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The Rotary Kiln Evolution and Phenomenon

This chapter introduces the reader to rotary kilns as an alternative to other unit operation devices. Here, the history and evolution of the rotary kiln and some processes that have found applications over the years are presented.

1.1 The Rotary Kiln Evolution

Rotary kilns have been synonymous with cement and lime kilns probably because of the history of their evolution and development. It has been reported that cement deposits characterized by Israeli geologists in the 1960s and 1970s place cement making at 12,000,000 BC when reactions between limestone and oil shale occurred during spontaneous combustion to form a natural deposit of cement compounds (Blezard, 1998). Between 3000 and 300 BC the cement evolution had continued with the Egyptians who used mud mixed with straw to bind dried bricks to carry out massive projects such as the pyramids. This evolution continued with the Chinese who used cementitious materials for the building of the Great Wall. Projects such as the building of the Appian Way by the Romans later led to the use of pozzolana cement from Pozzuoli, Italy, near Mt. Vesuvius. However, it is reported that the technology that uses the burning of lime and pozzolan to form a cementitious admixture was lost and was only reintroduced in the 1300s. In the United States, projects such as the construction of a system of canals in the first half of the nineteenth century, particularly the Erie Canal in 1818, created the first large-scale demand for cement in this country that led to various cement production businesses to compete for the market share. By 1824 Portland cement had been invented and developed by Joseph Aspdin of England; this involving the burning of finely ground chalk with finely divided clay in a lime kiln yielding carbon dioxide as an off-gas (Peray, 1986). In these early days, stationary kilns were used and it is said that the sintered product was wastefully allowed to cool after each burning before grinding. The history of cement (Blezard, 1998) has it that in the late 1870s one Thomas Millen and his two sons, while experimenting with the manufacture of Portland cement in South Bend, Indiana, burned their first Portland cement in a piece of sewer pipe. This perhaps marked the first experimental rotary kiln use in America. By 1885, an English engineer, F. Ransome, had patented a slightly tilted horizontal kiln that could be rotated so that material could move gradually from one end to the other. The underlying principle of this invention constitutes the rotary kiln transport phenomenon we know of today.

Because this new type of kiln had much greater capacity and burned more thoroughly and uniformly, it rapidly displaced the older type kilns. It has been further mentioned that the factor that contributed to the tremendous surge of Portland cement between 1880 and 1890, reportedly from about 42,000 to 335,000 barrels, was the development of the rotary kiln (Blezard, 1998). Like most early inventions in the United States, it is said that Thomas A. Edison played a role in furthering the development of the rotary kiln. He is credited for introducing the first long kilns used in the industry at his Edison Portland Cement Works in New Village, NJ, in 1902. His kilns are believed to have been about 150 ft long in contrast to the customary length at that time of 60–80 ft. Today, some kilns are more than 500 feet long with applications ranging far wider than cement and lime making. By the 1900s, most of the advances in the design and operation of cement and lime kilns had undergone a systematic evolution since the days of the ancient Egyptians. By this time, almost countless variations of patented kilns had been invented and promoted although some of these never found useful applications. It is fair to say that kilns have evolved from the so-called field or pot kilns that were crudely constructed of stone and often on the side of hills, to vertical shaft and rotary kilns with each evolution step carried out with the improvement of labor intensiveness, productivity, mixing, heat transfer, and product quality in mind.

Following cement, other industries also joined in the bandwagon. For example, the rotary kiln process for making lightweight aggregate (LWA) was developed by Stephen Hayde in the early 1900s in Kansas City, Missouri (Expanded Shale, Clay, and Slate Institute). In the expanded shale industry, natural lightweight aggregates had been used to make lightweight concrete since the days of the early Greeks and Romans, but it was not until the discovery of expanded shale, manufactured by the rotary kiln process, that a lightweight aggregate with sufficient strength and quality became available for use in the more demanding reinforced concrete structural applications.

