

Online Image Analysis of Nodule Particle-size Distribution for the Control of Lime Kiln Operation

Erik Berg¹, Sven Hermansson^{*2}, Jonas Wetterling², Peter Lingman¹, Richard Nordenskjöld¹, Anders Åkesjö².

1. Optimation AB, Box 27, SE-941 21 Piteå, Sweden
2. Södra skogsägarna ekonomisk förening, SE-351 89 Växjö, Sweden.

*Corresponding author, sven.hermansson@sodra.com, +46-340-633468

ABSTRACT

To maximize efficiency of the recausticizing process in a pulp mill, it is of great importance to produce a reburned lime with high and consistent reactivity. The reactivity of the produced lime has in prior investigations shown to be connected to the nodule size of the lime and, as well as the dusting behavior of the kiln. Therefore, keeping track of the size of the nodules produced in the lime kiln could be a promising indirect method to measure the performance of the lime kiln. The aim of this study was therefore to evaluate an image analysis camera, 3DPM, for the online monitoring of nodule size distribution of the lime kiln. A series of full-scale trials were performed in a lime kiln of a kraft pulp mill, in which a camera was mounted to the exit conveyor of the lime from the kiln. The nodule size distribution was analyzed for correlation with the lime temperature, flue gas temperature and rotational speed of the kiln. The 3D camera monitoring was stable over time and the results show that the lime temperature had the most significant effect on the nodule size. The rotational speed of the lime kiln and the flue gas temperature showed limited effect on nodule size but had significant impact on the specific energy demand. The overall conclusion of the study was that the 3D camera methodology can be used to correlate the effect of lime temperature with the nodule size distribution and is suggested to be implemented to automatically control the lime temperature, to produce lime of high and consistent reactivity at decreased specific energy use.

INTRODUCTION

Background

The lime kiln holds a central role in the regeneration of process chemicals in a kraft pulp mill. In the lime kiln, the reburning of lime mud from calcium carbonate (CaCO_3) to calcium oxide takes place. The process is energy demanding and, hence, a significant consumer of fuel. The fuel normally used is oil, natural gas or mill-internal by-products, such as wood or bark powder. The annual consumption of fuel for kilns is approximately 4 TWh, which means that even a marginal increase in efficiency could lead to high potential fuel savings [1].

To lower the fuel consumption of a lime kiln, it is important to minimize the consumption of lime in the subsequent recausticizing process. If there is a good precision of the lime dosage, less lime mud needs to be reburned and, hence, less fuel will be consumed. To achieve such good precision in the recaust., it is important that the lime quality is even and high. The reactivity of the lime has been shown to be coupled to the size of the lime nodules (marbles) that are formed in the lime kiln. Nodules in the range of 10-15 mm diameter have been shown to yield higher reactivity than a finer particulate lime [2]. To produce this kind of optimal nodules, it has been shown that the lime needs a relatively long residence time in the kiln to reach full calcination [3], while at the same time a too long residence time could lead to over-calcination with drop in reactivity. Furthermore, lime kiln may suffer from a dusting environment inside the kiln from small lime particles being entrained with the gas flow. The heat radiative transfer is then significantly affected, causing unstable operation, increased fuel consumption and inferior lime quality. Lime temperature, flue gas flow rate and lime particle size has been shown to influence the tendencies for dusting [4]. High lime temperature and low heating rate has, in experimental trials, shown to have positive effects on less dusting [5]. Overall, these issues underlines that a good control of the lime kiln is not only crucial for the direct reduction of fuel consumption in the

combustion, but also indirectly by limiting the amount of dead-load of lime that is circulating through the recaust. cycle and the lime kiln.

Available control systems for lime kilns typically use operational data from the lime kiln, such as lime mud flow, revolution speed of the kiln, lime temperature, flue-gas temperature, and flue-gas composition [6,7]. The response, as quality of the produced lime, is then typically checked on regular basis by manual samples of the lime and the white liquor, and in some cases also by more frequent automatic extraction and analysis. However, the state-of-the-art set-up does normally not include any direct and on-line monitoring of the quality of the lime exiting the kiln. In this study, a direct measurement of the nodule size has been investigated as a direct tool for a direct parameter of quality of the produced lime. By combining this measure with the standard input parameters, the residence time of the lime in the kiln could be controlled in real time, leading to better lime quality. Secondly, the nodule size could then also indirectly be used to investigate how the lime kiln should be operated to avoid dusting behavior of the kiln, also that leading to better operation and lower energy consumption.

