Essential Readings in Light Metals: Electrode Technology for Aluminum Production.
Edited by Alan Tomsett and John Johnson.

FLUE GAS MANAGEMENT

Prof. Dr. Wolfgang Leisenberg

Innovatherm Prof. Dr. Leisenberg GmbH+Co. KG, D-35510 Butzbach
FH Giessen-Friedberg University of Applied Sciences, D-61169 Friedberg
Email: Dr.Leisenberg@t-online.de

Abstract

Since with the recent developments the gas fired horizontal flue baking furnace is most frequently used, this paper will concentrate on this furnace type. Further, due to environmental demands, flue gas analysis and evolution became important. Contradicting targets as are minimum energy, sufficient preheating, maximum fuel efficiency at the burners and perfect volatile combustion ask for an advanced control strategy. The implications of CO and NOx content in the flue have to be taken in account as well. This shows the need of a consistent strategy of flue gas volume control and fuel injection, especially for energy efficient furnaces. A control strategy, which regards all those parameters can be called rather a management. The last investigations in this field and the results thereof will be presented.

1. Introduction

The anode baking process consists basically of two counter current convection heat exchangers (preheat and cooling area) with a fire area inbetween. Therefore, the basic requirement for the system is to control those three areas for each flue of a fire. Regarding the whole baking process, preheating, firing and cooling cannot be considered as separate control areas, but the whole fire resp. each flue has to be considered as an entire process with several interdependences.

The connection between the areas is caused by the flue gas that flows through the three areas one after the other. It serves as heat transfer fluid in the heat echange process and as oxygen supply for the combustion as well. Combustion takes place in the fire area and in the preheat area during the pitch burn phase.

2. Criteria for Flue Gas control

Since the individual areas and operational conditions put different requests on the flue gas volume, criterions after which should be dealt must be given to the control system. In order to analyze these criterions, we will follow the flue gas downstream through the furnace.

2.1 The Cooling Area

The last part of the fire is built by the final cooling area that usually consists of one or two sections. Here the anodes are chilled by an uncontrolled blower manifold ramp until they can be unloaded by the crane. The air is blown into the end of the last section and leaves the flue via open stokeholes. Because of the low temperature the waste air cannot be used in the process.

Normally a second cooling area connects to the final cooling. It is used to cool down the anodes and to provide the fire area with preheated air as well. Since the flue gas volume that is necessary for the heat exchange process normally is larger than the combustion air for the burners, exclusively preheated air from the cooling area is used for the combustion. This heat recuperation is the reason for the energy efficient operation of a ring furnace [1].

The longer the way of the air through the cooling zone is, the higher the temperature of the combustion air will be. But enlarging that way the fire becomes longer and the production capacity sinks. As a compromise, two or three sections are proved to be optimum [2]. Therefore the second blower manifold ramp is located on the end of the second or third section upstream the last burner ramp.

At recent installations, the air volume of the blower ramp is adjustable, either by motorized dampers or by speed variable fans. The reason for this additional equipment is the following:

Because the flue gas volume of the exhaust manifold ramp is adjusted after the demand of the preheat area, the difference between that exhaust volume and the cooling air which is fed into the flue is balanced by inleaked air [3, 4]. With constant air volume at the blower manifold ramp the pressure in the flue varies and no defined pressure conditions are given in the flue, especially in the fire area.

In order to avoid a blowing out of flue gas at the burners, a draft level is adjusted in the fire, which varies with the exhaust volume. By that draft air inleakes into the pits, chilling especially the top anodes, which show the lowest temperature anyway.

Furthermore the flue gas temperature sinks through the inleaked air and causes higher energy cost. By using a controllable air volume at the blower manifold ramp, the air cooling volume can be adapted to the exhaust flue gas volume.

Therefore the pressure is taken directly behind the fire using a zero point ramp and is kept at a value near the neutral point. Doing so, defined pressure conditions and smallest amount of inleaked air are ensured.

TABLE I: Influence of Burner Operration mode on NOx Generation

Burner operation mode	NOx with burner	NOx without burner	NOx by burner	Per cent
Contineous	1260 mg/m³	160 mg/m³	1100 mg/m³	100 %
Impulse	630 mg/m³	120 mg/m³	510 mg/m³	46 %
Impulse Low NOx	490 mg/m³	170 mg/m³	320 mg/m³	29 %

2.2 The Fire Area

In the fire area we find an interaction between the flue gas stream and the fuel gas of the burner. This has to be considered for the burner design and operation.