Currently, rotary kilns are employed by industry to carry out a wide array of material processing operations; for example, reduction of oxide ore, reclamation of hydrated lime, calcining of petroleum coke, hazardous waste reclamation, and so on. This widespread usage can be attributed to such factors as the ability to handle varied feedstock, spanning slurries to granular materials having large variations in particle size, and the ability to maintain distinct environments, for example, reducing conditions within the bed coexisting with an oxidizing freeboard (a unique feature of the rotary kiln that is not easily achieved in other reactors). The nature of the rotary kiln, which allows flame residence times of the order of 2–5 s and temperatures of over 2000 K, makes such kilns a competitive alternative to commercial incinerators of organic wastes and solvents. However, the operation of rotary kilns is not without problems. Dust generation, low thermal efficiency, and nonuniform product quality are some of the difficulties that still plague rotary kiln operations. Although the generally long residence time of the material within the kiln (typically greater than one hour) aids in achieving an acceptably uniform product as the early users had intended, there is considerable scope for improving this aspect of kiln performance. In order to achieve this improvement a more quantitative understanding of transport phenomena within the bed material is required; specifically of momentum transport, which determines particle motion and energy transport, which, in turn, determines the heating rate for individual particles. This book seeks to present the quantitative understanding of the transport phenomena underlying the rotary kiln.

Fundamentally, rotary kilns are heat exchangers in which energy from a hot gas phase is extracted by the bed material. During its passage along the kiln, the bed material will undergo various heat exchange

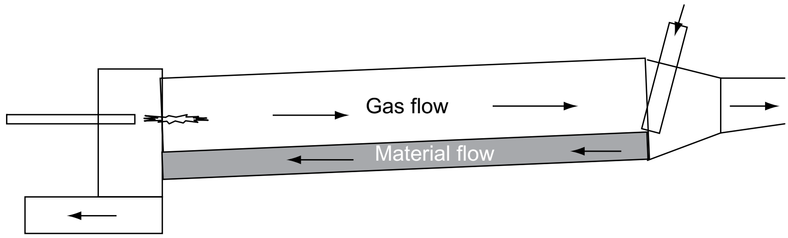

Figure 1.1 Schematic diagram of countercurrent flow rotary kiln configuration.

processes, a typical sequence for long kilns being drying, heating, and chemical reactions that cover a broad range of temperatures. Although noncontact (i.e., externally heated) rotary kilns are employed for specialized work, most kilns allow direct contact between the freeboard gas and bed material as shown in Figure 1.1. The most common configuration is counter current flow whereby the bed and gas flows are in opposite directions although co-current flow may be utilized in some instances, for example, rotary driers.

1.1.1 Comparison of the Rotary Kiln with Other Contactors

As can be seen from the history of its evolution, the design and operation of rotary kilns have undergone a systematic evolution since the days of the ancient Egyptians. Improvements include reduced labor, increased productivity, mixing, heat transfer, and product quality. Mineral processing kilns can be classified as vertical, horizontal, or other miscellaneous mixed types (Table 1.1). At one extreme, vertical kilns operate in the packed-bed mode whereby the material being processed (calcined) is charged from a top hopper and contained in a vertical chamber in which the static bed moves, en bloc, downward in plug flow. An example is an annular shaft kiln schematic shown in Figure 1.2.

Here the charge can be either in countercurrent or in parallel flow to the combustion gases that transfer heat to the solids (e.g., limestone) as the gas flows through the particle-gas interstices. To maximize heat and mass transfer in such devices, ample voidage within the particulate charge is necessary. This ensures uniform circulation of hot gases through the packed bed. Feed particle size and distribution must be selected to ensure an optimum voidage. Typically, particle size greater than 50 mm (2 in.) is normal for shaft kilns leading to a typical charge void

Table 1.1 Typical Features of Rotary and Other Contact Kilns

Vertical Kilns	Horizontal Kilns	Other/Mixed
Traditional shaft-type kilns	Conventional long wet, dry rotary kilns	Fluidized-bed type kilns
Indirect gas-fired	Direct or indirect fired	Gas suspension type kilns or flash calciners
Large capacity, mixed feed, center burners	Noncontact externally heated small capacity kilns used for niche applications	Rotary hearth with traveling grate or calcimatic kilns
Parallel flow regenerative type	Modern with recuperators such as cooler type, preheater kilns and internals	Horizontal ring type, grate kilns, etc.
Annular or ring type	Cylindrical	Cylindrical, rectangular, etc.

