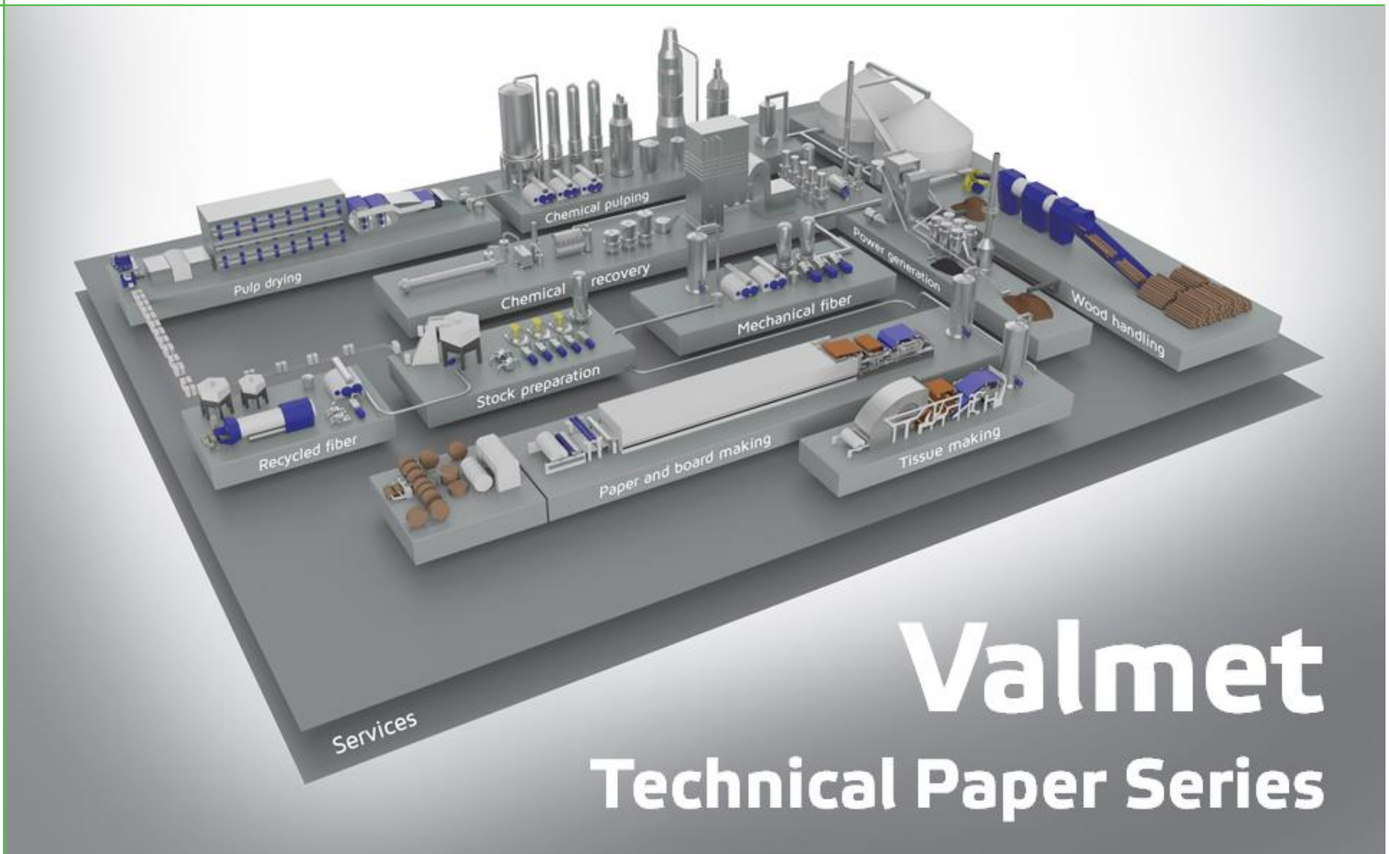


Using wood powder as fuel in lime kilns

Executive Summary

The lime kiln is today the only major consumer of fossil fuel in a modern pulp mill. There are several green or CO_2 neutral fuel alternatives to fossil fuel that can be used but it is important to acknowledge that replacing the kiln fuel may have an impact on the kiln design and operation.

This paper will discuss the use of wood powder as a replacement lime kiln fuel. Valmet has for the last decade installed systems where wood powder has replaced oil or natural gas as the main fuel for the lime kiln. The paper will discuss the factors that will have to be considered when evaluating using wood powder as kiln fuel and the lessons learned from operating with wood powder.

Introduction

Fossil fuel replacement has been on the agenda since the oil crisis in early 1980s but until the discussion of CO_2 emission impact on global warming, there really hasn't been any kilns that has operated with wood powder or gasifier gas. With the current focus on CO_2 emissions and a wish to use all the wood material entering the paper mill, many new mills installed the in last six years have chosen to use either wood powder or bark gasified gas as power source for the lime kiln.

Currently there is a lot of interest in converting kilns from using fossil fuels (oil and natural gas) to wood based fuel both in Europe and Canada but since there probably are less than 10 lime kilns in the pulp industry that uses wood or bark powder as fuel and most of these are in Sweden and Finland there isn't much experience with this technology in North America.

This paper will summarize some of the recent practical results and learnings that have been found in supplied wood powder systems. Södra has contributed to this paper based on their experience at Södra Värö mill with a wood powder firing system that was installed in 2014.

Wood powder design considerations

Wood types and particle size

The typical wood-based biomass fuels used for direct fired rotary kilns ranges from wood chips and pellets to sawdust. At least one mill is known to partly use dried bark powder, however, bark is normally gasified to a biogas before being combusted in the lime kiln due to non-process elements in the bark.

Wood is a composite material with a cellular fiber structure (**Figure 1**).

(a) (b)

Figure 1. (a) Example of possible wood powder sources (b) example of cellular fiber structure by confocal laser scanning microscopy [1]

Wood can be characterized as viscoelastic material. Due to its viscoelastic behavior, rotor impact mills like hammer mill is a suitable solution for wood grinding [2]. The grinding characteristics are impacted by the wood type, moisture content, temperature and mechanical pretreatment in the production of sawdust or pellets.

