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QUALITY AND PROCESS PERFORAMNCE OF ROTARY KILNS AND SHAFT CALCINERS

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Abstract

Rotary kilns have been used successfully for many years to produce calcined coke for the aluminium industry and they offer a high level of automation, performance and flexibility. Shaft calciners make a high bulk density, coarse particle size product and several papers have been published recently highlighting these benefits. This paper presents a comparison of the merits of these two different calcining technologies from a product quality and process performance perspective. It addresses several misconceptions about the technologies related to operability, product quality and their ability to handle a wide range of green coke qualities. Both technologies will continue to be used in a complimentary manner in the future.

Introduction

Several papers have been published over the last 5 years comparing rotary kiln calciners to shaft calciners [1,2,3,4]. Shaft calciners are common in China but there are very few operating outside of China. Rotary kilns on the other hand, have been the technology of choice for most of the rest of the world and the technology is generally well known and understood.

Most of the papers referenced above do a good job of describing the differences between the two technologies and the generic differences in product quality. What is not covered in much detail, are differences in operation and some more subtle differences in product quality. This has led to a number of misconceptions about the pros and cons of each technology.

Rain CII has operated rotary kilns for many years and has been a supplier of calcined coke to the aluminium industry for over 50 years. Rain CII's first experience with shaft calcined coke was in 2001 when it imported small volumes into the US for blending with rotary kiln product. Through a marketing arrangement, Rain CII has also supplied Chinese shaft calcined coke to the smelting industry for ~6 years. One such smelter, the Tomago smelter in Australia, has extensive experience using shaft calcined cokes.

In August 2009, Rain CII purchased a small 20,000 ton/year shaft calciner in China. The aim was to gain more direct operating experience with the technology. The combination of supplying shaft calcined coke to the aluminium industry and operating a shaft calciner has given the company a unique perspective on the merits of the two technologies.

The purpose of this paper is to present a suppliers perspective on the two technologies. Both have their pros and cons and these will be covered in detail in the paper. Combining the two technologies probably makes the most sense for the industry in the future.

Brief Review of Rotary Kiln and Shaft Calcining

The primary goals of calcining green coke are to: 1) remove volatile matter, 2) densify the structure to avoid shrinkage of coke during anode baking and 3) transform the structure into an electrically conductive form of carbon. Green petroleum coke typically contains 9-13% volatile matter (VM). Real density (RD) is the most common measurement for tracking development of coke structure. Most anode producers prefer coke with an RD in the range of 2.04 – 2.08 g/cc. The industry trend is towards lower RD and several papers have been published on this recently [5,6]. Rain CII's experience with shaft calcined coke is based on coke with a typical RD of 2.03-2.04 g/cc.

Rotary kilns are large diameter, sloped, refractory lined steel-shelled cylinders which rotate during operation. Green coke is fed continuously in one end and calcined coke is discharged from the other end at 1200-1300°C. The coke bed loading in the kiln is low (7-10% of the cross-sectional area) as depicted in Figure 1. Heat is transferred to the coke bed predominantly by radiative and convective heat transfer from the counter-current gas stream and refractory lining. 40-50% of the VM is combusted inside the kiln and the rest is combusted in a pyrsocrubber upstream of the kiln. The VM combusted in the kiln provides most of the heat for calcination but natural gas, fuel oil and/or pure oxygen can be added to provide additional heat.

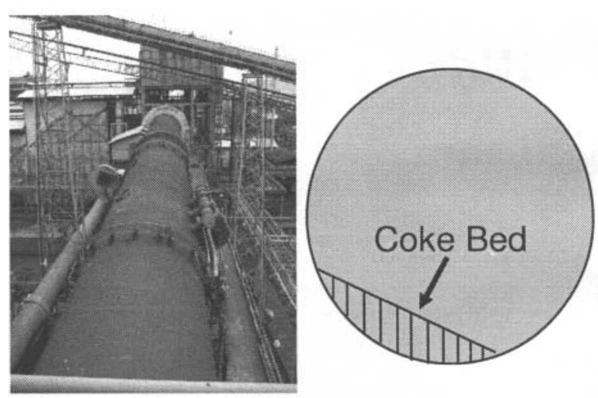

Figure 1. Rotary kiln calciner & coke bed loading in kiln

A shaft calciner has multiple vertical refractory shafts surrounded by flue walls. The green coke is fed into the top and travels down through the shafts and exits through a water cooled jacket at the bottom, Figure 2. The movement of coke is controlled by opening a slide gate or rotary valve at the bottom of each shaft to discharge a small amount of coke. The discharge is intermittent (~every 20 minutes) and green coke is added to the top to maintain the feed.

