LIME KILNS, HEAT TRANSFER, CONTROL AND COMBUSTION EQUIPMENT

Richard Manning
Director & Chief Technology Officer, KFS

INTRODUCTION

The location of the lime kiln on the Kraft recovery process is shown below.

WHAT IS A LIME KILN?

Rotary kilns are large steel tubes that are lined on the inside with refractory bricks. They are slightly inclined from the horizontal and are slowly rotated on a set of riding rings. Feed is introduced at the uphill end and slowly makes its way to the discharge end due to the inclination and rotation.

Rotary lime recovery kilns in the pulp and paper industry range in size from 7 ft (2.1 m) in diameter by 175 ft (53 m) long to 15 ft (4.6 m) in diameter by 450 ft (137.2 m) long. The refractory lining is from 6 in. (15.2 cm) to 10 in. (25.4 cm) thick. Production capacities for these units range from 50 tons/day of CaO (45 metric tons/day) to over 1,100 tons/day of CaO (> 1,000 metric tons/day).

The purpose of a lime kiln is to:
- regenerate (recover) CaO from CaCO₃ produced in the pulping process
- save cost of purchasing fresh lime

The causticizing reaction precipitates calcium carbonate (CaCO₃) which is separated from the liquor, washed to remove the residual liquor and dewatered on a precoating filter to a solids content of 65% or higher. The resulting lime mud is fed into a rotary kiln where it is dried and heated counter currently by combustion gases from an oil or gas burner at the other end of the kiln. As the mud temperature reaches about 800°C (1470°F) in the calcination zone of the kiln, CaCO₃ decomposes into CaO and CO₂. The resulting CaO or reburned lime is reused in the causticizing process.

\[
\text{CaCO}_3 (s) \rightleftharpoons \text{CaO (s)} + \text{CO}_2 (g)
\]

* The letters l and s in the bracket beside each compound respectively denote that the compound is a liquid or solid.

Reaction 1 is an equilibrium driven to CaO at higher temperatures. In reality, kiln operate at temperatures above the equilibrium temperature of 800°C (1470°F) to push the reaction rates faster.

The composition of lime mud varies from mill to mill depending on many factors: wood species, the impurities in the make-up lime and refractory bricks used in the kiln, the efficiencies of slakers, causticisers, clarifiers and mud washers, and the burning conditions in the kiln. On a dry basis, lime mud typically contains about 95 wt% CaCO₃ and 5 wt% of impurities.

As lime mud moves through the kiln, the composition changes as the mud begins to calcine. The calcination temperature of lime mud depends greatly on the local CO₂ partial pressure and the impurity content in the mud. Since the CO₂ concentration in the kiln gas varies from 12% CO₂ near the burner to about 25% in the back end, the decomposition temperature varies from 800 to 820°C (1470 to 1510°F). During calcination, the temperature of the solids remains constant due to heat absorption. It increases only when most of the CaCO₃ in the solids has been calcined.
The composition of the solids in the kiln lies between the composition of lime mud and the composition of reburned lime, which consists of the same ingredients as lime mud minus about 40 wt% CO₂ that has been released in the kiln. On a weight basis, reburned lime contains about 1.6 times more impurities than lime mud.

A burner is installed at the downhill or discharge end of the kiln where fuel is burned to form an approximately cylindrical flame. Heat transfer from this flame and the hot combustion gases that flow up the kiln dries, heats, and calcines the counter-flowing lime solids.

**LIME KILN PROCESS**

A generalized schematic of the exterior of a common rotary lime recovery kiln is shown below.

The material flow through the kiln is summarized below.

Key material testing points for the stable kiln operation are:
- wet mud flowrate AND density of wet mud to the filter
  - determines production rate
  - feedrate = mud flow x density x % solids
- dryness of solids from the filter to kiln
  - determines energy requirements for drying
- reburned lime product test
  - carbonate test – CaCO₃
  - determines product performance going forward to causticizing plant

A schematic of the interior features of a lime recovery kiln is shown below. Mechanical detail...
of the design and operation of the lime kiln is discussed in a later section.