Objectives

The overall objective of this study was to investigate online measurement of particle-size distribution of the reburned lime, as a possible input parameter to the control system of a lime kiln. A specific objective was to quantify the influence of flue-gas temperature, lime temperature and residence time on the particle-size distribution of the reburned lime and, as an extension, the resulting lime reactivity as well as the dusting behavior of the lime kiln. Furthermore, the long-term aim of this initiative is to contribute to an increased general understanding of how the operation of a lime kiln affects the particle-size distribution of the produced lime. By keeping track of the particle-size distribution, a control routine could be established that would automatically steer the operation towards optimal lime reactivity, low dusting behavior and, consequently, low energy use.

METHODOLOGY

Measurement of Particle Size Distribution of the Reburned Lime

Particle Size Distribution (PSD) of the reburned lime was measured using 3DPM®, a system created for harsh environments that uses laser triangulation to collect 3D data of material passing on a conveyor. Laser triangulation is a technology that combines a projected laser line, illuminating the material on the conveyor belt giving a height profile, and a camera capturing and extracting the laser height profile, see Figure 1 and Figure 2. An example of directly accessible output information from the camera is given in Figure 3. Calibration of the laser-camera setup can give high accuracy height information in the sub millimeter range. Height profiles are collected at a fixed movement interval, either based on time when there is a constant movement speed or using a pulse encoder/input signal when the movement varies.

The camera is capable of distinguishing between empty conveyor regions, regions of fines (fine powder like material), visible particles, and partially overlapped particles. With these capabilities a more robust PSD can be obtained. For instance, by excluding partially overlapped particles rather than including the smaller visible part, under-estimated particles can be avoided [8]. The only re-calibration procedure after initial setup is after any modifications to either laser or camera. When the relative position between laser and camera has changed, a calibration must be remade to give correct millimeter values. This will be the case for instance when replacing the laser. Since this is the only recalibration performed, and if done correctly, will not significantly affect any millimeter output (mean calibration error is in the range of 0.02 mm), from the camera, thus, PSD can be compared no matter how far back in time a comparison is to be made.



Figure 1. Measurement module showing a laser in the front and a camera in the back.

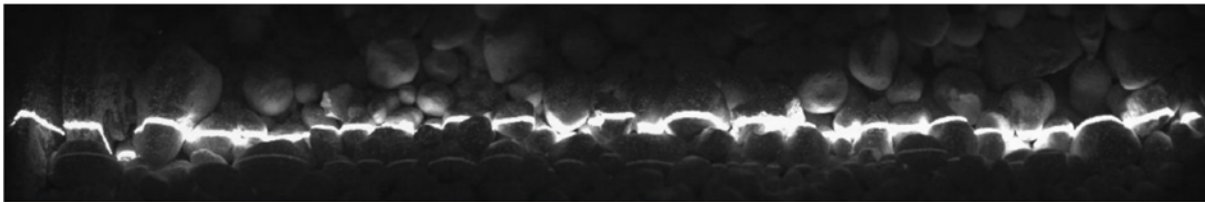


Figure 2 Laser line profile as the camera sees it (overexposed for viewing purposes).