The first demand to the burner system is a complete combustion of the fuel resp. a high fuel efficiency. The oxygen content in the flue gas is sufficient but not excessive. Therefore a momentary lack of oxygen can occur easily connected with bad fuel efficiency and CO emissions in the waste gas. To utilise all the oxygen in the flue the ideal burner operation seemes to be a contineous flow of the fuel gas.

However the contineous operation shows severe disadvantages. The mechanical impulse is low and therefore the reach of the gas beam is short. Consequently the bottom temperature of the flue is lower than the top temperature. Furthermore the speed of the gas beam varies with the burner capacity and the flame length with it. So the heat distribution in the flue depends on the burner capacity.

Therefore the impulse system has been introduced as an alternative which does not show those disadvantages. The gas speed is constant and independent of the burner capacity. The pulsations cause turbulences in the flue, which encrease the heat transfer. Due to the pauses between the impulses, the gas speed at the same burner capacity is higher than with contineous operation and higher temperatures are achieved on the flue bottom. By varying the nozzle diameter and the fuel gas pressure, the flame characteristic can be easily adapted to the baffle. Therefore the impulse system shows a high homogeneity of the temperatures in the pit, coming down to a spread of less than 70 °C at the baked anode.

Furthermore because of the high fuel gas speed the NOx emission is only half as big compared with the continuous operation [Table 1].

Finally the flame characteristic of an impulse burner shows practically no hot spots, which affects the refractory lifetime seriously.

Therefore, the impulse system has become a standard for modern installations because of the homogeneity of the temperatures and because of its excellent linear control characteristic.

Recently a discussion arised whether one should use long or short impulses. As arguments for long impulses less NOx emissions and longer lifetime of the flue walls were named.

An examination at a triple baffle furnace has yielded that no significant differences of the NOx emissions can be observed in the area between 0.5 and 6 seconds of impulse duration. With longer durations the NOx rises because the system approaches the continuous operation.

The concentration on low emissions and high energy efficience ask for a special LowNOx gas burner. As our experience has already shown in other applications, a small quantity of air added to the burners reduces the NOx emissions significantly. At the same time the fuel efficiency improves, particularly under oxygen lack conditions.

The extra air is added without any additional pipework or equipment. As an useful side effect the gas nozzle of the burner is chilled. So any cracking of the fuel gas is avoided and the service life of the gas nozzles extends significantly as well.

Table I shows the NOx emissions on the back burner ramp of a triple baffle furnace for different operation modes of the burners. Since some NOx is generated without any combustion due to the high temperature of the air (column 2), only the balance to the total NOx (column 1) is caused by the burner (column 3). If we set the contineous operation mode to 100 %, the NOx emissions, caused by the burners, are reduced to less than a half using the impulse mode and to less than a third using the LowNOx burner with additive air.

If we follow the NOx concentration downsteram the flue, we find, that the concentration at the exhaust is lower than that at the burner ramp.

With the LowNOx burner the total NOx of 490 mg/m³ (resp. 170 mg/m³ with burner turned off) comes down to 260 mg/m³ (resp. 140 mg/m³ with burner turned off) because of the partly reductional atmosphere and because of the inleakled air which decreases the concentration of the NOx.

The conclusion is, that the NOx is absolutely no argument for contineous or long impulse burner operation.

The refractory lifetime depends on many parameters as are refractory quality, flue design, fire length, fire cycle duration, temperature gradients, hot spots, baking temperature and last but not least on the definition of lifetime. We find furnaces with less than 60 fires lifetime and others with 120 and more fires. Within the same group there are furnaces with 120 fires at long impulses and 120 fires at short impulses. Also we find furnaces with 60 or less fires with long impulses, with contineous operation and with short impulses. Therefore we see that many parameters affect the refractory lifetime much more than the impulse duration. This makes it difficult to compare one furnace with an other and to find any significant correlation between lifetime and impulse duration.

If all other parameters are identical, only the atmosphere in the flue may be different. Our long years experience in the ceramic industry shows, that the refractory withstands better, if the atmosphere alternates between reduction and oxidation phases than if a reduction atmosphere stays for longer periods of time.