Figure 2. Wood chips (A) and sawdust (B) before and after grinding in a hammer mill

The wood type for wood powder fired kilns in Scandinavia are typical pine and spruce (both softwood) and birch (hardwood). Historical, many issues have been reported with safety and availability of wood powder systems [3]. Less attention has been made to grinding of wood to a size required as a fuel, which probably is because this hasn't been the most significant obstacles. However, as more wood sources will be used on a global scale in the future more attention is needed as described below.

Williams et al. has worked on correlating standard grindability tests used for coal (Hardgrove Grindability and Bond Work index) [4], however, these standard coal tests is not suitable to characterize viscous wood material being ground in a hammer mill. Laboratory test work with a pilot hammer mill has shown that milling of wood chips and pellets can be adapted to the Von Rittinger grinding model [5]. The Von Rittinger model is based upon the assumption that the new surface created during milling is directly proportional to the energy required for size reduction. For grinding of wood in a hammer mill Temmerman et al. propose the following model for specific grinding energy:

$E_{1\text{-}2} \propto MH(1/X_2 - 1/X_1)$, Where:

- $E_{1\text{-}2}$ Energy required to reduce a particle from size X_1 to X_2
- M Grindability factor. Depends on to wood specie and pretreatment
- H Moisture content
- X_1 Particle size of feed
- X_2 Particle size of milled product

They introduce a grindability factor M, which is proportional to the power consumption required for grinding the wood in a hammer mill. In their pilot test work the grindability was in the following order (starting with easiest grindable source):

Beech (M=5.1) < Oak (M=8.5) < Pine (M=9.7) < Spruce (M=11.9)

The fact that wood type influences the milling process is shown in the **Figure 3**. The particle size distribution of ground wood powder from two installations is shown using different feed materials. A summary is also shown in the following table (**Table 1**).

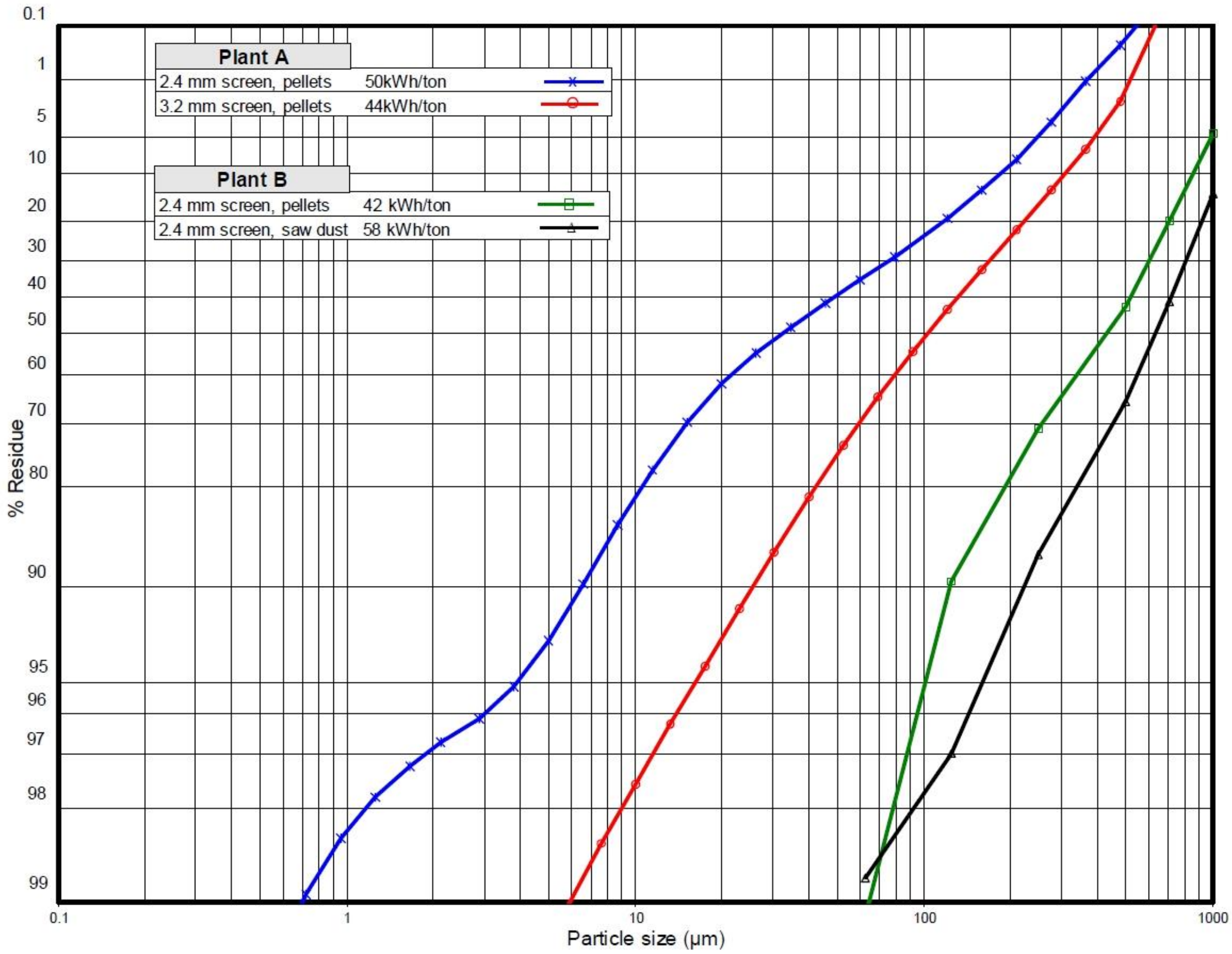


Figure 3 Particle size distribution (RRSB grid) of ground wood powder from same type of hammer mill, rotation speed and screen design

A. For the same wood type in Plant B the wood powder is slightly finer based on pellets compared to sawdust. The power consumption for grinding pellets is 28% lower than for sawdust. The difference in power consumption is thought to be due to the mechanical treatment when producing powder from sawdust.

B. Using similar hammer mill type and 2.4 mm screen, powder from pellets milled in Plant A is significant finer compared to powder from Plant B which is attributed to the different wood type and/or pretreatment of pellets.

C. The power consumption is 19% higher when grinding the finer Plant A powder compared to Plant B powder which confirms that more energy is required with finer grind of material which is in line with industrial experience and theory, as discussed above.

