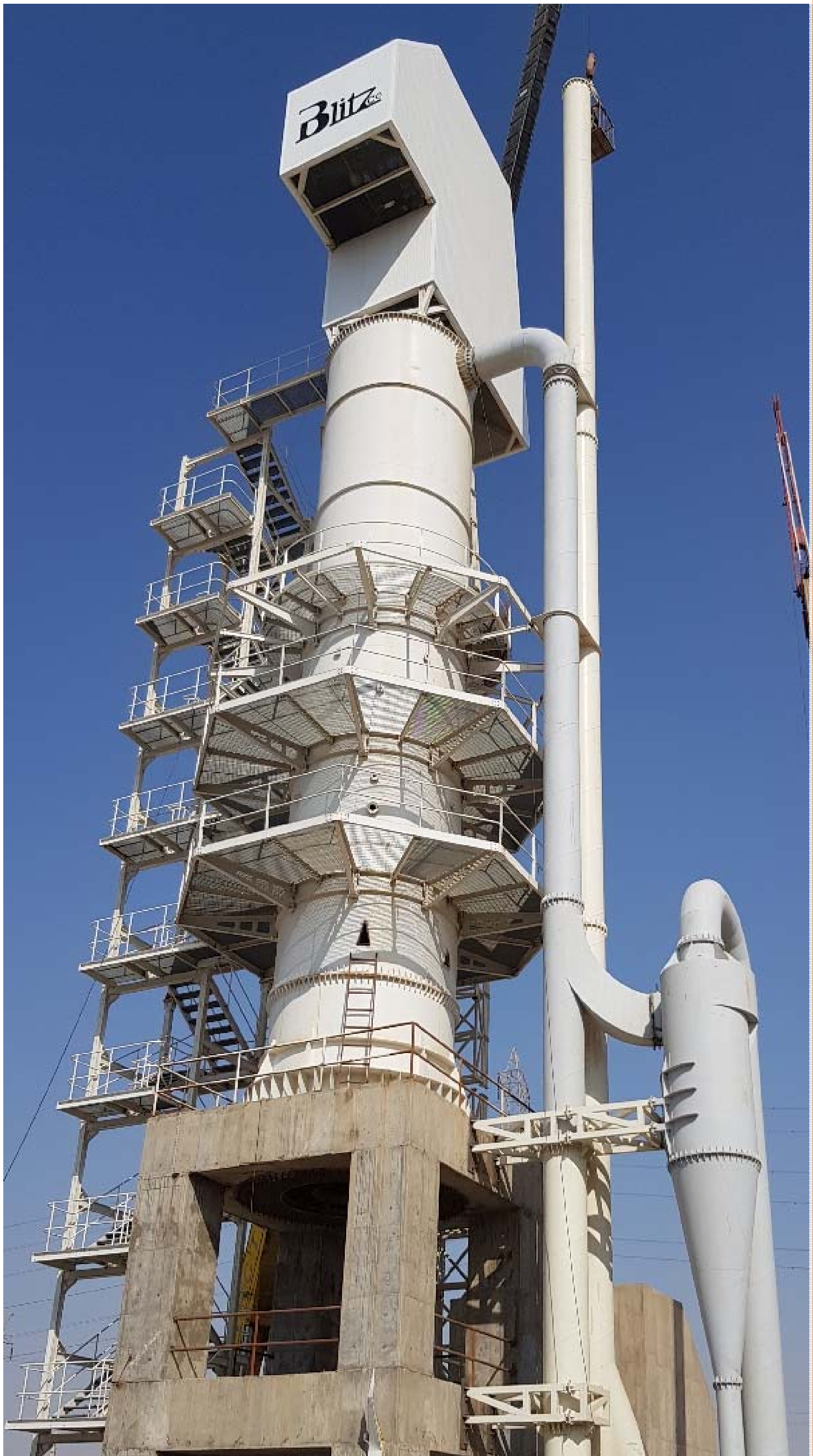
Comparison of lime kiln types



1. Processing of limestone

Limestone after its mining has to undergo several processing before it can be used in various processes. The basic processes in the production of limestone are quarrying of raw limestone, preparing mined limestone for its use by crushing and sizing, calcining of raw limestone, processing the burned limestone further by hydrating to produce hydrated lime if required for use, and miscellaneous transfer, storage, and handling operations. All these processes may not be necessary to be present in every plant.