The VM in a shaft furnace travels up through the coke bed and enters flue wall cavities at the top of the furnace. It is mixed with air at this point and then drawn down through a set of horizontally orientated flues. VM is combusted inside the flue walls and heat is conducted to the coke indirectly from the flue walls in an analogous manner to heat transfer in an anode bake furnace.

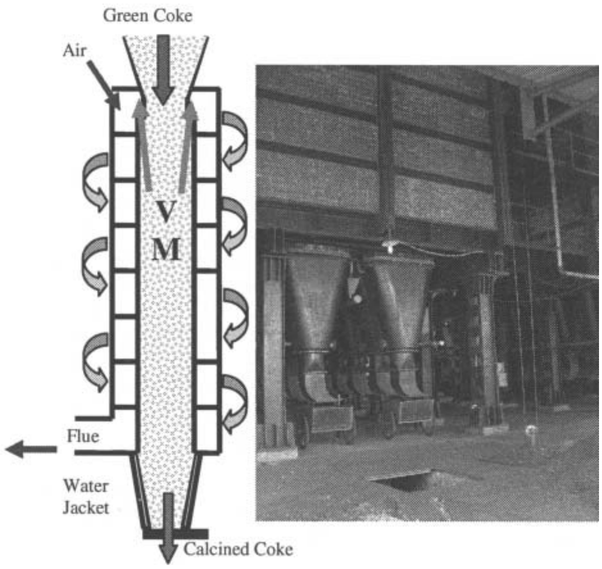

Figure 2: Shaft furnace cross-section and shaft outlets

With this brief overview, the major fundamental differences between the two technologies are as follows:

- There is a large volume of counter-current gas flowing inside a rotary kiln over the top of the coke bed. The air or oxygen required for combustion of VM is added through primary, secondary and tertiary air fans.
- The large gas volume in the kiln causes entrainment of fine green coke. Typically, ~10% of the green coke is entrained in the flue gas stream and combusted in a pyroscrubber along with residual VM from the kiln.
- There is very little counter-current gas flow inside a shaft calciner. The only flow is VM traveling up through the coke bed before it enters the top flue walls.
- There is virtually no carryover of fine green coke into the flue walls in a shaft calciner.
- The yield of calcined coke per ton of green coke is significantly higher in a shaft calciner. A typical yield in a rotary kiln (dry basis) is 77-79% which represents the yield after loss of VM and fines. The comparable yield for a shaft calciner is 85-88%.
- The coke residence time is much shorter in a rotary kiln than a shaft calciner (~50 minutes vs 28-36 hours). This translates to a significantly higher heat-up rate for green coke in a rotary kiln (~50-100°C/min versus ~1-2°C/min in a shaft calciner).

Impact of Differences on Calcined Coke Quality

Bulk Density & Apparent Density

The differences outlined above have a significant impact on some calcined coke quality parameters. The most universally reported difference is the higher bulk and apparent density achieved with a shaft calciner. This is due to the slower heat up rate of green coke.

The loss of VM creates porosity in coke. Lower VM gives lower porosity (and higher density) so lower VM green coke is always preferred. Porosity is also a function of the heat-up rate of the coke and this is a well known and documented phenomenon [7,8]. Faster heat-up rates create higher porosity and lower bulk density.

In a shaft calciner, the slow heatup gives more time for thermal cracking and polymerization reactions and can almost be considered an extension of the delayed coking process. The typical mercury apparent density of shaft calcined coke is 1.79-1.82 g/cc. The same coke calcined in a rotary kiln might yield a mercury density of 1.73-1.77g/cc depending on how it is calcined.

The differences in density between shaft calcined coke and rotary kiln coke are relatively small at low VM (9-10%) but increase as the green coke VM increases. Some high VM (>13.5%), fine particle size green cokes calcined in a rotary kiln can give mercury apparent densities as low as 1.67-1.70 g/cc. Such low densities may also be driven by structural differences between cokes (degree of isotropy) as well as VM content.

