Optimization of lime kilns based on strategies of advanced process control - case study Cenibra

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Abstract

Lime reburning is the process of converting lime mud sludge (essentially, CaCO₃) generated in the causticizing plant to reburned lime (CaO) that takes place at high temperatures in a rotary lime kiln, which is both a chemical reactor and heat transfer device. In this project, a control strategy was developed for the lime kilns in a Brazilian pulp mill in order to reduce the variability on calcination process and decrease the consumption of fuel. This control strategy was developed based on the concept of APC (Advanced Process Control) with automatic generation of set points, that varies depend on the characteristics of the process. It works according to thermodynamic principles of lime kiln operation and based on the physic-chemical of combustion and calcination reactions. In this project, a multivariable controller was developed in the DCS, through which the main control variables for the lime kiln are adjusted automatically, without operator intervention. The following gains were reached after the implantation of this project: reduction of more than 3% in fuel consumption, less variability in the amount of residual carbonate in the lime, with a higher incidence of analysis in the desired range and fewer occurrences of analysis in the unwanted range (results of residual carbonate too low or too high), resulting in a better quality of lime to the causticizing process.

Key words: Advanced Process Control; Lime Kiln, Calcination Process.

Introduction

The purpose of the lime reburning is to convert the CaCO₃ produced in the causticizing process to CaO that is reused in the slaker in causticizing plant. This is possible by heating the CaCO₃ until the follow reaction occurs:

\[ \text{CaCO}_3(s) \rightarrow \text{CaO}(s) + \text{CO}_2(g) \]  \hspace{1cm} (1)

In a pulp mill, this reaction called calcination, takes place at high temperatures (850°C) in a rotary lime kiln, which is basically a large steel tube that is slightly tilted, typically between 1.5 and 3.5 ° [1] and it works as a chemical reactor and heat transfer device.

Basically, in this process, the lime mud sludge (CaCO₃), that is a byproduct of the causticizing process, is firstly washed to remove the residual cooking liquor and then dewatered on a filter to solids content of 70% or more, depending on the efficiency of this device. The dewatered mud is fed to the lime kiln where the calcination occurs, generating reburned lime (CaO) that is sent to a green liquor slaker. Figure 1 illustrates the lime cycle, where causticizing and calcination processes are extremely interdependent.
Specifically in the lime kiln, wet lime mud enters at the feed end and is transported towards the discharge end due to the rotation and inclination of the kiln. On its way through the kiln, lime mud is heated by hot flue gases that move counter-current compared to the solids. Heat is supplied from a burner located at the discharge end. The process can be described into the following stages, each representing a specific section of the lime kiln [2].

1. Drying of the lime mud.
2. Heating the lime mud to calcination temperature (about 850 ºC).
3. Calcination of CaCO$_3$ according to (1). The solids will remain at calcination temperature until all CO$_2$ has been driven off.
4. Sintering of the lime. When the lime powder is heated further the small particles agglomerates, resulting in larger particles.

The quality of reburned lime is classified by its residual CaCO$_3$ content, availability and reactivity [3]. The residual CaCO$_3$ content is typically controlled between 1.5 to 2.5% by adjusting the calcination temperature. This control target is necessary in order to avoid overburning, and to ensure the production of reactive lime. Lime availability is the amount of CaO present in the reburned lime that is available for slaking. It typically ranges from 85-95%, depending on the amounts of inert materials, and residual CaCO$_3$ in the reburned lime. Lime reactivity refers to the speed which the reburned lime can be slaked in the slaker. A highly reactive lime has a porous structure and will slake within 5 minutes. A low-reactivity lime has low availability and low specific surface area, and may take 15 to 20 minutes to slake, causing problems in slakers and causticizers [4].

The flue gas leaving the feed end of the kiln consists of combustion products, carbon dioxide from the calcination reaction and water evaporated from the wet mud. Flue gas flow is mainly controlled through the induced draft fan located at the feed end [5].