**Key Material Testing Points**

- Wet mud flowrate AND density to filter
  - determines production rate
  - solids feedrate = mud flow x density x % solids

![Graph showing key material testing points](image)

Key points in operation of the lime kiln are:

- **counter current heat exchanger**
  - wet mud fed at one end is dried, heated then calcined
  - the process required heat which is provided by the burner at opposite end

- **chemical reactions**
  - drying of wet mud (vaporizing water)
  - calcining of dry mud (CaCO₃ to CaO)
  - combustion of fuels to release heat

**COMBUSTION AND HEAT TRANSFER**

The combustion process involves conversion of fuel to oxidized components releasing energy primarily in the form of heat and light. For traditional fuels used in the kraft recovery process, the core components of the fuel are carbon and hydrogen in the form of hydrocarbons. Using the simplest form of hydrocarbon, methane, the basic combustion process is:

\[
\text{CH}_4 + 2 \text{O}_2 + 7.7 \text{N}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O} + 7.7 \text{N}_2
\]

The actual heat released in the kiln is the ‘net’ heat reflecting the conversion of fuel to CO₂ (gas) and water vapor. In the US heat release values are quoted in ‘gross’ terms reflecting higher energy release to produce CO₂ (gas) and liquid water.

The primary air has high momentum (mass flowrate x velocity) compared to the surrounding secondary air. This difference in momentum causes the primary air to drawn into the center the secondary air.

Since the main control of flame profile and combustion is fuel and air mixing, cold flow modeling techniques can be used to visually simulate the combustion process in lime kilns as shown below.

- **Optimized Flame Profile**

The burner and flame play an important role in product quality and refractory service life. As with all combustion fired heat exchange equipment, higher flame temperatures mean higher production capacity and efficiency. However, excessive temperatures cause refractory damage, and over-burned, slow-reacting lime product. This tradeoff in performance results in a compromise in flame length. Three types of rotary kiln flames are shown below:
Longer flames are cooler, lazy and less well defined often washing on the kiln refractory and releasing heat well down the kiln. Shorter flames are too hot and cause refractory damage and overburned lime, while longer flames cause some loss in production capacity and efficiency, and loss of control of the product quality. A compact, medium-length flame is a good tradeoff between efficiency and refractory service life. The heat transfer from each type of flame shape is shown below.

It can be seen that the fuel requires oxygen to burn. The balance shown is stoichiometric i.e. exactly the right amount of air is provided to burn with the fuel, no more and no less. In practice, combustion process operation with excess air to ensure that all the fuel is consumed and pollutants such as carbon monoxide are released. However too much excess air results in energy being wasted heating up the spare oxygen and additional nitrogen to combustion temperatures. So minimum excess air is often used, and particularly in lime kilns. Excess air is measured as spare oxygen metered at the feed-end of the kiln and/or at the stack.

This optimum flame length varies slightly for different kiln configurations; a kiln equipped with a discharge end dam will typically operate more efficiently with a shorter, slightly wider flame. This is due to the deeper and wider bed that is formed behind the dam allowing the heat transfer to occur over a greater area without directly impacting the refractory. The material also has a slight increase in retention time in the kiln allowing the heat to “soak” in more thoroughly. A kiln without a discharge end dam will have a narrower bed and shorter retention time requiring additional kiln length and therefore time for the bed to be fully heated. In general; flame length for a kiln with a discharge end dam is typically 3 to 5 times the kiln diameter in length measured from the discharge end of the kiln, without the dam; 6 to 8 times the kiln diameter. Flame length can be monitored by recording the temperature profile on the kiln shell, a significant drop in temperature will show at the end of the flame.

However, irrespective of the shape, the flame must not touch the refractory, or serious refractory washing will occur.

More recently combustion equipment suppliers have developed validated physical and computational means to “model” flame and heat transfer characteristics in a given kiln. This is valuable as it accounts for external effects such as secondary air flow paths that can dramatically affect the flame. Many “modeled” burner designs have been installed and have resulted in increased...
operating efficiency, improved product quality, increased capacity and reduced refractory wear.

**TRADITIONAL FUELS**

The most common fuels used in lime kilns are natural gas and fuel oil as they are readily available. Fuel oil is more efficient in terms of heat transfer and results in higher kiln capacity. Natural gas easier to use and currently cheaper.

Commercially used liquid fuels range from gas (diesel) oil through to heavy fuel oil. The liquid fuels are atomized to create a spray of tiny droplets (see below). Combustion takes place in the vapor phase around the droplets before finally burned at the surface of the remaining fuel creating a very visible and luminous flame.

Natural gas burns with significantly less luminosity resulting poorer radiation and flatter heat flux profile along the kiln starting further from the kiln discharge as shown below.