Two types of limestone are produced. They are quicklime products, and hydrated lime products.

Lime production is a global industry that contributes greatly to social and economic development throughout the world. Many beneficial industrial and consumer applications are made possible by the use of lime.

The choice of the lime kiln is of paramount importance to a lime producer. It must be suitable for burning the selected feed-stone and for producing the required quality of quicklime. Several different types of kilns are used for the calcination process. These kilns can be rotary kilns or shaft kilns. The type of the kiln to be selected strongly depend on the characteristics of the limestone, anticipated production rate, cost of fuel, investment costs, available fuel, local conditions, infrastructure, and other things.

2. Early kiln types

The earliest kilns produced quicklime in batches, in what is described as a clamp or sow kiln. A shallow bowl was scooped out of a bank, open at the front, and with a flue, rather like an upside-down igloo. A grid was added near the base on which to start the fire, with kindling, then alternate layers of coal (or other fuel) and limestone were stacked, at a ratio of 1:4 or 1: 5. The kiln was covered with turf or clay and left to cook. Eventually, the whole thing was broken apart to recover the lime.

A similar principle was used for smelting lead ore in a ‘bole’, which was usually located on a hilltop to maximize the available draft.

A field kiln, like that shown in Figure 1, would also have been operated on a batch basis. Alternate layers of limestone and fuel would have been stacked in the kiln and the fuel set alight. After about 60 hours the quicklime would be removed from the base of the kiln. Succeeding batches were likely produced one after another because it would waste fuel to fire the kiln from cold each time. Most of the quicklime produced from these early kilns was consumed locally.

Field kilns are semi-permanent structures made entirely of stone. Field kilns, in a simple form, appeared in the north of England in the seventeenth century. Only in the mid to late nineteenth century did this design go out of use. Some may have been operated continuously, with new layers of limestone and fuel being added to the top as quicklime was withdrawn from the base.

It is difficult to assess the fuel efficiency of early kilns; a reasonable estimate would be that more than 250 kg of coal were required to produce 1000 kg of quicklime [1, 2, 3].

3- Rotary kilns

Rotary kilns started to be used for lime manufacture at the start of the 20th century and now account for a large proportion of new installations if energy costs are less important. This cylinder is set at an incline of 3 to 5 degrees and rotates at a rate of 35 to 80 revolutions per hour. The inner surface of the cylinder is lined with refractory brick. Surrounding the brick is a layer of insulation, then an outer casing of a steelboiler plate. The early use of simple rotary kilns had the advantages that a much wider range of limestone size could be used, from fines upwards, and undesirable elements such as sulfur can be removed. Most rotary kilns are fired by coal; however, with the correct adaptations, coke, oil, and natural gas can also be used [4].

3-1- Process Description

Rotary lime kiln, as demonstrated in Figure 2, is essentially a long, direct contact, counter-flow heat exchanger. The kiln is slightly sloped and rotates about its axis at approximately 1 RPM. Primary air and fuel enter through the burner pipe with additional hot secondary combustion air entering through the kiln hood. Raw limestone is fed from the elevated end and slowly moves down the kiln by the combined effects of gravity and rotation, before dropping out at the hot burner end into a cooler. The endothermic reaction that takes place in the kiln uses the hot flowing gases to decompose raw limestone ($CaCO_3$) and form calcium oxide, CaO, otherwise known as burnt lime.

$$CaC\,O_3 \dashrightarrow CaO + CO_2$$

Rotary Kiln

At the core of the sintering process, the kiln shell is a long cylinder made of steel, with a typical length ranging between 60-100 m and weighing around 1000t. Despite this impressive mass, the kiln shell is a giant with feet of clay, exposed to harsh environmental conditions. The inner part of the kiln is heated on one side by a flame to 2000˚C. The internal temperature, on the other side, is around 900˚C, while the outer layer of the shell can have to support a temperature of -10˚C during cold winters. These strong temperature gradients induce important mechanical stresses on the kiln shell, with possibly dramatic consequences on the refractory lining strength. Refractory bricks protect the kiln shell from overheating, as shell materials start to weaken at temperatures above 500˚C and the refractory brick linings in all kilns must be replaced periodically. Therefore, early detection of hotspots on the kiln shell, resulting from a refractory failure, is critical to quickly take preventive action and avoid costly maintenance and unplanned shutdowns.