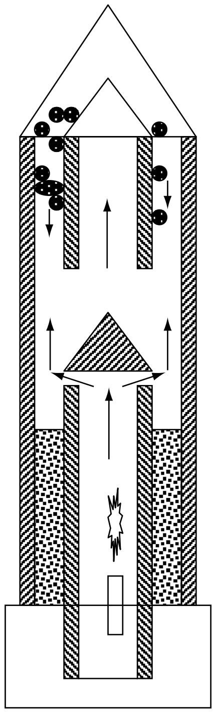

Figure 1.2 Schematic diagram of annular shaft kiln.

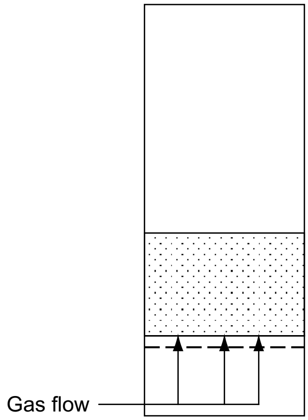

Figure 1.3 Schematic diagram of a fluidized-bed calciner.

fraction of about 45 percent. At the other extreme to packed beds, as encountered in vertical shaft kilns, are fluidized bed contactors or related kilns whereby the charged particles are suspended by the hot gases in a dilute phase (Figure 1.3).

In fluid-bed suspension kilns, the void fraction can be on the order of 60–90 percent. The hot gases perform two functions, that is, they fluidize or suspend the particles, and, at the same time, they transfer heat to the particles. Although heat transfer is extremely efficient at the gas-particle level, a tremendous amount of energy is required to keep the bed in suspension and to move the charge. Since fluidization is a function of particle size, feed particles can only be fed as fines. Additionally, because of vigorous mixing associated with fluidization, attrition and dust issues can be overwhelming. In between these two extremes are the horizontal rotary kilns (Figure 1.1) that offer a distinct environment for combustion gases (freeboard) and the charge (bed). Unlike packed bed vertical kilns, some degree of bed mixing is achieved by kiln rotation and associated phenomena although not to the extent achieved by fluid-bed suspension kilns. Rotary kilns have evolved as the equipment of choice for most minerals processes because they provide a compromise between the packed and suspension bed type mode of operation thereby allowing large capacity processing with few process challenges.

In spite of the distinctions described herein, most kilns, vertical or horizontal, when used for thermal processing, for example, calcination, oxidation, reduction, and so on, in a continuous operation will have distinct zones along their axial length. These will include a preheating zone where the particles are preheated, a combustion zone that normally coincides with the location along the vessel where the combustion or the flame is situated, and the discharge or cooling zone behind the flame. The extent of the intended reaction and, for that matter, product quality, is most influenced by the conditions in the combustion zone where heat must be supplied to the solids, for example, in limestone calcination well above the dissociation temperature. For product quality purposes, it is important to ensure that the temperature in the calcining zone is uniform, with no hot or cold spots and that it can be controlled within a tolerable limit. Of all the furnace types described above, one can say that the rotary kiln offers the best potential to control the temperature profile.