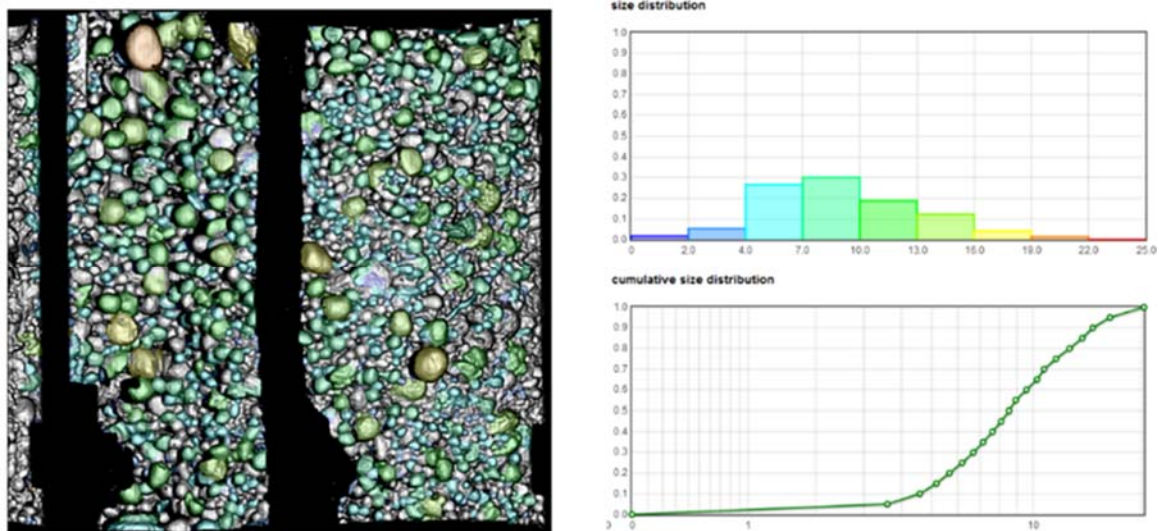


Figure 3. Example of output from the camera web interface. Left: laser triangulation plot. Upper right: size distribution. Lower right: cumulative size distribution.

The 3D camera is a surface-based measurement tool that gives the PSD of the visible bulk surface. It is known that material tend to segregate [9], i.e., moving larger particles towards the surface. A PSD of the surface will therefore overestimate the size of the material. This is relevant information when comparing a vision-based surface PSD with,

for instance, manual sieve samples. It is however less relevant when using results from PSD systems for optimization or control as the surface PSD tends to be strongly correlated to the PSD of the entire bulk. The 3D camera outputs the surface PSD without any conversion to bulk PSD as the main usage is for control. In case of conversions, assumptions of the bulk must be made and can become invalid due to production changes. This 3D camera has been used to produce a patent [10] concerning surface to bulk conversion, where simulations of segregation in specific process steps have been used to find a conversion that best fits all possible production variations in that process step. This feature was, however, not used in this study as the main purpose was not to produce a PSD equivalent to manual sieving.

Experimental Trials in Full-scale Lime Kiln

The experimental trials were performed in the Lime kiln no. 2 at the Södra Mönsterås Kraft pulp mill. The mill, Figure 44, is situated in the south part of Sweden at the east coast and produces approximately 750 ADt yearly of kraft pulp in campaigns from softwood and hardwood feedstock. The lime kiln is a traditional, counter-current, 2,5%-reclining kiln with a cyclone dryer of the lime mud. The kiln is designed to produce 275 tonnes of lime per day and holds a length of 80 meters and an inner diameter of 2,9 meters. The kiln is fired with on-site dried bark, topped with bio-oil and (occasionally) crude stripper-methanol for incineration.



Figure 44. The Södra Kraft Pulp Mill at Mönsterås, Sweden.



Figure 55. Lime kiln no 2, in which the experimental trials were carried out.

The experimental trials were planned in a way that the operation of the lime kiln would provoke changes in the quality of the produced lime by means of particle size distribution. Parameters that prior have been indicated as important are lime temperature and heating rate [5]. Therefore, the lime temperature, flue-gas temperature and kiln rotational speed were aimed to be varied in the experimental trials. The experimental plan is given in Table 1. In practice, the operational conditions were achieved by setting target values to the automatic control system, as described above, letting the system work into a new operational point satisfying the input condition.

Table 1. Achieved target parameters for the experimental trials.