Moreover, fuel consumption was relatively high because of poor heat exchange compared with shaft kilns, leading to excessive heat loss in exhaust gases. Old fashioned "long" rotary kilns operate at 7 to 10 MJ/kg. Modern installations partially overcome this disadvantage by adding a preheater, which has the same good solids/gas contact as a shaft kiln, but fuel consumption is still somewhat higher, typically in the range of 4.5 to 6 MJ/kg [5].

4. Shaft kilns

The theoretical heat (the standard enthalpy) of reaction required to make high-calcium lime is around 3.15 MJ per kg of lime, so the batch kilns were only around 20% efficient. The key to development inefficiency was the invention of continuous kilns, avoiding the wasteful heat-up and cool-down cycles of the batch kilns. The first were simple shaft kilns, similar in construction to blast furnaces. These are counter-current shaft kilns. Heat consumption as low as 4 MJ/kg is possible in the lime kiln.

Modern variants have been developed to reduce energy costs and to increase productivity such as regenerative and normal shaft kiln with different modifications.

4.1. The Normal Shaft Kiln

Traditional shaft kilns operate continuously and are fired with fuel introduced into the calcining zone. Various fuels have been used, including bituminous coal, producer gas, fuel oil, and natural gas.

3.1.1. Process Description

Vertical kilns are large vertical cylinders that are filled from the top with large chunks of limestone. These kilns have three zones, or sections: the preheating zone, the calcining zone, and the cooling zone. These zones are not physically separated from one another. They are terms used to indicate areas within the kiln, which is a continuous cylinder. Figure 2 shows a schematic diagram of a shaft kiln.

Burning fuel is injected into the cylinder just beneath the calcining zone, causing the limestone in this zone to burn. The term calcinations refers to the process of limestone thermal decomposition into quicklime and carbon dioxide. The following chemical reaction takes place in the kiln with limestone.

$$CaC\,O_3 \dashrightarrow CaO + CO_2$$

Hot gasses from the calcining zone migrate upward, warming the stone in the preheating zone. Finished lime drops into the cooling zone, where cool air is blown through it. Airblown into the cooling zone carries recovered heat upward into the calcining zone, where it also provides air for Combustion. Cooled lime is removed from the bottom, making room for the limestone and lime in the upper levels to descend.

The major problem with traditional shaft kiln is obtaining uniform heat release and movement of the burden across the shaft. Fuel-injected at a wall usually does not penetrate more than 1m into a packed bed. This limits the kiln productivity and effective kiln diameter to about 2 m.
The challenge of operating a shaft kiln to obtain high productivity is dependent on efficient control strategies.
Various techniques were used to enable the diameter of the kiln, and hence it's productive capacity, to be increased. Three important features are common to the various designs of shaft kilns: heat flow pattern, burner's type, fuel.

On producer gas kilns, the large volume of the low calorific value gas favored greater penetration and was often assisted by the injection of additional or "primary" air into the calcining zone (e.g. the Priest design). Some oil-fired kilns used recycled kiln gases to increase the penetration of the vaporized oil. Others gasified the oil in the refractory-lined combustion chamber, using 50% stoichiometric air, and injected it 1 m into the burden via water-cooled pipes thereby enabling a 4 m diameter shaft to be used.

Moreover, in modern shaft kilns, some of them are equipped with burners external to the shell and one central burner plunged in the material and also a particular arrangement of the burners at two levels. These kilns allow the production of a wide range of lime using natural gas as fuel.

4.2. Parallel flow regenerative kiln

This type of lime shaft kiln was developed at the beginning of the 1960-is in a lime factory in Wopfing / Austria. The patent was transferred in 1965 to Maerz Ofenbau AG in Zurich / Switzerland which then further developed the kiln process and the kiln design.

4.2.1. Process Description

The parallel-flow regenerative kiln is shown in Figure 3. Its characteristic feature is that it consists of two interconnected vertical cylindrical shafts (some early designs had three shafts, while others had rectangular shafts, but the operating principles were the same.