So we cannot find a physical, chemical or empiric justification for the argument that long pulses will increase the lifetime of the flue walls.

Contrary on the triple baffle type furnace long impulses show clear disadvantages:

During the long impulse a lack of oxygen can be recognized, and during the pause phases we find an excess of oxygen. Short impulses of something 0.5 – 1 sec yield a combustion with optimum utilization of the oxygen in the flue similar to the contineous operation. Particularly at furnaces which are operated at highest energy efficiency corresponding with lowest exhaust volume, the CO content of the flue gas increases significantly with the pulse duration. At longer pulses one can observe the high fuel and the no fuel phases in the flue with bare eye.

Further we found, that the temperature significantly sinks at the bottom of the flue if the impulse duration exceeds a value of approximately one second. This is shown in the diagrams 1 and 2, representing the flue temperatures in a depth of 1, 2, 3 and 4 meters from the stokehole at different impulse durations versus a period of time of some minutes. This result first appeared paradoxically because a long impulse normally yields a long flame and so high temperature on the bottom of the flue. As cause of this effect it turned out that with long impulses a convection vertically to the flue gas flow is estabished, which hinders this stream. Therefore periodically phases with low bottom convection and oxygen are established. As shown in the diagram, these low temperature phases on the bottom cannot be compensated by the hot phases.

The result is a significant lower average of the bottom temperature. This phenomenon did not appear with short impulses (diagram 2). Here the bottom temperature is kept in the same range as in the remaining flue. The upper flue temperature (1 m) is somewhat higher. This is helpful because the top anodes schow the lowest temperatures because of the coke packing and the inleaked air.

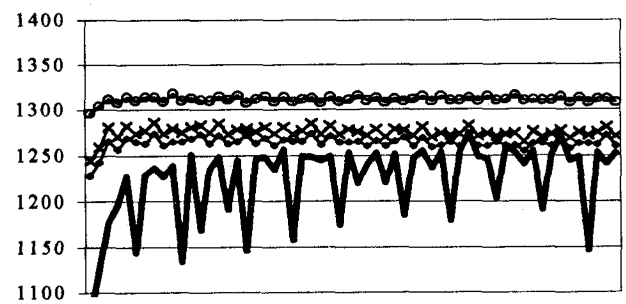

Diagram 1: Flue temperatures vs. time at 5 sec impulse duration.

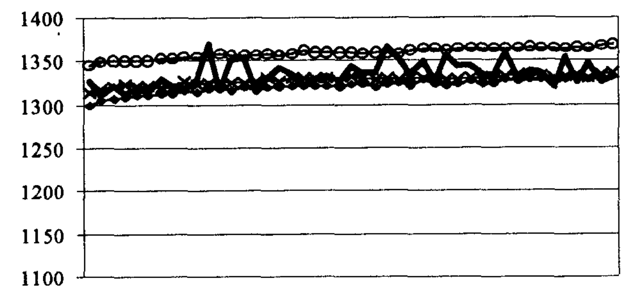

Diagram 2: Flue temperature vs. time at 1 sec impulse duration.
Both diagrams: Upper line: 1 m from stokehole;
thick line: 4 m from stokehole;
other lines: 2 and 3 m from stokehole.

Adding all those facts we cannot recognize many disadvantages but no benefit for the process using long impulses. As conclusion we state, that for the triple baffle furnace the short impulse operation mode is the most appropriate.

This conclusion is not applicable for the single baffle Alcoa-type furnace which requires a long lazy flame. On this type of furnace only long impulses can be used.

From the system point of view it is absolutely no problem to switch over from long impulse mode to the short impulse mode. But not all systems are able to turn over from long to short impulses because of the lifetime of the solenoide valves. For the high frequency short impulse operation special solenoide valves are required with an extreme service life of some 100 millions of switching cycles.

2.3 The Preheat Area

In the preheat area the hot flue gas, coming from the fire area, transfers its heat to the cold anodes and is cooled down to the exhaust temperature between 150 and 400 centigrades depending on the time within the cycle and on the operation mode of the furnace.