An unfortunate quality trend for green cokes is increasing VM. The trend towards heavier, sour crudes increases vacuum resid. volumes and refineries have to increase the throughput of their cokers. This is typically achieved by lowering cycle times and reducing coking severity. Higher throughputs usually mean lower coker feed temperatures and both of these favor higher VM. Historically, the calcining industry has used cokes with VM in the 9-12% range. This range is growing, and cokes with VM >12% are used more and more frequently in blends.

Shaft calciners are much better at dealing with this problem than rotary kilns but there is a caveat to this which is discussed in more detail later. When high VM cokes are used in a shaft calciner, they must be blended with lower VM green cokes and calcined coke to maintain the average VM in a narrow range, typically 11-12%.

Particle Size

Another commonly reported benefit of a shaft calciner is coarser particle size. This is generally true with one significant qualifying comment. Shaft calcined coke has high levels of -75μm fines. This can result in significant dusting problems that have not been mentioned in previous papers and which is not obvious when one first looks at the coke.

Shaft calcined coke is very coarse when it comes out of the bottom of the shafts and +4.75mm (4 mesh) levels above 60% are common. The lower heatup rate minimizes explosive shattering of large particles caused by rapid VM release. Mechanical attrition of coke particles is also dramatically lower in a shaft calciner. The coke bed moves very slowly through the shafts. In a rotary kiln, the coke is tumbled to improve heat transfer and consistency of calcination and this reduces the average particle size. Mechanical handling of the coke in screw conveyors, bucket elevators, conveyor belt transitions and silo's also contributes to particle attrition in a rotary kiln calciner as previously reported [9].

When the product from a shaft calciner coke is inspected more closely, a high level of agglomeration is evident. Coarse and fine particles are stuck together in odd shapes and sizes. This has been reported previously as a benefit rather than a problem [4,10]. The agglomerated coke pieces are usually very friable and easy to break by hand. The more it is handled after this, the more it breaks down and the more dust is generated. The scanning electron microscope images below show this quite clearly, Figure 3. Agglomeration occurs on both a macro and a micro scale.

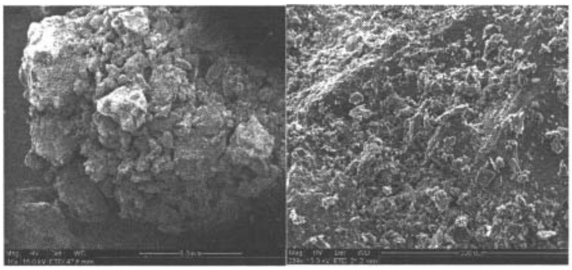

Figure 3: SEM images of shaft calcined coke agglomeration at low (10x) and high (300x) magnification.

The root cause of this goes back to one of the fundamental differences between the two calcining technologies. In a rotary kiln, most of the fine green coke (<250 μm) is blown out the back of the kiln with the flue gas. In a shaft calciner, there is no mechanism to remove fine green coke and it stays with the product. The fine coke attached to the surface of coarser particles is easily abraded when the coke is handled and dust is generated.

This phenomenon was not known by Rain CII when the company began its experience with shaft calcined coke. Similarly, Tomago was unaware of the issue until they increased their use of shaft calcined coke. Dusting problems become more evident during vessel unloading and subsequent handling in the carbon plant. Tomago uses a modern vacuum unloading system and they noticed a significantly higher -75μm dust content in shaft calcined coke relative to rotary kiln coke. A comparison of the -75μm dust content of typical shaft calcined coke and rotary kiln calcined coke after vessel unloading is shown below for nine different shipments, Figure 4.

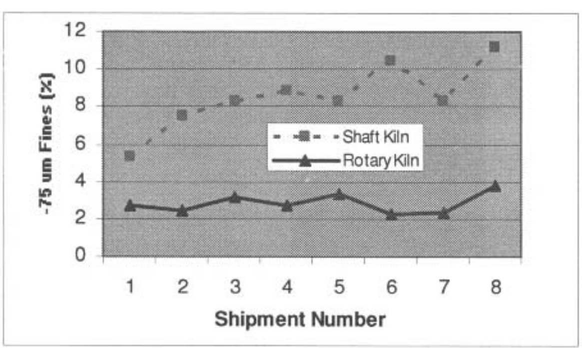

Figure 4: -75μm fines content of vessel unload samples.