Traditionally, the design criteria for the wood powder size has been maximum 1-2% above 1 mm size to ensure complete burn-out of all wood particles. Both the very fine and coarser wood powder with up to 2% of >1 mm particles (**Table 1**) will result in complete burn-out in the kiln.

Reference	Screen size in hammer mill / wood source	D50, micron	D99, micron	Power consumption kWh/t wood
Plant A	2.4 mm, pellets	30	550	50
	3.2 mm, pellets	100	650	44
Plant B	2.4 mm, pellets	450	1400	42
	2.4 mm, sawdust	650	1400	58

Table 1. Summary of wood powder size and related hammer mill power consumption for various wood sources and hammer mill screens sizes.

From the table, it is seen that increasing the hammer mill screen size will slightly increase the particle size (Plant A). This is not directly proportional to the increase in screen size. By increasing the screen size and reducing the grinding, the power consumption is reduced. Based on this, it will be possible to install a screen size that will produce a satisfactory wood powder size, while minimizing the operational and maintenance costs.

Moisture content

Wood moisture is the most important factor for the grinding process and lime kiln operation.

The mechanical properties of wood are highly dependent on the moisture content [6]. Water in the wood is found as free water in cell lumina and cavities and as bound water within the cell walls. The drying process has been shown to be somewhat irreversibly which can be interpreted as the drying process is below the fiber saturation point where bound water is lost from the cells and thereby changes the mechanical properties.

For grinding of wood, it is well known that the higher the moisture content, the higher the power consumption. Temmerman et al. have found that the power consumption increases linearly with the moisture content in their pilot hammer mill for various wood chips (beech, oak, pine, spruce) [5]. It should be noted the work was based on oven dried wood (at 105 °C) that may vary from industrial drying process and this may have an impact on their results.

It has not been possible to verify Temmerman et al.'s work from the existing industrial installations but the practical experience from wood powder fired lime kilns is that the wood moisture should be less than about 10% to maintain good milling operation and preferably less than 8%.

For higher moisture content, it has been found that the fine and moist wood powder starts to block the hammer mill screen and eventually blocks the hammer mill as shown in **Figure 3**. The figure shows that the power consumption started to fluctuate after the wood powder moisture started to increase to about 12-15%. At constant mass loading the hammer mill screen starts to be partly blocked by wood powder and eventually the power consumption fluctuates badly indicating that the hammer mill is blocked.

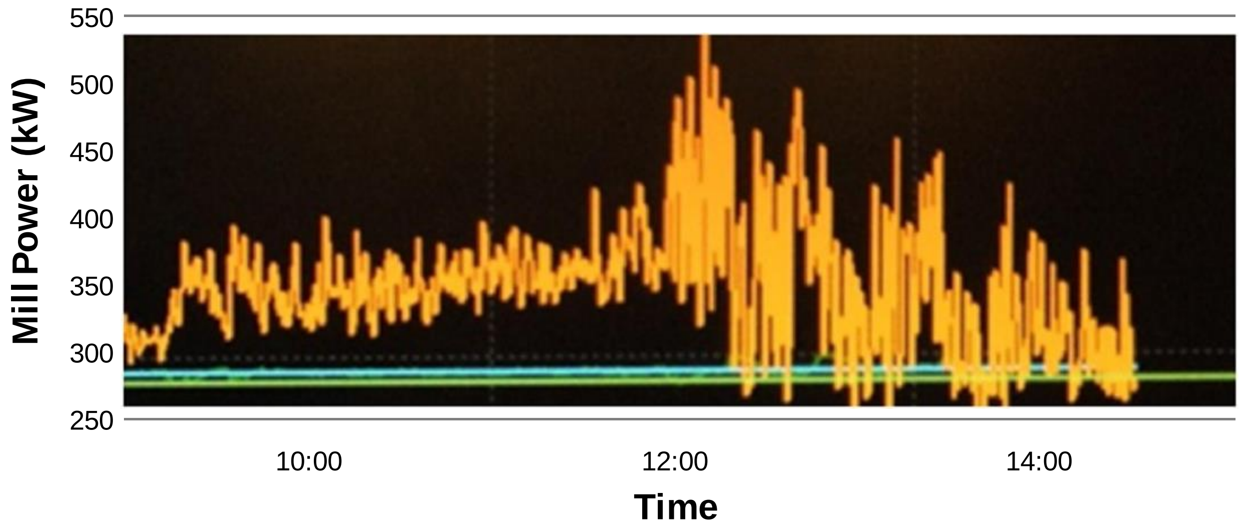


Figure 3. Hammer mill power consumption after feed moisture increases to 12-15% moisture. Initially some higher fluctuations are seen and after some minutes the power consumption increases erratically showing the hammer mill screen is getting blocked. The feed to the mill is decreased 12:30, lowering but still fluctuating power consumption.

The hammer mill power consumption during the grinding turns into heat which heats up the wood powder and evaporates some of the moisture. Typical 1-2% moisture is evaporated during the grinding process.

Burner and Kiln Operation

Moisture has a significant impact on the kiln operation as the moisture in the wood powder will evaporate which reduces the flame temperature in the burning zone. **Table 2** shows the impact on the kiln temperature profile, exhaust gas flow and fuel consumption when increasing the moisture in wood powder. The values are compared to the main fossil fuels oil and natural gas.

	Exhaust gas temperature, ºC	Exhaust gas flow, Actual m^3/s (wet)	Fuel consumption, %
Oil – reference, typical values	~285	~52	100%
Natural gas	+50	114%	105%
Wood powder, 0% H_2O	+3	99%	101%
Wood powder, 3% H_2O	+12	102%	101%
Wood powder, 5% H_2O	+18	104%	102%
Wood powder, 10% H_2O	+35	110%	104%
Wood powder, 15% H_2O	+56	117%	107%

Table 2. Estimated temperature profile, exhaust gas volume and fuel consumption relative to heavy fuel oil reference case for natural gas and wood powder with various moisture level. The values in the calculations are typical values for a 700tpd modern lime kiln with cooler and flash dryer and should only be used for illustration. Lower heating values were LHV(Oil) = 40.9 MJ/kg, LHV (natural gas) = 35.8 MJ/Normal m^3, LHV(wood) = 19.3 MJ/kg. All results should only be used for illustration as impact of changing fuels.