The heat transfer which is related to the heating gradient in the pits is adjusted by the exhaust gas volume. As an suitable specific parameter for the characterization of the exhaust volume we found the ratio of tons per hour of waste gas versus tons per hour of baked anode. Regarding the data available to us this parameter varies between 6 and 20. Since the waste gas causes the most important heat loss of the furnace, this figure correlates with the specific energy consumption of the furnace. Furnaces with narrow flues resp. large relations of pit vs. flue geometry show generally better energy efficiency. But they are also challenging to operate, especially in the pitch burn phase.

The variation range of the exhaust volume is restricted however. On the one hand due to gas safety reasons the combustion air at the burners which is directly connected to the exhaust volume cannot be reduced at will. On the other hand the draft cannot be increased at will because the portion of inleaked air in the waste gas becomes larger with the draft. At too high draft the system overturns so that with an increase of exhaust volume the temperature gradient does'nt rise any longer but it falls [4]. We also have to ensure, that sufficient oxygen for the combustion is supplied to the pitch burn area. These partially contradicting requests are complicated by the fact that the volatile combustion in the pitch burn area is more or less uncontrollable [5].

Since the exhaust volume is a key parameter for fuel efficiency, anode quality and pollution, the task for the control is easy to formulate [6]. It should

- ensure a controlled temperature gradient at the anode
- reduce the heat losses by the flue gas to a minimum and
- ensure a complete burn of fuel and volatiles.

But this is by far not so easy to meet these damands considering the preconditions mentionned above.

3. Flue gas management

The control system has to regard the inter-dependences between the furnace areas. Especially it has to look at the oxygen content in the flue. A lack of oxygen leads at first to poor fuel efficiency and, at a higher degree to a „flooding" situation and finally to pollution and smoke at the chimney. Therefore the control system at first has to be able to detect an upcoming flooding situation and to interact in a way, that removes the problem before it becomes serious.

Since the flue gas volume affects not only the gradient of the preheat zone, but also the oxygen content in the pitch burn and fire area, two basic situations have to be considered.

3.1 Normal situation

A normal situation we may call the phase where no pitch burn takes place. Here the heat transfer in the preheat area is determined by the volume of hot flue gases coming from the fire area. The adjustment of the flue gas is done by a draft temperature cascade regulation which takes its temperature readings from the measure ramp (see diagram 5). According to the set temperature profile the master PID sets the draft setpoint within a allowed draft range. The slave PID adjusts this setpoint using the exhaust dampers.

In this „normal" situation in general we have sufficient oxygen in the fire area. Therefore the exhaust volume can be adjusted after the gradient of the preheat area in a way that the pitch burn phase is reached at a defined time for all flues.

For high energy efficient operation corresponding with lowest waste gas volume, the oxygen in the flue will be rather tight. Therefore the risk of a flooding situation can occur also in this normal situation at high burner capacity, especially on the front burner ramp. For detection of a flooding situation we proved several methods:

The extreme state of flooding is smoke at the chimney. Before that situation occurs one can detect opacity in the collection pipe of the exhaust ramp. Diagram 3 shows one singular phase with a clear correlation between opacity in the collection pipe and the burner capacity of one flue. Especially after a fire move too high burner capacity may cause opacity. The opacity reading is proved to be reliable but it cannot select, from which flue the opacity is coming. So additional indicators are necessary to identify the flooding flue.

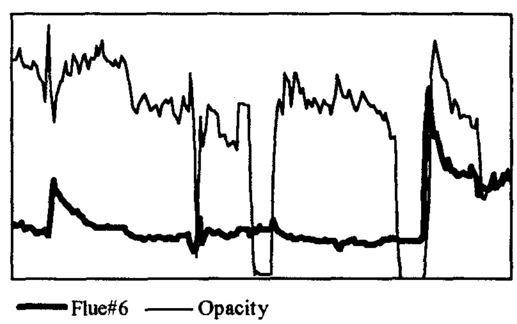

Diagram 3: Correlation between opacity and burner capacity over a period of abt. 90 hours.

Since for the control system all informations concerning burner capacities are available, one can calculate the entire fuel which is fed into an individual flue by all burners of a fire. Further we can take the readings of the pressure before (measure ramp) and behind (zero point ramp) the fire. The difference allowes an estimation of the flue gas volume going through this area.

Doing so, we can create a „flooding monitor" which calculates the specific fuel load of the flue at any time. If there is an opacity detected, the flue with the highest fuel load propably will cause the flooding situation.