Samples of shaft calcined coke taken before vessel loading do not typically show a high -75μm content. Breakage and attrition starts occurring during vessel loading and thereafter. Shaft calcined coke can also "hang-up" on the inside of the cargo holds at very high angles of repose (>60°). This is believed to be due to breakage of agglomerated coke during shipping resulting in higher packing densities. The higher density and more irregular particle shape of shaft calcined coke probably also plays a role.

Shaft calciners that export coke typically need to screen and crush oversize lumps (at 30mm or 50mm). The crushed oversize coke is then recombined with undersize coke and de-dust oil is added. This process generates significant amounts of dust which must be removed by dust collectors and disposed of. It does not remove all the dust however, and additional dust is generated during vessel loading, unloading and use in the carbon plant.

Ironically, the manual handling of calcined coke at many shaft calciners exacerbates the dusting problem for end-users. The coke typically receives very "gentle" treatment after calcining relative to what happens at a rotary kiln calciner where mechanical handling of the coke contributes to breakage and attrition.

Real Density, Coke Reactivity and Impurity Levels

There is no difference in the ability of a rotary kiln or shaft calciner to meet RD targets. This is contrary to what has been reported in some other papers and is based on Rain CII's experience with multiple rotary kiln and shaft calciners. Both technologies are capable of making coke with RD's ranging from 2.01–2.10 g/cc and it is a matter of changing operating conditions to achieve this. When green coke quality changes significantly, it is easier and quicker to adjust a rotary kiln due to the high level of automation and multiple control variables available.

There are also no fundamental differences in coke CO_2 and air reactivities between the technologies. Coke reactivities are dependent on impurity levels in the coke (S, Ca, Na, V etc) and the level of calcination. Many aluminium companies have moved away from coke CO_2 and air reactivity specifications because they typically show no or little correlation to anode CO_2 and air reactivities [11]. The latter are dependent on a range of factors including coke impurity levels, butts cleaning efficiency (which controls anode Na levels), anode forming and anode baking level and consistency. Calcination technology also has no influence on coke impurity levels. These depend on green coke impurity levels.

Operation of Rotary Kilns Versus Shaft Calciners

Operability with High VM Cokes

There is a general belief that shaft calciners handle high VM cokes much better than rotary kilns. This is the caveat mentioned earlier that needs some clarification. It is very important when operating a shaft calciner, to control the average VM of the feed within a narrow range, typically 11-12% (these numbers are not absolute since VM values depend on the method used).

The feed VM is controlled by blending in lower VM green cokes and calcined coke. Calcined coke has essentially no VM so it can be used to offset the high VM of other green cokes in the blend. Calcined coke used like this is referred to as "recycle coke" and rates of 5-15% are common. When this is done, a shaft calciner still makes a very high bulk density product but the overall production rate drops since more recycle coke is used.

The need for careful VM control of the feed is driven by the processes occurring inside a shaft calciner. High VM coke produces more condensable hydrocarbons when heated. The coke softens and becomes "sticky" before the residual tars thermally crack into lower molecular weight volatile species. The coke bed is relatively densely packed and when the coke becomes "sticky" it acts like a glue that causes particles to stick together. This is what causes the particle agglomeration that is evident both visually and microscopically.

If the average VM of the feed is too high, the coke bed will literally fuse together inside the furnace and result in a solid plug that blocks the shafts. If this happens, the coke must be physically removed before operation can continue. This is hazardous and damaging to the refractory shafts and must be avoided.

The best way to illustrate this phenomenon is to show a photograph of two green coke samples after a VM test. In a VM test, green coke is crushed to -0.25 mm, dried and then placed in a crucible which is heated at 950°C for 7 minutes. Most low VM cokes go into the crucible as a powder and come out as a free-flowing powder. High VM cokes (>~13%) come out as solid, fused, disk. Some particles appear to melt and assume the same flat profile as the crucible bottom, Figure 5. The higher the VM, the more deformation that occurs and the harder the pellets are.

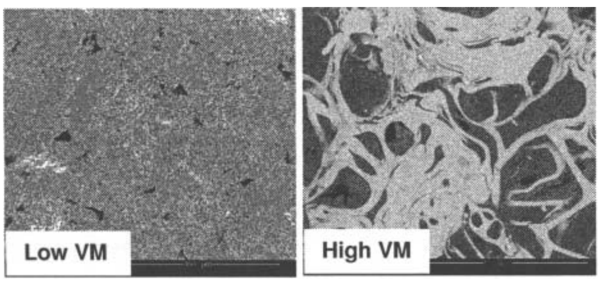

Figure 5: Samples after green coke VM test.