The wood powder moisture reduces the adiabatic flame temperature which moves the temperature profile from the burning zone towards the kiln inlet increasing the fuel consumption and exhaust gas flow. This is important for rebuild of an existing lime kiln if dust abatement equipment like Electrostatic Precipitator (ESP) and ID fan are close to the design points and thus possibly could become bottlenecks. At wood powder moisture above 5% the increase in exhaust gas starts to be significant. Assuming 1-2% of the moisture is evaporated in the hammer mill (ref to section above) leads to the recommendations that the target of dried wood moisture should be less than 8% to minimize the impact on the kiln operation.

Another issue with operating with very moist wood powder can be challenges with flame hold to the burner tip and monitoring the flame with flame scanner. The feedback from operating installations is, that when moisture increases above 10%, the flame scanner signal may start to fluctuate which can lead to trip of the burner.

Based upon the above, it is concluded that wood moisture less than 5% is optimal to ensure a good and stable kiln operation and maintain the kiln production peak capacity.

Equipment design and considerations

Before the wood can be used as fuel in the lime kiln, it needs to go through a drying step and a grinding step to obtain suitable characteristics. If the wood is pelletized the drying step can be omitted as the wood is dried before pelletizing.

Figure 4. Block diagram for wood treatment before firing in kiln.

Dryer design

After the screening process, the wood is dried. In the drying process wood moisture is reduced from typical 30 – 55% (wet bases) to 5 – 8% moisture. The lower the moisture level in the dried wood the more efficient the kiln operation and kiln capacity.

There are several types of dryers available, like rotary, pneumatic and belt dryers. The type of dryer is depending on site layout available, heat sources and cost of commodities, dried wood properties, environmental issues etc. One of the most used dryer type is a low-temperature belt dryer (also known as conveyor dryer or fixed bed dryer) which enables several benefits such as utilization of secondary heats from other process areas, long residual time, robust design and it is suitable for heterogeneous particle size [7].

A belt dryer uses ambient air which is heated up in liquid-to-air heat exchanges. The need of heating power is depending on ambient air temperature, ambient air moisture and wood temperature. The need is typically 0.9 – 1.5 MJ/kg of evaporated water. Figure 6 shows a schematic for a doubled layer dryer.

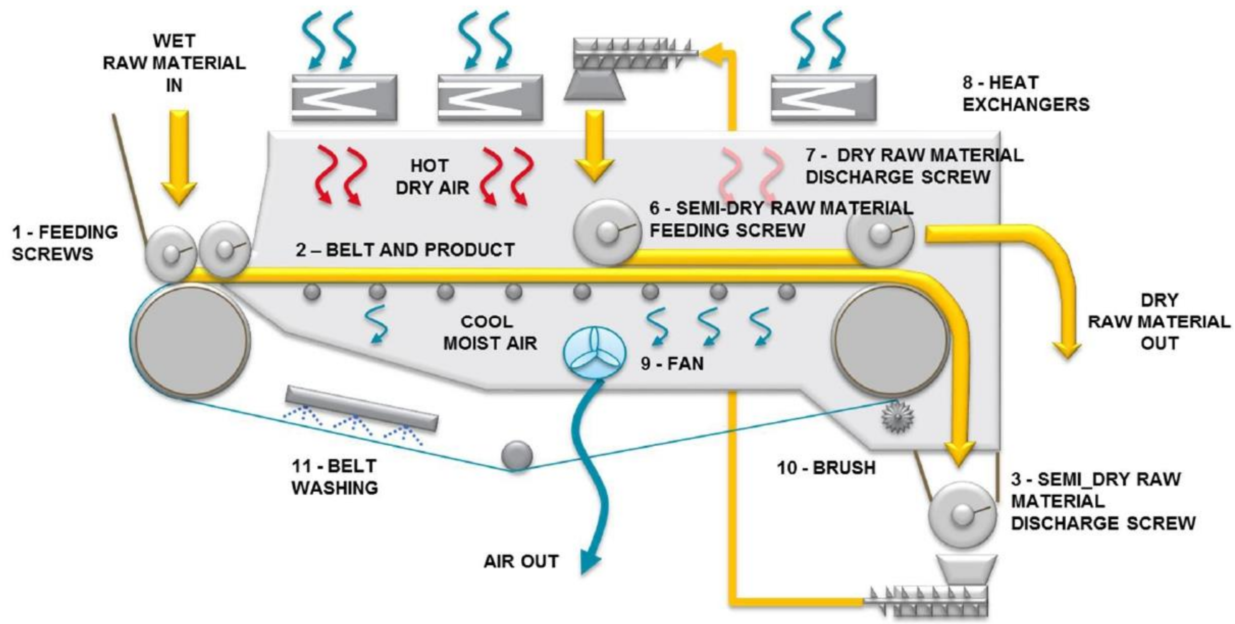


Figure 5. In a doubled layer, raw material is circulated inside the dryer resulting in low and even residual moisture, longer drying time, lower heat consumption and lower power consumption.

The belt dryer can often run on 100% mill waste heat. Typical heat sources are flue gas scrubbers, condensates, excess low-pressure steam and flue gas cooler. The heat can be collected from different heat sources and combined in one or two drying air generation stages. If the ambient air temperature is below 0 °C, freezing of the system is a potential risk. That is the reason, why in many cases heat from hot water or steam is transferred to antifreeze liquid like water glycol dilution.