Air for the combustion is supplied by primary and secondary air at the firing end of the kiln. This makes it possible to control the flame pattern of the burner. The burner should produce a long soft flame so that the release of heat is spread out over a large area of the kiln. A shorter flame has a higher temperature which makes the heat transfer more efficient but may result in overburned lime and cause damage to the refractory of the kiln [5].
Energy Efficiency

The energy entering the lime kiln can go three directions [1]:

1. Into the lime solids.
2. Out through the shell of the kiln.
3. Out through the back end with the flue gas.

The energy put into the solids is used for heating, drying and calcination of the lime mud. The total energy required for calcination process depends on the amount of energy for drying the mud that is associated to the moisture content of the lime mud. An efficient separation of lime mud from white liquor resulting in high solids feeding the kiln is, therefore crucial for the energy efficiency of the lime kiln.

Hot lime drops through holes at the discharge end of the kiln, into the tube coolers where it preheats the combustion air to 260-370 °C. The lime thereby leaves the kiln with a temperature of 200-300 °C instead of ~1100 °C, reducing the amount of energy that has to be provided to the process [5].

The amount of energy leaving out the shell will depend on the proportions, temperature profile and insulation of the kiln. For energy efficiency, insulation is the most obvious tool for minimizing this kind of heat loss. This problem can be minimized by using a refractory lining with double bricks [1]. In a lime kiln, heat losses from the shell are usually 10-15 % of the energy input [6].

In some lime kilns, the drying zone is usually equipped with a chain system to promote heat transfer from the flue gas to the solids. As the kiln rotates, the warm chains dip into the wet solids that will stick to the chain and thereby exposing a large surface area to the flue gases. These kind of low temperature heat exchangers are very efficient and may lower the temperature of exit gas in kilns from ~650 °C to less than 200 °C [5].

Modern lime kilns are equipped with flash drying systems that offer means of increasing production rates and reducing fuel consumption. This device dries the mud outside of the kiln, thereby increasing the volume of the kiln that devoted to preheating and calcining. A production increase of up to 40% and a fuel use reduction of 10-30% are possible when a dryer is retrofitted to an older kiln [3].

The energy efficiency of a lime kiln may be described by the heat rate. The heat rate is the amount of energy that is consumed to create a certain amount of reburned lime. For an efficient lime kiln, the heat rate is about 1.5 Gcal/ton of CaO [6].

Cenibra’s Lime Kilns

There are three lime kilns in the mill. The Kiln 1 started in 1977 and has been hibernated since 2006. Its drying zone is equipped with chain system and it doesn’t have flash drying system. The Kiln 2, which has been running since 1995, has the capacity of 470 ton/day of lime, equipped with flash drying system and a satellite cooler. Kiln 3, the newest one, started in 2006 and can process 650 ton/day of lime. As Kiln 2, is also equipped with flash drying system and its cooler is a sector cooler. The flash drying system presents in the Kiln’s 2 and 3 is called Lime Mud Dryer (LMD). Until October 2010, the kiln fuels were oil and hydrogen (a byproduct of the production process of chlorine dioxide from sodium chloride). Afterwards, the oil was replaced by natural gas.
The Traditional Method of Lime Kilns Control

In the past, the control method of heat to the kilns was simple and constantly depended on the manual action of the operators. The set point of heat to the kiln was set in mega calorie (Mcal). According to the process changes such as altering of the flow of mud in the feed end, residual carbonate in the output of the kiln, temperature variations in the burning zone, in flue gas or in the LMD, the operator defined, on his own discretion, the total amount of heat to the kilns in Mcal.

The rotational speed of the lime kiln, which is a control variable in the retention time of the material inside the kiln was also controlled manually by the operator, this being a very important variable for the calcination reaction to be successful.

Other control strategies worked in automatic, operating in cascade with some process variables, may include:

- Variation of speed of the fan forced air, cascaded with the excess oxygen in flue gas leaving the kiln;
- Variation of speed of the feeding screw of mud to the LMD, cascaded with the temperature of flue gases leaving the kiln and the temperature of the LMD.