In the fire area, for each burner ramp a „fuel efficiency monitor" can be established. It determines contineuously whether the momentary burner capacity corresponds with an adequate temperature gradient in the flue. If it is lower than that with sufficient oxygen, a flooding situation is detected.

Both indicators, opacity and fuel efficiency, enable to establish a model for the oxygen content of each flue at any time (diagram 5). Since the state of the flue changes by the time, the flooding monitor is enhanced by an automatic adaption which verifies the estimation using periodic test procedures.

3.2 Pitch burn situation

Recently more and more furnaces are operated with „pitch burn". This mode of operation uses the heat content of the volatiles and it avoids gaseous emissions. The benefit of this operation mode is a better fuel efficiency, less or no pollution and better anode quality. But the pitch burn asks for a more sophisticated control philosophy.

When the pitch burn starts due to the combustion of the volatiles, additional oxygen is required in the flue. The first step to handle this situation is to detect the start of the pitch burn. Since in the countercurrent heat exchange process a specific flue gas volume corresponds with a specific heating gradient, each gradient which is higher than that indicates additional heat in the flue. This heat can be generated by the volatiles only. So a first parameter for an estimation of the volatile heat flow is the excess gradient.

A second can be found from the fact, that the keeping of the higher tempera-ture requires also additional heat. Both parameters, gradient and temperature are used to estimate an equivalent fuel capacity which is fed into the flue by the volatiles.

Diagram 4 shows, that several phases of opacity, which cannot be explained by the fuel injected by the burners, are correlated with an equivalent volatile fuel. Of course there is no complete correlation between the fuel load of one individual flue and the opacity in the collection pipe because several or all flues contribute to the opacity and because there is no a linear correlation between fuel load and opacity. But using this estimation we can give a correct interpretation of the opacity.

If we add up all burner capacities and the equivalent capacity of the volatiles in a specific flue as well, we will obtain an estimation of the total fuel load in the flue. Relating this fuel load to the exhaust volume we finally find a flooding indicator, which gives an estimation for the specific fuel load of a flue and for the oxygen situation in the flue (diagram 5).

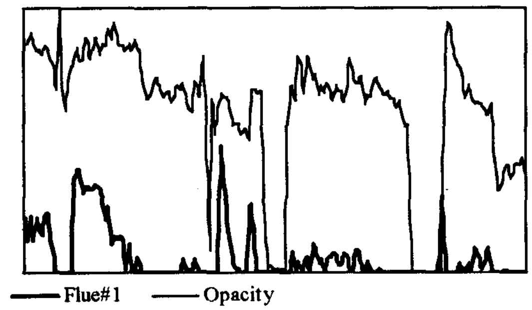

Diagram 4: Correlation between opacity and the estimated volatile load over a period of abt. 90 hours.

The task of the control system is, to avoid flooding situations. With the aid of the flooding monitor the system can react, before a flooding situation takes place. Depending on the furnace operation and situation three options for reaction are possible:

- The draft can be increased.

This can be done so far a maximum draft or a specific temperature gradient or a maximum exhaust temperature is not exceeded.

- The pressure behind the last fire ramp can be increased.

This mean can help if the flooding mainly is caused by the burners. To give an imagination for the influence of the zero point pressure on the oxygen: An increase of the pressure by 20 Pa lead to an increase of the oxygen on the front burner ramp from 4% to 10%. The limitation of pressure is given by the blow out of flue gases.

- The burner capacities can be reduced.

Because for a given flue gas volume a maximum of fuel cannot be exceeded, it may be necessary to reduce the fuel at the burners for a period of time. The least critical ramp is the front burner ramp. So normally the reduction starts at the front burner ramp. The back burner ramp should never be affected because of the anode quality.

Due to the demands mentioned above, temporary deviations from the set firing profile will occur. The time integral of the deviation corresponds to a portion of heat which is transferred tho the anode. If this integral over the whole fire cycle varies, the total heat transferred to the anode and so the final baking temperature will vary too. To eliminate this source of variance, a firing index [6] is calculated, which shows the integral of the deviation from the set temperature over the elapsed time. Using that figure, the control system calculates a corrected firing curve for the remaining time, that finally brings the deviation to zero.