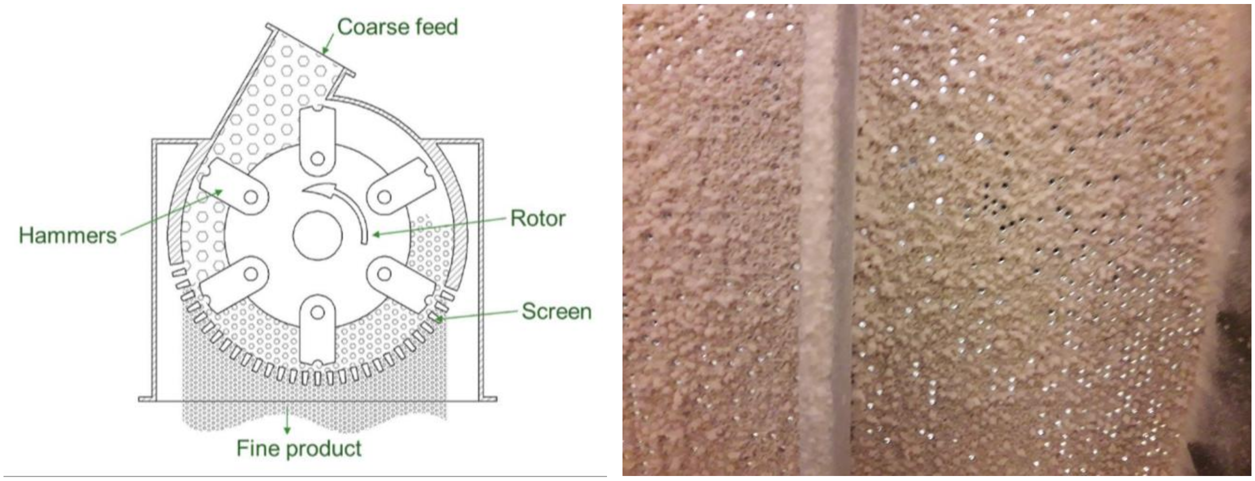
Mill design

To obtain the appropriate particle size of the wood fired in the kiln, the wood must pass through a grinding application. The grinding is a mechanical process that introduce force using balls, hammers, discs, pins etc. There is typically three ways of applying force to enable fracture; tensile stress and shear stress either parallel or perpendicular to the fracture front. The tensile stress is the energy that can be applied before a fracture appear. Shearing forces are forces pushing the object in different directions.

The wood structure is a matrix of cellulose fibers in a matrix of lignin. The wood is anisotropic due to the fibers and the longitudinal tensile strength is higher than the radial tensile strength. The direction of the wood particles entering the mill will be random and in addition the wood has high compressive strength, it must therefore be ensured that the wood particle is subjected to high impact forces for grinding to take place.

The mill chosen by Valmet for wood grinding, is a hammer mill using the impact principle. The mill consists of a mill grinding chamber wherein a shaft with mounted hammers rotates. The wood particles entering the mill will be subjected to impacts both from the hammers and on the walls of the grinding chamber.

Hammer mills typically have a screen in the outlet, which together with the speed of the rotor gives control of the product particle size. When choosing the correct mill for wood grinding the properties of the wood must also be considered, this goes for the correct size of screen also. It is thus not possible to grind wood with high moisture and use a fine screen to control the particle size, as the wood will stick to the backside of the screen. The buildup will eventually block the screen and a stop is required for cleaning (**Figure 6**).



(a) (b)

Figure 6. (a) Principle sketch of Hammer mill. (b) Hammer mill Screen after grinding wood with high moisture content.

Control of wood flow to kiln

Controlling the flow of wood into the kiln is an important aspect regarding stable kiln operation. Unstable flow will cause variation in heat input to the burning zone and impact product quality. Over-firing will cause the oxygen content to drop and CO may be formed which is a potential hazard.

To obtain good controllability of the wood flow an accurate and reliable gravimetric system is used (**Figure 7**). The wood powder from the mill is transported into a buffer hopper. The hopper acts both as homogenization, and to form a stable flow into the weighing device even if the flow from the mill is not constant or interrupted shortly (minutes). The weighing device is a rotor wheel with compartments that is being filled with wood powder as it rotates. It is suspended on a load cell which weighs the content in the rotor wheel gravimetrically. By controlling the speed of the rotor, it is possible to accurately control the wood flow to the kiln.

Figure 7. Gravimetric wood feeding system.

From the weighing device, the wood is transported to the kiln burner pneumatically. The system is flexible and it is possible to position the weighing device up to 80-100 m away from the kiln burner.

Burner design

The lime kiln burner is vital to good kiln operation. The burner needs to be flexible and incorporate several different types of fuel, and it needs to be designed to control and create a suitable flame formation. The flame must be luminous and not impinge on refractory or charge.

Flame control can be done with different streams of primary air, typically a flow going forward (axial air) and a flow rotating (radial or swirling air). The settings of primary air flow and pressure together with splitting the flow in different streams, ensures that the burner can be adjusted depending on the fuel types used and quantities available.

During commissioning of the wood powder fired kilns, it was found that changing the nozzle for axial air from the normal ring nozzle to jet nozzles, had a positive effect on stabilizing the flame. The jet nozzles improve the mixing of wood and air, and therefore creates a more continuous and robust flame formation.

For further improvement of the burner design a swirler was added in the wood channel. The swirler causes turning of the air/wood flow and enhance the mixing with the primary air. It is believed that improved mixing capability is a requirement when firing solid fuels, as opposed to liquid and gas which has been used for many years in the industry.

CFD modelling of wood powder fired lime kiln burner

A CFD model was made to learn more about flame performance and increase the understanding of how different air streams affects the flame. The goal was to be able to run the kiln with better flame stability and minimize NOx formation. The CFD tool used was ANSYS Fluent, revision 18.2.0 for the ANSYS Release Version 18.2.

Wood powder distribution

The wood powder feed line from the feeder to the burner connects to the burner on the upper right side (**Figure 8**). The circular pipe transforms to a rectangular nozzle to spread the wood powder evenly in the burner channel.

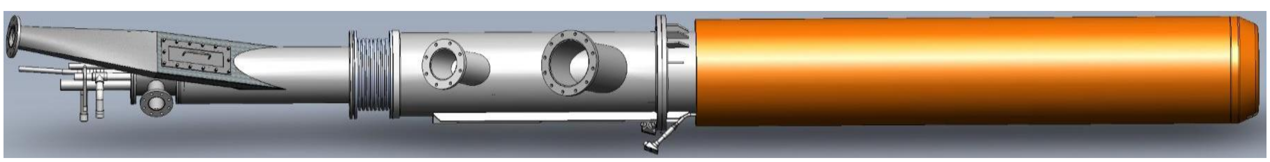


Figure 8. Basic burner model with oil burner, primary air and rectangular wood powder channel.

CFD modelling shows that in the feed line to the burner there is a size separation by gravity. A higher concentration of large particles is found in the bottom. In addition, particles are not spread over the cross section but remain initially in the top-right of the burner channel. When entering the burner, particles in the bottom (mainly large particles) ends up with a swirl path. The swirl is created both at the entrance to the burner and by swirl blades at burner head. This swirl path is important and results in:

- Concentration of wood powder is higher in the outer radius of the burner channel all the way to burner head. Also, there is a tendency that large particles are found closer to the outer wall.
- Particle concentration in the powder channel is high in top-right close to inlet, in the middle of the burner the concentration is higher in low section and when particles exit the burner concentration is highest in top.