Although the main heat control for the kilns was fully manual, CENIBRA's kinls, had an average specific consumption of 1.4 Gcal / ton of lime, aiming a residual carbonate in the lime 2 to 3%, and this number is a good value for a specific consumption of lime kilns.

Aiming to reduce the specific fuel consumption of lime kilns, a project was developed to improve the controls, whose main points are presented here.

Project Development

The project challenge was to create an automatic system free from operators’ interference seeking optimal points of operation. Hence, a system was developed using the concept of APC – Advanced Process Control, with automatic generation of set-points according to the process characteristics and control based on mathematical equations.

The first step in the development of the APC was to conduct mass and energy balances to better understanding of CENIBRA's kilns. A simplified diagram of mass and energy balances of a lime kiln is presented in Figure 2. Moreover, some equations developed in those balances could be useful for implementation of control strategies.

![Figure 2. A simplified diagram of mass and energy balances of a lime kiln](image)
Through mass and energy balance, it was possible to determine the thermal efficiency of each kiln. The kilns energy balance identified how energy is used within a kiln. Table 1 presents energy use in kilns as percentage of the total input. The data analysis shows that the thermal efficiency of the two kilns is very similar.

<table>
<thead>
<tr>
<th>Energy use</th>
<th>Kiln 2 (%)</th>
<th>Kiln 3 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcining</td>
<td>58.5</td>
<td>58.0</td>
</tr>
<tr>
<td>Shell losses</td>
<td>5.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Lime losses</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Flue gas</td>
<td>33.0</td>
<td>31.5</td>
</tr>
</tbody>
</table>

The second step was the realization of bump tests to identify the response time of the process and temperature variations within the kiln, due to changes in flow or density of the lime mud. Once established, an anticipatory control was developed based on a ramp to increase or decrease the amount of heat to the lime kiln, according to information of flow and mud density.

The third step was to assess the behavior of temperatures in the burning zone, LMD and flue gas. For each of these temperatures specification limits were established. Besides reviewing the tuning of the existing control loops, a control logic, based on structured programming, has been developed, acting in the following set points: heat rate to the kiln, residual oxygen and speed of the screw which feeds mud to LMD, in order to maintain the temperature within the specified standards.

The fourth and most important step was the introduction of equations of mass and energy balances in the control strategy.

The main reaction of the lime kiln is the calcination where calcium carbonate is decomposed into calcium oxide and carbon dioxide. The fraction of the ingoing calcium carbonate that is transformed to calcium oxide in the control strategy is regulated through parameter CD (calcination degree) and is therefore decided by the operator. The mass flow of calcium oxide in the reburned lime in ton/hr is calculated as:

$$m_{CaO,RL} = m_{CaCO_3,LM} \cdot CD \cdot \frac{M_{CaO}}{M_{CaCO_3}} \quad (1)$$

where $m_{CaCO_3,LM}$ is the mass flow of calcium carbonate in the lime mud in ton/hr and $M$ represents the molar mass of the different components in g/mol. In the same way, the mass flow of residual calcium carbonate in the reburned lime in ton/hr is calculated as:

$$m_{CaCO_3,RL} = m_{CaCO_3,LM} \cdot (1 - CD) \quad (2)$$

The carbon dioxide in the flue gases through the calcination in ton/hr is calculated as:

$$m_{CO_2} = m_{CaCO_3,LM} \cdot \frac{M_{CO_2}}{M_{CaCO_3}} \quad (3)$$

The energy that comes into the lime kiln is used to dry, heat and calcinate the lime mud. Some of the energy is lost in the flue gases and by radiation and convection through the kiln shell. In the lime kiln control strategy, some equations of energy balance are used. Figure 2 is a simple model of the energy balance developed for this project.
The energy for calcination in kJ/hr is calculated as:

\[ E_{\text{Calc}} = m_{\text{CaCO}_3} \cdot LM \cdot CD \cdot H_{\text{Calc}} \]  