1.2 Types of Rotary Kilns

Several rotary kiln designs have evolved, each specific to the process application it is intended for. They also come in several forms and shapes. Although the majority consist of straight, cylindrical vessels, dumbbell-shaped designs (Figure 1.4) take advantage of the benefits that variable drum sizes can bring to process application. With regard to internal kiln fixtures, most direct fired kilns are lined with refractory materials for several reasons but the primary purposes are to insulate and protect the outer shell, in high temperature applications, from thermal damage and to save energy. Kilns may also be equipped with dams to increase the material dwell time or with lifters and tumblers (Figure 1.5) to aid the materials to flow axially and in some cases to improve particle mixing achieved through surface renewal. Table 1.2 presents some of the energy-saving advantages of using lifters in various applications and processes. Some of these savings can be substantial.

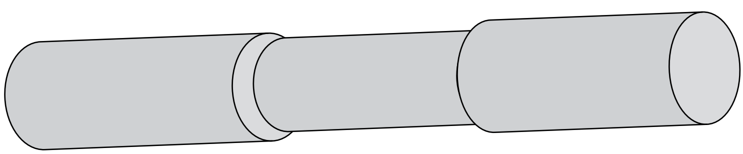

Figure 1.4 Schematic diagram of a dumbbell-type rotary kiln.

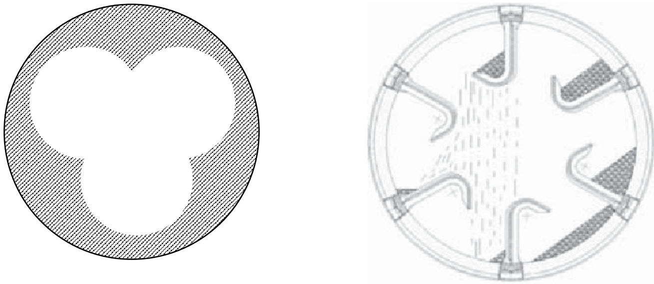

Figure 1.5 Schematic diagram of kiln internal fixtures: trefoil (left) and J-lifter (right).

Table 1.2 Advantages of Using Lifters (Data in Imperial Units)

	Before Lifters Installed	After Lifters Installed	Percent Change
12 × 250 ft LWA kiln	Added 3 rows of lifters + 3 dam		
Product rate [STPD]	650	970	47
Specific heat consumption [MBTU/ton]	2.6–2.8	2	–35
Exit gas temperature [°F]	1200	730	39
Kiln speed [rpm]	1.6	2.7	70
11 × 175 LWA Kiln	Added 3 rows of lifters + 1 dam		
Capacity [TPD]	550	625	14
Specific heat consumption [MBTU/ton]	2.53	2.24	–12
Exit gas temperature [°F]	1050	850	19
Kiln speed [rpm]	1.75	2.3	31

Owing to the poor thermal efficiency of earlier long kilns and the need for fuel efficiency, most designs are aimed at maximizing mixing and heat transfer. To accomplish this, kilns are often equipped with heat recuperators, such as preheaters, in which part of the energy in the exhaust gas is recovered to preheat the feed before it enters the kiln. Although coolers are often used to cool the product for safe material handling, they are also used to recuperate the energy, which would otherwise go to waste, as in the earlier-day kilns, to preheat the combustion air and/or to provide other energy needs. Of the modern day rotary kilns the following can be distinguished: wet kilns, long dry kilns, short dry kilns, coolers and dryers, and indirect fired kilns. Some of these are discussed on the following page.

1.2.1 Wet Kilns

Wet kilns are those that are usually fed with slurry materials. Wet kilns are usually long with kiln lengths on the order of 150–180 m (about 500–600 ft). The feed end is usually equipped with chains that serve as a heat "flywheel" by recuperating the heat in the exhaust gas for use in preheating the feed to assist the drying. Chains are also used to break up any lumps that the material might form during the transition phase of changing from slurry to solids upon drying. In the cement industry these kilns are often not efficient and are becoming a thing of the past replaced by long dry kilns. Nevertheless, there are certain applications that are not amenable to the alternative use of long dry kilns, for example, lime mud kilns found in the pulp and paper industry and some food applications.