The operation of the kiln consists of two equal stages, of 8 to 15 min. duration at full output. In the first stage, fuel is injected through the lances in shaft 1 and burns in the combustion air blown Down that shaft. The heat released is partly absorbed by the calcinations of limestone in shaft 1. The cooling air in shaft 1, together with the combustion gases and the carbon dioxide from calcinations, passes through the interconnecting cross-duct into the shaft 2.

At the same time in both shafts cooling air is added from the bottom to cool the lime and to make exhaust of gases via the bottom of the kiln impossible via maintaining always a positive pressure. In shaft 2, the gases from shaft 1 mix with the cooling air blown into the base of shaft 2 and pass upwards. In so doing, they heat the stone in the preheating zone of that shaft. If this mode of operation were to continue, the exhaust gas temperature would rise to well over 500°C.

However, after 8 to 15 min., the second stage commences. The fuel and air flows to shaft 1 are stopped, and “reversal” occurs. After charging limestone to shaft 1, fuel and air are injected to shaft 2 and the exhaust gases are vented from the top of shaft1.

The direction of flow is reversed periodically (Typically 5–10 times per hour) shaft 1 and 2 changing the role of "primary" and "secondary" shaft. The kiln has three zones: preheating zone on the top, burning zone in the middle, and cooling zone close to the bottom. The cycling produces a long burning zone of constant, relatively low temperature (around 950 °C) that is ideal for the production of high quality soft burned reactive lime. With exhaust gas temperatures as low as 120 °C and lime temperature at kiln outlet in 80 °C range, the heat loss of the regenerative kiln is minimal, fuel consumption is as low as 3.6 MJ/kg.

because the cooling air is not used for combustion in this kiln process the concentration of CO_2 in the kiln off-gases is between 20% and 23% and the concentration of oxygen is between 7% and 11%. These values are not suitable for the soda ash and the sugar industry, which need a higher concentration of CO_2 in the off-gases to be used in their downstream processes [6].

Although the PFR lime kiln is currently the most important and most established lime kiln type, it is still important to continue with research work to extend its application possibilities. The following list is a summary of the topics which still need to be researched in more detail:

- ✓ more flexibility regarding the product reactivity.
- ✓ the higher concentration of CO_2 and the lower concentration of O_2 in the kiln off-gases.
- ✓ production of low sulfur lime with high sulfur fuel.

5. Heat consumption of different lime kiln types

As mentioned, Lime production is a global industry that contributes greatly to social and economic development throughout the world. Many beneficial industrial and consumer applications are made possible by the use of lime. A variety of business sectors including industrial manufacturing, utility suppliers, and environmental technologies, rely on the affordability, versatility, and practicality of lime.

The cost of lime production is mostly influenced by fuel costs. The increase in fuel prices is one of the most important problems for the lime industry. The lime industry is a highly energy-intensive industry with energy cost accounting for up to 50% of total production cost. The rapid coke price increase in the last three years caused the tendency of substituting coke with other fuels. One of the alternatives is a gas with a low calorific value (weak gas). The use of natural gas has grown substantially over the last years. Table 1 shows the distribution of the fuel types used in the EU in 1995 [6, 7, 8].

Table 1: Distribution of fuels used by the European lime industry in 1995 [8].

Fuel	**1995**
Natural gas	48%
Coal (including hard coal, coke, lignite and pet coke)	36%
Oil	15%
Other	1%

A Comparison of data for different kilns typically used for limestone calcination with important consumption figures is given in Table 2.

Table 2: Comparison of data for different kilns.

Type of calcining kiln	Kiln capacity	Limestone size	Specific consumption	Specific power consumption
	TPD	mm	kcal/kg	kWh ton
Rectangular PFR Kiln	100-400	30-120	810-870	Around 20
Circular PFR Kiln	300-800	30-160	810-870	Around 20
Annular shaft kiln	200-600	15-200	910-980	Around 30
Single shaft kiln	50-300	10-100	980-1100	Around 12.5
Rotary kiln with preheater	300-1200	10-50	1150-1350	Around 30
Long rotary without preheater	300-1000	20-50	1600-1700	Around 20

According to results, rotary kilns, with or without preheaters, usually process limestone with material size between 10 mm and 50 mm. The heat balance of this type of kilns is categorized somewhat by the high losses with the off-gases and through the kiln shell. Typical values for the off-gas losses are in the range of around 25 % and for the kiln, shell losses are in the range of around 20 % of the total heat requirement. Only around 60 % of the fuel energy introduced into the kiln with preheater is used for the process of calcining.