In addition to VM content, green coke particle sizing also influences coke bed agglomeration. Shaft calciners do not operate well with fine green coke. It reduces the bed permeability for VM release and the high surface area causes more agglomeration which increases the risk of shaft plug-ups. Shaft calciner operators are all very aware of these problems and they are controlled by increasing recycle rates.

Rotary kilns are more forgiving in their ability to operate with a wider range of green coke VM. Higher VM cokes will however, more negatively affect the coke bulk density – much more so than in a shaft calciner. This is the major benefit of a shaft calciner relative to a rotary kiln. It can still make a dense product when high VM cokes are used in the blend.

If the average VM level of the feed to a rotary kiln gets above ~13.5%, it can also be problematic. A layer of coke can build up on the inside of the refractory lining at the feed end of the kiln (known as a coke ring) and this reduces the effective diameter of the kiln and eventually reduces the production rate. An excellent paper was published on this problem over 30 years ago [12].

Automation

Differences in the level of automation between rotary kilns and shaft calciners have been well covered in previous papers. Modern rotary kilns are highly automated and can be operated with a small labor force. There is no physical handling or contact with green and calcined coke and the entire process can be operated from a central control room. Issues occur from time-to-time occur that require manual intervention but they are not common.

Many shaft calciners in China are operated manually and green coke is lifted to the top of the shafts in small hoppers with electric hoists and then added to the shafts using an overhead crane. Calcined coke is discharged into carts and then hand wheeled and dumped into storage areas. Operating a shaft calciner this way is very labor intensive and a 200,000 MT/yr plant may require 150 employees vs 30 for an equivalent rotary kiln calciner.

Automation of the green coke feed and calcined coke discharge systems at shaft calciners is straightforward and becoming more prevalent in China. It does add some additional cost to the construction and requires development of maintenance systems to maintain equipment such as belt conveyors. The high number of individual shafts requires a lot of replication of equipment. Automation can help avoid problems such as those associated with allowing feed hoppers to run low which can cause visible emissions of VM into the work environment.

One aspect of a shaft calciner operation which is more difficult to automate is the frequent cleaning required inside fluewalls. Tar builds up inside the fluewalls due to inefficient combustion of VM and the small amount of fines carried into the flues. The buildup must be removed manually by scraping with a rod. Cleaning can be as frequent as every 2 hours and is dictated to some extent by the green coke type, VM content and particle size.

To eliminate this, a change in the sophistication of the combustion control and draft systems would be required. Today, combustion air is added via manually operated sliding metal dampers or in some cases, refractory bricks. A main guillotine damper on the flue gas duct entering the stack can also be adjusted to change the overall furnace draft. Buildup of tar inside the fluewalls changes the draft level and must be removed to maintain a stable operation and ensure proper combustion of VM.

Waste Heat Recovery, Safety and Environment

All rotary kilns built in the last 20 years (and many built prior to this) have sophisticated waste heat recovery systems. The waste heat is used to fire boilers and steam is either sold to neighboring process plants or used to drive turbines for power generation. The two kilns at Rain CII's Visakhapatnam plant in India (300,000MT/yr each), generate enough waste heat to drive a 50MW turbine generator. At current energy prices, waste heat is valuable and considered a "green" form of energy since it avoids the need for thermal power generators to burn coal or other fuel.

Waste heat recovery systems are also being used more and more with shaft calciners. Smaller plants use waste heat for lower grade heat applications such as preheating pitch and paste if they are attached to an anode plant. The principle of application is identical to a rotary kiln but waste heat production is lower (per ton of coke) due to the lower fines carryover. This represents lost value in terms of waste heat recovery but must be compared to the lower green coke cost per ton of calcined coke produced

Waste heat recovery and flue gas desulfurization systems are very advanced and easy to operate with a rotary kiln. Controlling the flue gas flow and draft in one large rotary kiln producing 300,000 MT/yr of coke is easier in principal than controlling drafts in multiple furnaces and fluewalls in a shaft calcining plant of similar capacity. A shaft calciner producing 300,000 MT/yr comprises ~350-400 shafts each with its own set of fluewalls and manual damper systems to control airflows. It should be possible to increase the capacity of individual shafts by making them longer but the maximum width will always be limited by heat transfer just like an anode bake furnace. The number of shafts will continue to remain relatively high even in newly built furnaces.