1.2.2 Long Dry Kilns

These are shorter than wet kilns with lengths on the order of 90–120 m (about 300–400 ft). For long dry kilns, as with wet kilns, the drying, preheating, and calcination all occur in the one single vessel (Figure 1.6).

Figure 1.6 Wet, long cement kiln. (Courtesy of FLS Minerals.)

However, they work well when the feed particles are large. The reason for the relatively shorter length is that the feed is dry with a moisture content the same as granular solids rather than slurry. Applications include lime kilns and lightweight aggregate kilns where the mined stones are crushed to about 1.3–5 cm (0.5–1.5 in.) before feeding them into the kiln.

1.2.3 Short Dry Kilns

Short dry kilns are usually accompanied by an external preheater or pre-calciner (Figure 1.7) in which the feed is dried, preheated, or even partially calcined prior to entering the main reactor (kiln). As a result the thermal load on the kiln proper is reduced. Hence kilns equipped with preheaters or precalciners tend to be short, on the order of 15–75 m (about 50–250 ft) depending on the process. The shorter kilns are those in which the entering feed material is almost calcined. Applications include cement and some lime kilns. Because of the large feed particle size encountered in limestone calcination, modern lime kilns are equipped with preheaters which function as a packed bed of stone with a countercurrent flow of kiln exhaust gas rather than the typical cyclone preheaters in cement kiln systems.

1.2.4 Coolers and Dryers

Some coolers and dryers can be in a form of contactors such as the rotary kiln itself, although some are packed-bed contactors such as grate coolers. Rotary coolers can be either in-line or attached (Figure 1.8), the number of which is determined by a simple formula

$$N = \pi \times (D + d + 2)/(d + 1) \tag{1.1}$$

where D and d are the respective diameters of the kiln and the cooler. However, attached coolers place extra mechanical load that must be accounted for in design calculations. They also present maintenance challenges. Rotary coolers and dryers would normally be equipped with tumblers and lifters, which cascade the material well above its angle of repose to take advantage of better solid-gas contact.

Figure 1.7 Cement kiln equipped with cyclone preheaters.

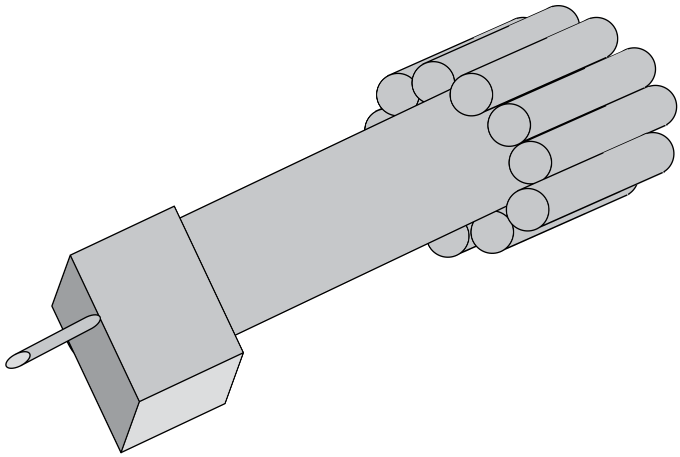

Figure 1.8 Schematic diagram of an attached cooler arrangement.

1.2.5 Indirect Fired Kilns

Indirect fired kilns are those heated externally. They are usually designed for applications where direct contact between the material and the gas providing the heat source is undesirable. In this case, the heat source is external to the kiln (Figure 1.9). Any internally flowing gas that is in the freeboard is used for purging any volatile or gas that arise from the bed as a result of chemical/physical reactions. Because of their low thermal efficiency, externally heated kilns are small, typically up to 1.3 m (50 in.) diameter and are used for niche applications such as calcining of specialty materials.