Besides, the refractory brick linings in all kilns must be replaced periodically, because heat, abrasion, and temperature changes cause them to disintegrate. Plants try to avoid cooling and reheating lime kilns as much as possible because this hastens disintegration [4].

In the case of vertical single shaft kilns, there exists an imbalance between the heat available from the calcining zone and heat required in the preheating zone. Even with the ideal calcination process, the temperature of the waste gases may be higher than 100 deg C.

For the solution of this problem, various techniques were used to equip with central burner, external burners at two levels, etc.

As mentioned in the process description of the modern single shaft kiln, the kiln is kept in negative pressure by a centrifugal fan sucking the combustion gases and the dissociated carbon dioxide.

In this kiln type, due to the non-periodic calcination process, the temperatures of each point of the refractory layer are almost fixed and not create any thermal shock.

The limitation of the modern lime kiln is in the production capacity because the lime kiln diameter is limited due to the burner’s technology and kiln diameter. Therefore, producing about 100 t/Day is economical and appropriate for single shaft lime kiln. The modular design of the kilns to increase production capacity up to 300-400 t/Day is quite economical.

the case of parallel flow regenerative (PFR) type of kilns, there is better utilization of the heat of the calcining zone and minimization of the loss of heat in the waste gases, resulting in lower heat consumption per ton of lime.

In the Double Shaft kilns, due to the difference in the type and the arrangement of the burners, a larger diameter can be used to design the kiln, which also includes capacities up to 1000 t/Day.

However, the process periodicity and compressed air for combustion are the main defects in the system, which will lead to more electricity consumption and high mechanical stress caused by temperature changes on refractory bricklayers.

According to the study, the gas consumption per ton of product in the double shaft kiln is less than 6-8 m^3/ton as compared to the single shaft, but consumes about 20 kWh/ton of electricity more than the one, which increases the total consumed energy costs.

6. Conclusion

Comparing the performance of the types of kilns, in addition to comparing energy consumption and different product quality, comparisons in terms of repair and maintenance costs and the time to overhaul the kilns types are also very important. Temperature changes in a different part of the double shaft kilns, which work periodically, are very high and resulting in strong mechanical stresses in kiln shell, with consequences on the strength of the refractory layers.

On the other hand, compressed air is produced by compressors, which require repairing and replacing after a short time.

A good kiln must be economical. The True economy depends not only on a kiln's cost but it is the return on investment. A good kiln will not be unduly expensive and should be also economical to operate.

Increasing overhaul time and repair and maintenance costs of refractory layers and compressors in the double shaft lime kiln raise the operating costs.

While single shaft lime kiln does not require compressed air produced by the compressor. Due to the temperature uniformity in different areas of the refractory layer, the thermal shock and the need for repair and maintenance are considerably reduced.

References

1. Smith, Nicky (May 2011). "Pre-industrial Lime Kilns" Introductions to Heritage Assets. English Heritage. Retrieved 21 April 2013.

2. Siddall, Ruth. "Kiln Architecture and Technology" Materials Science. University College, London. Retrieved 21 April 2013.

3. David Johnson, Limestone Industries of the Yorkshire Dales: 2nd edition, Amberley, ISBN 978-1-4456-0060-4.

4. Robert H. Beach, A. Michelle Bullock, Katherine B. Heller, Jean L. Domanico, Mary K. Muth , lime production, Research Triangle Institute Center for Economics Research, Research Triangle Park, NC 27709.

5. James Macphee, CFD Modelling of a Rotary Lime Kiln, Department of Mechanical Engineering University of Canterbury Christchurch, New Zealand January 2010.

6. P. C. Okonkwo, S.S Adefila, Strategies for Operations of Vertical Shaft Kilns, International Journal of Applied Science and Technology Vol. 2 No. 2; February 2012.

7. Zur Erlangung, Akademischen Grades, Dynamic Process Simulation of Limestone Calcination in Normal Shaft Kilns, PH.D. Thesis, 1974.

8. European Commission: Reference Document on Best Available Techniques in the Cement and Lime Manufacturing Industries, March 2000.