(4)

where \( m_{\text{CaCO}_3} \cdot LM \) is the mass flow of calcium carbonate into the kiln in kg/hr, CD is the calcination degree, the fraction of the calcium carbonate that is calcinated, and \( H_{\text{Calc}} \) is the enthalpy for the calcination of \( \text{CaCO}_3 \), 1786 kJ/kg \( \text{CaCO}_3 \) at 25°C [7].

\[ E_{\text{Dry}} = m_{\text{H}_2\text{O}} \cdot LM \cdot H_{\text{Vap}} \]  

(5)

where \( m_{\text{H}_2\text{O}} \cdot LM \) is the mass flow of water in the lime mud in kg/hr and \( H_{\text{Vap}} \) is the heat of vaporization for water, 2260 kJ/kg \( \text{H}_2\text{O} \) at 25°C [7].

Besides the energy for calcination and drying, the heat of energy of the losses must be estimated as showed in Table 1. The percentage of energy loss in lime kilns is used as a parameter of the control strategy.

The last step of the project was the construction of a multivariable controller in the DCS, through which the main control variables for the lime kiln are adjusted automatically, without operator intervention.

Two variables are used as input parameters of the multivariable controller:
- Lime mud flow
- Lime mud density

The following variables are target parameters of the control, whose values were previously defined according to best practices of operation which can be modified at any time, in the event of a significant change in process or equipments. The aim is to keep control of these variables within the desired values. Besides being target parameters, these variables are responsible for the feedback in the controller input:
- Range of temperature in burning zone
- Target of temperature in flue gas
- Target of temperature in LMD
- Target of residual carbonate
- Residual oxygen

The multivariable controller was developed based on structured programming, into which were inserted equations 1, 2, 4 and the performance of the lime kiln (according to the percentage of energy loss), obtained from mass and energy balances.

The output of the controller acts in the following manipulated variables:
- Speed of fan forced air
- Speed of feed screw of lime mud into LMD
- Heat rate to the kiln (Mcal / ton of lime)

Figure 3 is a simple diagram of working principle of the multivariable controller installed in the DCS.
Results

The overall results of specific fuel consumption of the two Cenibra kilns, are shown in the following charts, where the historical average of Cenibra is compared with 19 months of operation with the APC system being used. In the months 5, 11 and 17 there were general shutdowns of the plant for maintenance.
Effective dewatering of lime mud is of great importance in lime kiln operation. The thermal efficiency of the kiln strongly depends on the mud solids content, since heat is needed to dry off water in the mud. In principle, the fuel consumption for a lime kiln may be lowered by as much as 2% for every 1% increase in mud solids content. In practice, however, such fuel saving is more moderate, about 1%, due to the difficulty in controlling the kiln feed end temperature and keeping the residual CaCO$_3$ content of the product lime at an acceptable level [8].

In Figure 5, the specific consumption was adjusted, considering 75% of mud solids in all months. For this, it was followed the rule that for every 1% increase in mud solids content, 1% of fuel is saved.

![Figure 5. Fuel specific consumption – Mud solids = 75%](image)

Figure 6 shows the percentage of fuel saving after the implementation of the APC. Out of 19 months, only two had greater consumption than the historical figures. It is noteworthy that these two months (5 and 11) were months of general shutdown in the mill. In average the reduction of fuel was about 3.4%, representing an annual saving of US$ 450,000.
Concluding Remarks

In October 2010 the fuel oil was replaced by natural gas. With the new fuel, the operating conditions of the lime kilns modified. Therefore it was necessary to conduct a review of control strategies developed in order to adjust them to the new operating characteristics.

Conclusion

Many benefits have been achieved with the development of an APC system for lime kiln control based on the development of multivariable controller. Among the obtained gains, some of them have stood out, such as the reduction of more than 3% in fuel consumption and less variability in the amount of residual carbonate in the lime, resulting in a better quality of lime to the causticizing process.

Before APC, the operators changed the control parameters using rule of thumb for adjusting the process to get the right residual carbonate. After its development, there was standardization of operation mode. It’s worth stressing that the developed APC is fully automatic and based on absolute targets and programmed responses.

References