A unique feature of indirect-fired rotary kilns is multiple and compartmentalized temperature control zones, which can be electrically heated or gas fired individually. Therefore, they provide the capability of achieving high temperatures. In some cases, for example graphite furnaces, they can attain temperatures on the order of 2400 °C. The zones can also facilitate tightly defined residence times and controlled atmosphere including flammables. Typical applications include calcination, reduction, controlled oxidation, carburization, solid-state reactions and purification, including waste remediation on a small scale, that require extremely high temperatures and tight control. Materials processed in indirectly fired rotary kilns include phosphors, titanates, zinc oxide, quartz ferrites, and so on. These are usually small in quantity but with a high margin of commercial materials that are economical to process in small quantities.

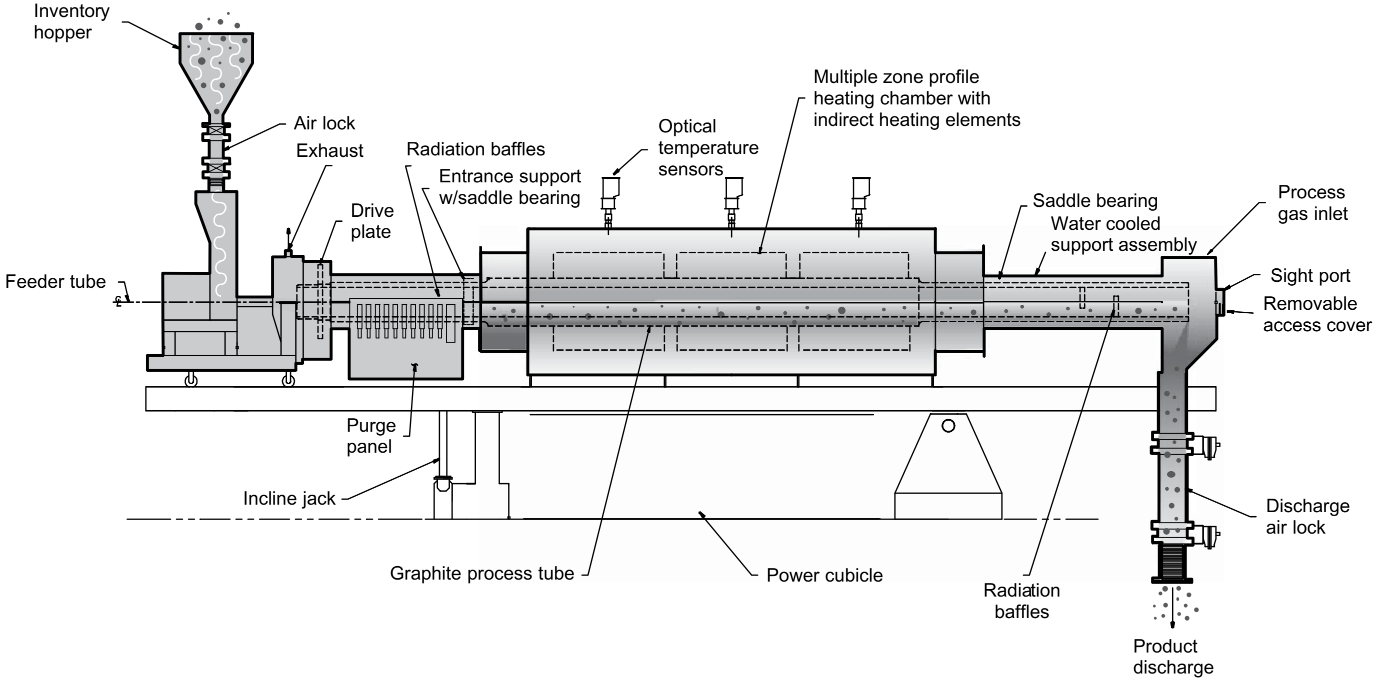

Figure 1.9 Indirect-fired small rotary kiln used for niche applications. (Courtesy of Harper International, Lancaster, NY.)

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