The result is different positions for the calcination zone in the kiln which leads to very different temperature profiles in the kiln for the operator between oil and natural gas firing.

The zones for drying, heating and calcination change also which impacts on the kiln dynamics, responsiveness and capacity.

It is important to recognize that achieving 100% oil flame characteristics with natural gas flame is not possible in any combustion system. It is possible to increase the heat transfer from gas flame but this must be considered within the system constraints of each kiln and take into account:

- moderate increase in luminosity
- increase flame temperature
- flame shape and size
- dual fuel firing

The challenge is to bring the heat closer to the front-end of the kiln thereby making the kiln longer and more productive.

There has been in recent years a number of kilns are at least partially fired with petroleum coke (petcoke) when traditional fuels have elevated prices. Petcoke, a by-product from the oil refining process and historically has been a relatively
cheap fuel. Petcoke is a difficult fuel to burn due to low volatiles content and hence has to be co-fired with natural gas or oil to support flame stability, typically contributing 60-75% of the total heat load.

Petcoke is an efficient kiln fuel and performs well in the lime kiln as long as the sulfur and vanadium contamination is not too high. The sulfur content of petroleum coke can slightly derate the kiln due to the formation of CaSO₄, and the metals require somewhat higher use of purchased lime. These two impacts are offset by the lower cost and better energy efficiency. While petcoke firing often produces much higher NOx in terms of kiln performance, it acts more closely to heavy fuel oil. A comparison of heat transfer for natural gas, heavy fuel oil and petcoke/gas co-firing is shown below.

![Impact on Heat Transfer - Fuel Types](image)

**BIO-FUELS**

The concept of the bio-refinery and pump mills being self-sufficient in energy is growing pace rapidly. A number of pulp mill derived fuels are already being tested or used.

Solids include wood derived fuels such as wood and bark powder which have been fired directly in kilns as the main kiln fuel. The non-process elements (NPEs) in these fuels are usually low enough so that modest increase in lime makeup can control buildup of NPEs in the recovery loop.

Wood, coal and other fuels have been used for many years to provide clean fuel-gas by gasification. The lower cost of the gasification fuel offsets the high capital cost of the equipment needed to gasify these fuels. Good, stable operation is possible with gasification at on-line availability of around 85%. Performance of gasifier fuels in lime kilns is similar to natural gas in terms of production capacity and Heat Rate. Wet gasifier feedstocks can de-rate the kiln and the both the burner and chain section need to be designed for gasifier fuels.

There are several fuels generated within the pulping and recovery process. Turpentine, methanol, stripper off-gas (SOG), and non-condensable gases (NCG) have all been burned in lime recovery kilns. The energy content of these “fuels” varies considerably, but each makes a contribution to overall heat input. These materials contain some sulfur that can derate the kiln capacity, and all of them lower the heat rate of the kiln.

Tall oil has been used to fire lime kilns where its value as a mill product is low. It is a good kiln fuel with relatively low sulfur and good heating value. It would have a Heat Rate similar to fuel oil.

Pyrolysis oils have also been proposed for lime kilns and are being trialed. Some fuel handling problems need to be overcome to make this attractive.

There are several schemes to separate lignin from the black liquor to increase recovery boiler capacity. There is a number of commercial options being developed for lignin use but it has also proved difficult to handle due to its low melting point and explosive characteristics, however it has been successfully operated continuously in recently in Finland.

**KILN COMBUSTION EQUIPMENT**

The burner is supported on the hood on a carriage. Primary air and fuels are delivered to the burner on flexible hoses to allow adjustment of the burner alignment.
Waste gases (non-condensible gases, stripped off-gases, etc) are often disposed of in the kiln via dedicated separate lances as shown below. These gases can often have serious impact on flame profile, production and product quality if not correctly designed.

Natural gas and fuel oil are metered and controlled to the kiln burner using dedicated valve trains.

In North America these are designed in accordance with NFPA 86 combined with FM in the US or CSA in Canada. In Europe use the EN746-2 standard and CE marking. These govern:
- fuel handling to the kiln
- flame proving
- high and low pressure failure
- fuel shut-off

Flame detectors are used to ensure that fuel is only delivered to the kiln while the flame is ignited.
- optical flame scanners
- UV primarily for natural gas
- IR for radiant fuels e.g. heavy fuel oil, petcoke, biomass
- historically hood mounted devices
- latest options for burner mounted devices to mitigate issues with dust
FURTHER READING ON LIME REBURNING KILNS