The swirl in the wood powder channel rotates clockwise since feed line connects on the right side. The swirl blades at burner head gives counter clockwise direction. The direction of the swirl blades is chosen so that transport air has the same rotation as the kiln rotates. Since swirl in the burner channel is opposite from the swirl blades at the burner head, a high degree of collision is achieved. When wood powder collides with swirl blades, particles are collected into streams with higher wood powder concentration. These collected particle streams can visually be seen as "fingers" on the burner camera.

The result is an even distribution of wood powder particles entering the kiln. Over all, the distribution of wood powder particles out of the burner is good and does not result in any disturbances.

Flame shape temperature

During operation, the wood powder moisture content can vary from 6–13%. Experience from the operation tells that moisture content has big impact on flame stability. If moisture is more than 11-13% normally support fuel (oil or methanol) is needed to stabilize flame. Lower moisture is better, but approximately 8% is good enough for high flame stability using 100% wood powder as fuel.

In the CFD model, the moisture content of the wood powder is set to 8 w-%. Figure 10 shows the stages of combustion. Light blue and green colors is the drying stage of wood powder. Most of drying is complete after approximately 1 m from burner head. It is easy to understand the moisture content impact on flame stability when the drying zone can vary from 0,5 m to 2 m depending on the amount of water needed be dried.

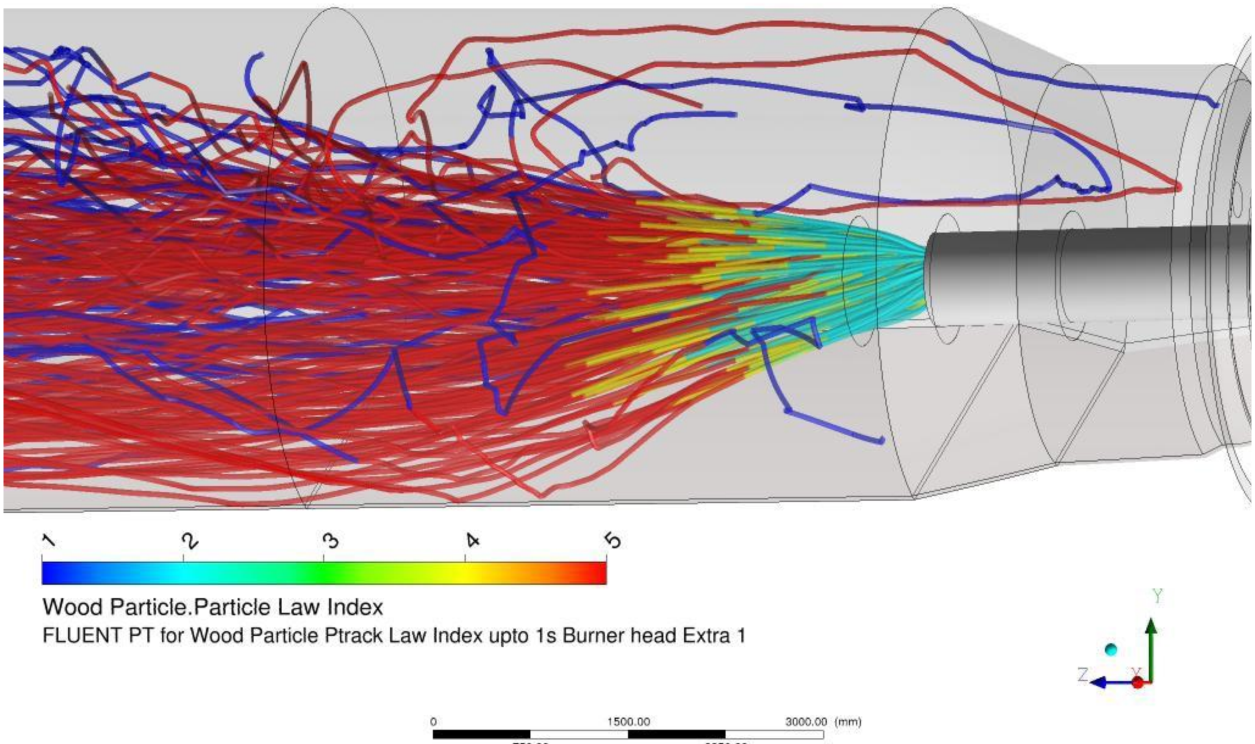


Figure 9. Combustion stages of wood powder; 1 heating, 2 evaporation, 3 boiling, 4 – devolatilization, 5 char combustion. Cross section shows volumetric reaction heat, first cross section is three meters from burner head.

After drying the wood particles are devolatilized, this is shown by yellow color in **Figure 9**. Wood powder particles devolatilization are complete after approximately 2 m from burner head.

Figure 10 shows gas temperature. The flame has a temperature over 1500 °C for the first 13 m. There are two high temperature zones (1600-1660 °C).