Construction, Startup, Operation and Shutdown

A major benefit of a shaft calciner (at least in China) is that it can be built cheaply and quickly at a very small scale. A company may choose to build a 20,000 ton/yr or a 200,000 ton/yr calciner because the technology is readily scaleable. By comparison, modern rotary kilns are large: 250,000-300,000 MT is a standard size today and necessary to achieve economies of scale.

The volume and mass of refractory required to build a shaft calciner is significantly higher than a rotary kiln of comparable size (~2.5x the mass). This does not present a problem in China where refractory costs and refractory labor costs are low but it can be problematic elsewhere. In an internal study completed at Rain CII several years ago, the estimated cost of building a shaft calciner in the US was ~1.5x the cost of a rotary kiln on a $/ton of installed capacity basis. This assumed the same level of pollution controls as a rotary kiln. In 2007, Rain CII engaged a Chinese engineering company to estimate the capital cost of building a large shaft calciner and rotary kiln calciner in China with waste heat recover and flue gas desulfurization. The capital costs estimates were very similar.

All shaft calciners in China are built with high silica (>95% SiO_2) refractory bricks for the shaft and flue walls. These bricks are readily available at low cost in China but their use has one significant drawback. Silica brick undergoes a very high thermal expansion compared to the 60-70% alumina bricks used in rotary kilns or the 40-60% alumina bricks used in baking furnaces. The coefficient of thermal expansion (CTE) is shown in Figure 6. As a result, shaft calciners have to be started very, very slowly and startup typically takes ~2 months.

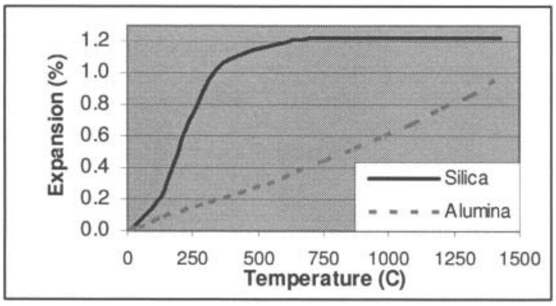

Figure 6: CTE of high silica brick vs 60% alumina brick.

Expansion tie rods with a spring assembly must be adjusted carefully to avoid cracking and damage during the critical expansion range from 25-700°C, Figure 7. Once a shaft calciner reaches its operating temperature, the high silica bricks are very stable and have a low thermal expansion coefficient above 750°C. High silica brick is an excellent material for any refractory application like this involving continuous high temperatures.

The thermal expansion of the bricks is reversible however, and once a shaft calciner is started, it cannot be shut down. This is generally not well known outside of China but all shaft calciner operators in China are very aware of this. It would be very difficult, probably impossible to cool a shaft calciner uniformly enough to avoid cracking the high silica flue-wall bricks. Coke oven batteries used to make metallurgical coke use the same type of refractory brick and suffer the same problem.

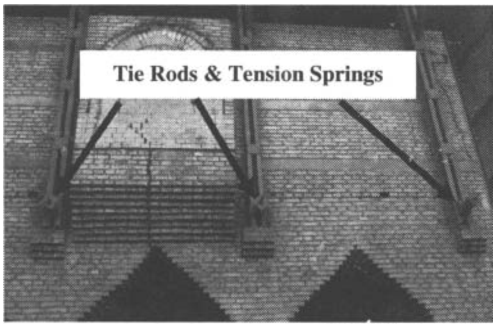

Figure 7: Expansion tie-rods with adjustable tensioning system.

This problem is easy to manage with a stable green coke supply and a low level of automation. It becomes more problematic as automation is added to the calciner. A fully automated shaft calciner with belt conveyors and a waste heat recovery system requiring pumps, fans etc. now becomes more dependent on the reliability and maintenance of ancillary equipment. Contingencies for unplanned events like power failures could get quite complicated when there is no ability to shut a furnace down.

Rotary kilns on the other hand, are easy to startup and shutdown. It is typically a 3-4 day process to start a cold kiln using a natural gas or oil fired burner. The green coke feed to a rotary kiln can be stopped easily at any time without the risk of refractory damage. This is partly due to the higher grade (and higher cost) bricks used and their lower expansion rates but also the very simple refractory geometry and design used in a rotary kiln.

