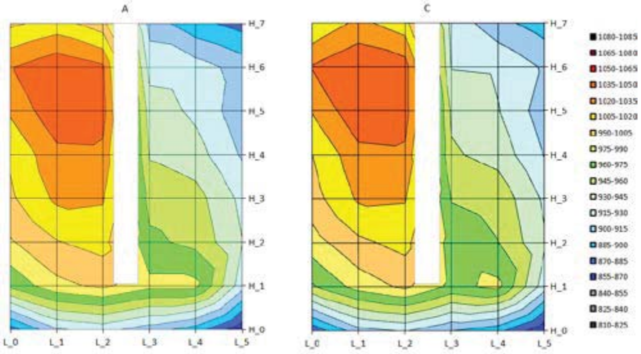

Figure 12 Temperature distributions along the flue wall

A first contract based on NOx abatement performance

Shortly after obtaining these promising results for NOx reduction, Fives Solios was contacted by a carbon producer in Europe subject to tighter environmental regulations. The company involved in a project to modernize one baking furnace decided to upgrade the firing system with a new architecture[3] for centralized control including automatic combustion optimization and equipped with the new generation of low NOx gas injectors, the industrial version of the injector C. Sign of times, the contract technical performance guarantee includes NOx emissions at stack

Conclusion

Significant resources have been allocated by Fives Solios to strengthen its expertise in the field of combustion and flame applied to the anode baking furnaces. The main target is to develop a clean and efficient injection technology in open type furnaces. With an actual scale testing unit, the company is now able to explore a technical domain remained fallow since the introduction of prebaked technology. Significant improvement has been recorded in NOx emission abatement and flame temperature homogeneity with the use of a new design of injector. Further works have to be engaged in optimizing the convective and radiant heat transfers between the flame and the refractory wall in order to further improve the thermal efficiency and the anode baking consistency.

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