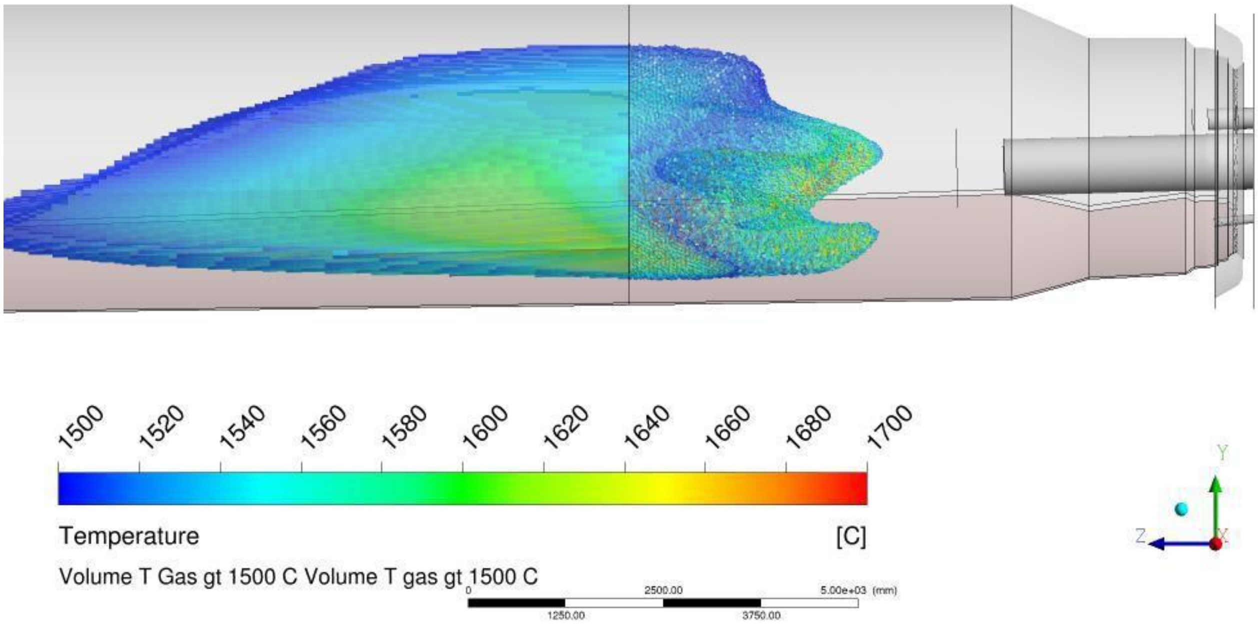


Figure 10. Gas temperature > 1500 °C.

Simulations shows that the flame is located with an intense zone around the burner axis but is also longer on bottom side. The flame is dominated by combustion of volatiles.

NOx formation

In the case of wood powder, where nitrogen in the fuel is low, NOx is formed mainly by thermal mechanism, i.e. NOx formation is mainly based on high temperature oxidation of N_2 in the combustion air.

In the central flame, there is a lack of oxygen and consequently limited formation of NOx. NOx is mainly formed in an area where the temperature is high enough and oxygen is supplied from either primary or secondary air. NOx rate of formation is highest about 2.5 m from the burner head. **Figure 11** shows that there are one dominating and two secondary thermal NOx formation zones. The dominating zone is supported both by primary and secondary air. The second zone originates from large wood particles spreading fast out in secondary air. The third zone is fed by both fuel and primary air streams.

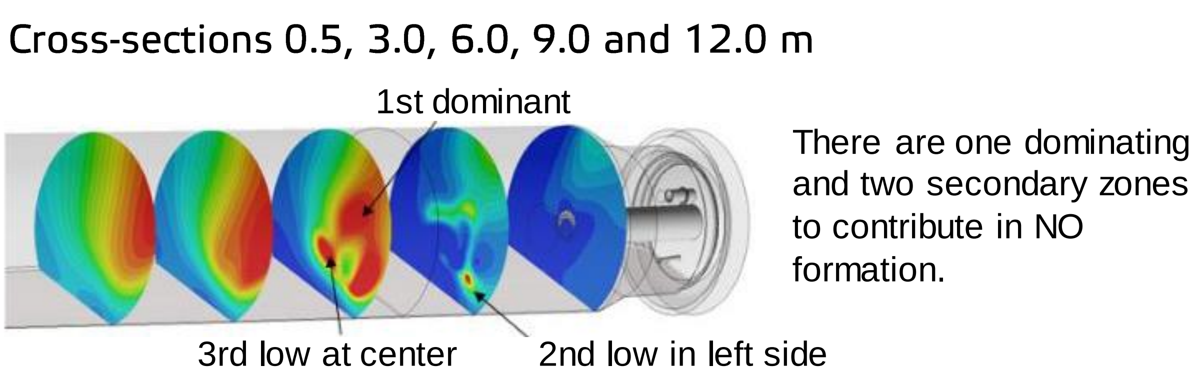


Figure 11. CFD modelling showing different NOx formation zones.

Second important NOx forming mechanism is prompt NOx. Prompt NOx is normally formed where there are over stoichiometric conditions and hence the central Prompt zone is somewhat closer to burner head than the thermal zone.

Fuel NOx of course is dependent on the amount of nitrogen in the fuel. Wood powder analysis shows nitrogen content of only 0.08% in dry fuel. The formation zone is 1-10 m from burner head.

Safety considerations

Any industrial process that reduces a combustible material and some non-combustible material to a finely divided state presents a potential for a serious fire or explosion [7].

Wood powder is a combustible that can catch fire, explode or self-ignite. The risk of explosion for a specific wood is characterized by K_{st} value and P_{max}. The parameters are determined by testing in a laboratory, and testing can also include measuring Minimum Ignition Temperature of dust layers, Minimum Ignition Energy (MIE) and Lower Explosion Limit (LEL). The K_{st} value [bar*m/s] expresses the normalized rate of pressure rise and P_{max} [bar] is the maximum overpressure created in the test chamber. In short, the values will indicate how much pressure an explosion will create and how fast it travels. It is important to remember that various dusts of the same material can have different characteristics depending on particle size, moisture and shape.

To avoid wood unintentionally catching fire, the temperature is usually monitored and sometimes controlled. This is especially critical after the wood drier, as the moisture in the wood is low (less than 10%) and the grinding process produce heat.

Certain conditions must be met for an explosion to happen (**Figure 12**):

- The dust must be suspended in air
- The dust concentration must be within the explosive limits
- Oxygen must be present
- There must be an ignition source
- The dust cloud must be confined

Removing either the dispersion or confinement element will prevent a dust explosion, but the wood powder can still catch fire. The risk of explosion in areas around the wood grinding system, can be reduced greatly by simply keeping everything clean and remove any dust leaked or spilled.

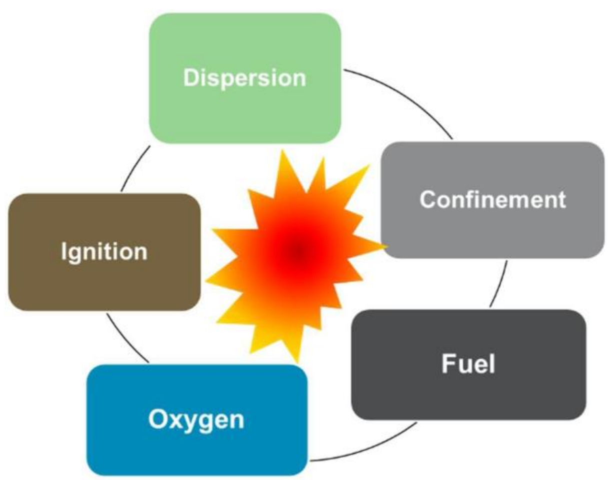


Figure 12. Conditions for Dust Explosion.