The brick linings in rotary kilns are very stable. Bricks in the lower temperature, feed-end can last >20 years. Bricks in the hotter discharge-end, need to be replaced more frequently (typically every 4-5 years) and the repairs are staggered so small sections are replaced at a time. Most kilns will take a 2-3 week shutdown every 12-18 months for refractory and other plant maintenance work. The highest refractory wear components are tertiary air nozzles (for kilns that have them) which protrude into the kiln. These typically drive the maintenance cycle. Refractory in the cooler is usually also repaired every 12-18 months.

During operation, there are no refractory maintenance costs with shaft calciners and this is a very attractive feature. Small shaft calciners with little automation and no waste heat recovery can be built and operated very cheaply. The furnaces are generally run to failure and this can be anywhere from 5-10 years. Replacement after 5 years is costly and a more typical life is 8 years. Replacement of the furnaces typically takes 6 months so there is a lot of incentive to run the furnace as long as possible. The life of a shaft calciner can be increased by running the furnace with a stable green coke feed and good operating practices. Maintaining clean fluewalls, drafts and temperature profiles is important for prolonging the life of the furnace.

Discussion

The objective of this paper is to present a balanced view of the merits of rotary kiln and shaft calcining technology. Both technologies are widely used (albeit one predominantly in China) and both will continue to be used in the future.

Shaft calciners make a high bulk density product and this is very appealing for a smelter and anode plant. The coke can be very dusty however, and may require modification of dust collection systems in carbon plants if it is used in high volumes. Shaft calciners do a better job of making a high density product with high VM green coke but high VM cokes are typically softer and finer in particle size and this can compound dusting problems. The VM of the feed to the furnace needs to be kept constant and whilst this is not difficult, it ultimately translates to lower production. This is easily solved by building more shafts.

The trend towards higher VM green cokes makes shaft calcining attractive in terms of density but the technology does not deal as well with the finer particle size that comes with higher VM. Rotary kilns have a built in mechanism to remove fine green coke via entrainment in the flue gas stream. As long as the kiln has waste heat recovery, value will be recovered from these fines.

The level of automation is improving with shaft calciners but there are some fundamental problems related to tar buildup that will be difficult to overcome without improvements in combustion control. This ultimately means a higher capital cost if more sophisticated control systems are used. A shaft calciner is unlikely to ever compete with a rotary kiln in terms of manpower requirements, ease of operation and flexibility. It is very easy to startup and shutdown rotary kilns. The more a shaft calciner is automated, the higher the capital and maintenance costs and the more it starts resembling a rotary kiln. The inability to shut a shaft calciner down becomes more of a problem when the level of automation is increased.

A refinery building a calcining plant as an off-take for green coke would be unlikely to ever build a shaft calciner. A case in point is the rotary kiln calciner commissioned in mid-2010 at the CNOOC refinery in Huizhou, China. It is a modern rotary kiln with waste heat recovery and is much more in line with the refinery's standards for automation, manpower requirements, environmental and safety performance, flexibility and so on.

Perhaps the most significant benefit of shaft calcining is the low cost to build and operate small calciners in some parts of the world. Rotary kiln calciners are better suited to large volume applications which make the most of their economy of scale advantages. This makes the combination of a shaft calciner and a rotary kiln potentially very attractive.

A relatively small amount of shaft calcined coke (10-20%) can provide a significant density boost to a rotary kiln product without creating too many dusting problems. This can be considered a recommendation to the industry when considering these two calcining technologies. Both have their pros and cons and some of these are regional in terms of capital and operating cost. Rotary kilns are very efficient at producing high volumes of coke and they will continue to be built and used in many parts of the world. Shaft calciners produce a high bulk density product that can be used in a complimentary way with rotary kiln product to increase average bulk density. Blending the two cokes together makes a lot of sense for the industry.

Conclusions

Based on experience supplying both rotary kiln and shaft calcined coke to the aluminium industry, Rain CII believes that both technologies have a strong future. The pros and cons of each need to be recognized.

Shaft calciners are easy and fast to build but are more suited to regions with low labor rates and low cost refractories. They make an excellent bulk density product but dusting can a problem. Automation of shaft calciners is increasing but there are some practical limits which will constrain the level automation relative to a rotary kiln.

The aluminium industry needs both of these calcining technologies in the future. The products from each can be blended together in a complimentary manner. The addition of 10-20% shaft calcined coke to a rotary kiln product can provide a good density boost if needed and will minimize the impact of dusting problems. This could serve as a good model for the industry to pursue as green coke VM continues to increase.

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