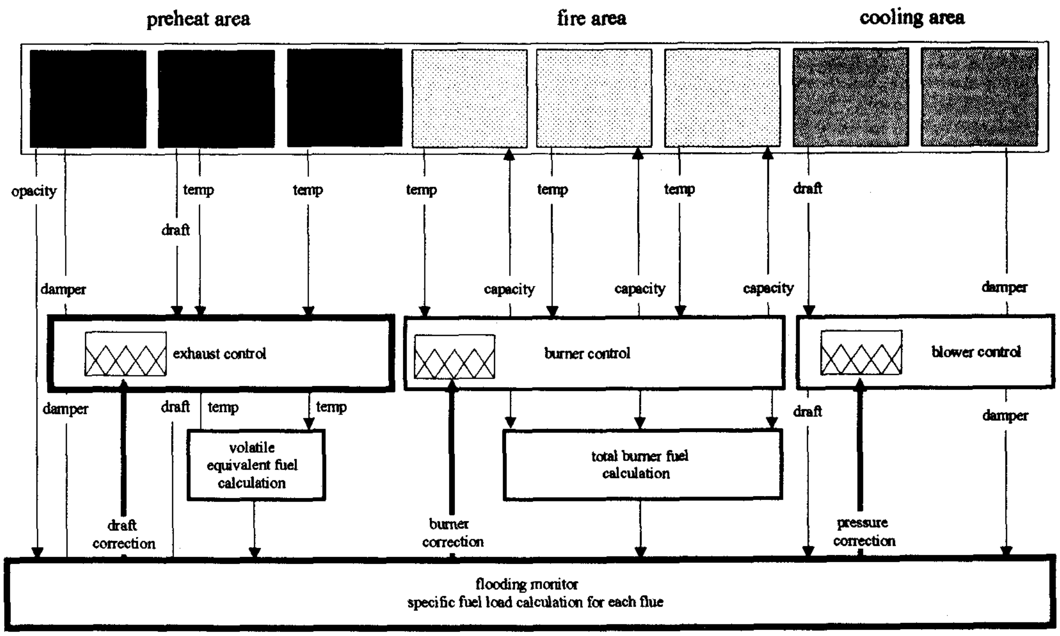

Diagram 5: Control structure of the flue gas management.

The explained criteria for an optimum flue gas control can be transformed into a control strategy as shown in diagram 5. Compared with a conventional control system, besides one opacity sensor per fire, no additional sensors or actuators are necessary for a flue gas management. As mentioned above, at first the entire fuel load of the flue is calculated. The draft difference between measure ramp and an zero point ramp and the damper positions are taken for a flue gas volume estimation.

Opacity and fuel efficiency are used for an adaption of the fuel load model which builts the flooding monitor. The flooding index, corresponding with the free oxygen in each flue, is fed into the control structures of the exhaust, burner and blower ramps. For finding a compromise between the counterspeaking demands of the individual control loops, fuzzy-PID has been found as the adequate control structure. In spite of the sophisticated structure the system is transparent because of the additional informations and it is easy to operate.

Summary

The benefits of state of art equipment for horizontal flue furnaces as are zero point control and short impulse low NOx gas burners are explained. An advanced method to detect and avoid flooding situations and to ensure maximum energy efficiency at a minimum of emissions without loosing any quality of the anodes is described. This flue gas management is based on the flooding monitor which contineously estimates the specific fuel load resp. the amount of free oxygen for each flue.

References

1. B. J. Racunas,
„Anode Baking Furnace Thermal Balance"
AIME Light Metals, 1980, 525 - 530

2. W. F. Crowell,
„Anode Baking Furnace Developments at Noranda Aluminum"
AIME Light Metals 1981, 583 – 595

3. E. Dernedde,
„The leakage of Air in Horizontal Flue Ring Furnaces"
AIME Light Metals 1987, 591 – 595

4. J. G. Perarcy, J. Auton, J. Kaiser,
„Reduced Fuel Consumtion in Noranda Aluminum's open Pit Baking Furnaces"
AIME Light Metals 1983 777 - 789

5. E. Dernedde, A. Charette, T. Bourgois, L. Castonguay:
„Kinetic Phenomena of The Volatiles in Ring Furnaces",
AIME Light Metals 1986, 589 - 592

6. W. Leisenberg,
„New tools for supervision and control of open pit anode bake furnaces"
AIME Light Metals 1998, 729 - 732