However, no installation is entirely risk free, and it will have to be evaluated in each case what safety measures should be installed. Typically, explosion vents will be included, as they offer an affordable and simple solution to protect the system.

It may not always be enough to use explosion vents, and it can be necessary to include the following based on HAZOP analysis:

- Spark detection and subsequently water injection
- Explosion suppression with a chemical (for example bicarbonate powders)
- Inerting capability with for example N_2

Operating experience

Measuring temperature in a lime kiln is challenging. An oil flame will always be intense close to the burner. Changing to less energy dense fuel which contains moisture as wood powder makes the flame longer and less intensive. Peak temperature will move longer from the burner and lower temperature close to the burner will be registered. However, that does not mean that lime will be of poorer quality.

When changing between different fuels it is important to take product samples often and run the kiln targeting residual carbonate. Trusting in the reference temperatures in the kiln does not work.

The experience of running with wood powder as main fuel and oil as start and back up fuel is that the change from one fuel to the other can be done rapidly and without any production disturbances. Normally changing from oil to wood powder is done in approximately one hour.

The trend in **Figure 13** shows a change in fuel during performance test. In this case the change was made in 4 and a half hours.

During the transition, more fuel is fed and the heat consumption increases. Registered burner temperature decreases as the flame change position. After the transition burner temperature rises because of previous over feeding of fuel. Wood powder feed is reduced due to product analysis showing too low residual carbonate.

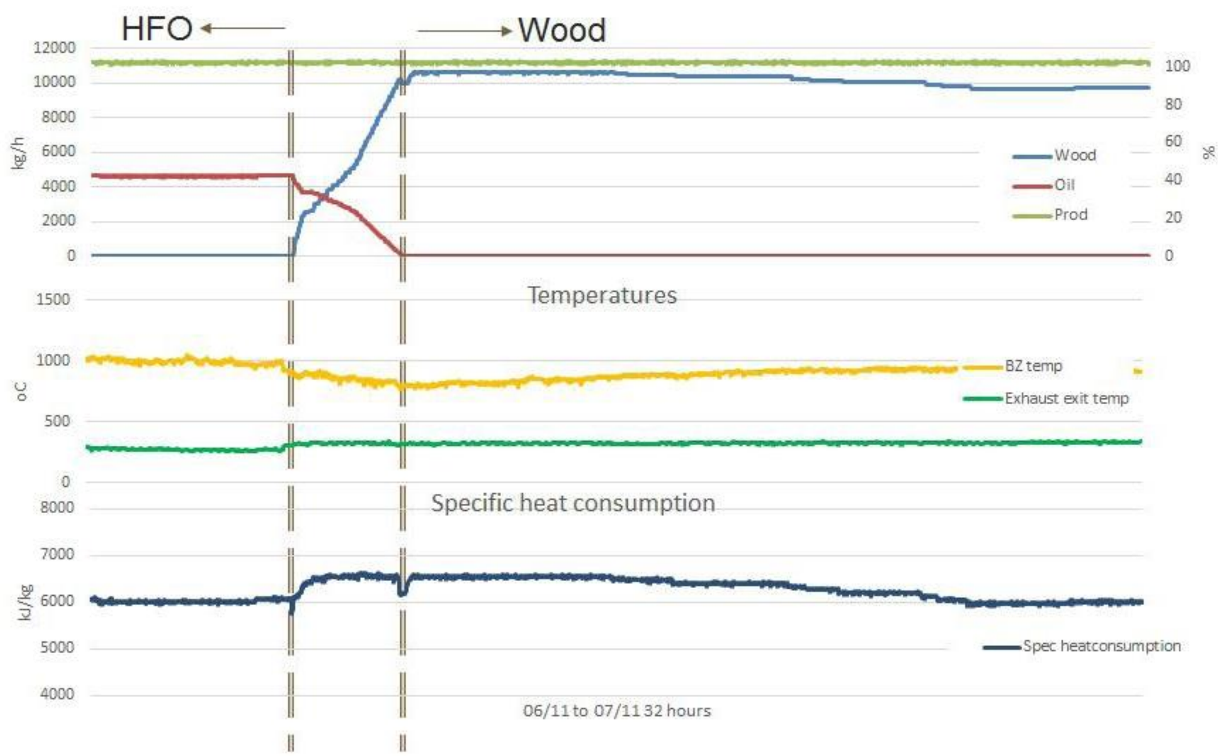


Figure 13. Changing fuel from oil to wood powder.

Maintenance

Not much maintenance has been required at Värö, mainly replacing of hammers in the hammer mill. The hammers are seldom changed as they are not worn on the outer surface, but they do wear in the hole being fixed to the shaft. Replacing the hammers are done during planned maintenance shutdowns and takes 15-20 hours.

Occasionally, the screens are damaged if foreign material like stones are not separated in the stone trap system and then enters the hammer mill. This has been seen from time to time in particular when the sawdust has been stored in a dirty area. Replacing a screen takes about one hour.

Conclusion

In this paper, Valmet has shown that wood powder firing in the last decade, has been developed to be a fully commercial, proven and most important safe solution for lime reburning kilns. It is therefore today possible to convert a pulp mill into a fossil-free mill and by that reduce the mills carbon footprint and fuel costs.

To successful implement a wood powder firing solution with high availability, it is important to understand and master each unit operation from drying, grinding and dosing to burning in the kiln. It is possible to substitute 100% of fossil fuel with wood powder without any negative impact on lime quality, lime kiln operation or capacity providing:

1. the moisture content is preferably less than 5%
2. the correct burner design is being used

More understanding of grindability of new possible wood sources is required as the wood powder solution is going to be used more and more on a global scale.

Acknowledgements

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This white paper combines technical information obtained from Valmet personnel and published Valmet articles and papers.

Valmet provides competitive technologies and services to the pulp, energy and paper industries. Valmet's pulp, paper and power professionals specialize in processes, machinery, equipment, services, paper machine clothing and filter fabrics. Our offering and experience cover the entire process life cycle including new production lines, rebuilds and services.

We are committed to moving our customers' performance forward.