Trial no	Variation of condition	Duration time	Validation
1. a. Lime temperature	850 -> 760 -> 810 -> 850°C	3 days	Screening, residual carbonates
b. Lime temperature	850 -> 760 -> 850°C	5 days	No screening, residual carbonates
2. Flue-gas temperature	613-640°C	2 days	Screening, residual carbonates
3. Kiln rotational speed	1,2 -> 1,0 -> 1,25 rpm	2 days	Screening, residual carbonates

The target parameters of the experimental trials were achieved by defining them as setpoints to the automatic control system. The lime kiln, since 2021, is equipped with a new control system delivered by Optimization that is based on a patented strategy that can be simply described as follows. The temperature level in the kiln is mainly determined by the energy supply. The fuel flow is controlled by a calculated average value of the flue gas and lime temperatures. An

increase in flue gas flow moves more heat from lime to flue gases. Therefore, the flue gas flow is controlled by a calculated temperature difference between flue gases and lime. Setpoints for the new regulators are calculated based on setpoints for lime temperature and flue gas temperature so that previous experience on suitable temperature ranges can be used. The control system has proven to be robust to operating disturbances and can advantageously be used shortly after a start of operation to control the kiln towards the desired operating mode. In addition to control of flue gas and lime temperature, the control has functions that control O₂ of the flue gases, the production speed, the production changes, the specific energy, the fuel change, and the kiln rotation speed. Detailed information about the system may be found in the patented APC [11].

Measurement of temperatures and validation of lime particle-size distribution

In the experimental trials at Södra's lime kiln, the 3D camera equipment was mounted after the lime cooler, looking down into the conveyor, as seen in Figure 66. The data from the trials was recovered continuously to a server, using internet communication. Output from 3D camera was distributed between customizable size classes, percent passing values, and bulk volume. For the experimental trials, three D-cut-values for the volume (projected area) in the cumulative size distribution were used as parameters to quantify and trace the particle-size distribution of lime nodules:

- D20: particles inferior to this diameter value make up 20 % of the total volume.
- D50, particles inferior to this diameter value make up 50 % of the total volume.
- D80, particles inferior to this diameter value make up 80 % of the total volume.



Figure 66. The installation with 3DPM measurement in the trials at the Södra mill in Mönsterås, Sweden.

The temperature of the lime is measured at the burner side of the kiln, using three parallel pyrometers. The measurement values are low pass filtered to avoid disturbances caused by the kiln rotation, and the maximum value of the three signals is used. Prior to the trial start, the pyrometers were air cleaned. Later, automatic cleaning was installed.

The flue-gas temperature was measured continuously at two positions at the end of the kiln, before and after the cyclone. Temperature sensors were used that were recently installed in shielded positions that will not be deposited by lime mud powder. Other operational parameters were measured or calculated with/from standard online instruments.

The particle-size distribution was validated by screening of manual samples extracted after the cooler, in basically the same position as the automatic 3D camera. The screening was performed manually using frames resulting in fractions of <1 mm, 1-10 mm, 10-15 mm and >15 mm. Sampling for screening was performed for all trials, except for Trial 1b due to the excessive work, which could unfortunately not be covered. Furthermore, the residual carbonate of the lime was analyzed and quantified for all trials.

RESULTS AND DISCUSSION

The 3D camera measurement was used successfully during the entire period of experimental trials for the online measurement of particle size distribution of the reburned lime. The instrument delivered the data in a stable way throughout the entire campaign and did not need any extra cleaning or service. By this, the instrument and method should be seen as successfully demonstrated for the use in an industrial lime kiln.

A summary of the ordinary operational parameters from the trials is given in Table 1 as mean values for the period in question.

Table 2. Summary of operational conditions during the trials.

Trial	Rotation (rpm)	Production (tonnes/h)	Specific energy (MJ/kg)	O2 (%vol)	H2S (ppm)	CO (ppm)	Lime temp (°C)	Flue gas temp (°C)	Temp to cyclone (°C)	Comments
<i>1a. Lime temperature</i>										
-High	1,1	200	6,77	1,8	1,4	0	850	652	274	
-Low	1,1	200	6,53	1,9	1,4	687	760	673	287	
-Medium	1,1	200	6,33	2,1	1,3	800	808	642	263	
<i>1b. Lime temperature</i>										
-High	0,87	190	6,90	3,0	0,6	0	849	588	304	
-Low	0,87	190	6,90	3,5	0,7	0	758*	588	301	
-High	0,97	213	6,90	2,0	0,8	0	819**	629**	305	
<i>2. Flue-gas temperature</i>										
-Low	0,96	210	6,82	2,0	0,6	0	808	613	290	
-High	0,96	210	6,92	3,7	0,8	27	818	640	319	
<i>3. Kiln rotational speed</i>										
-Low	0,96	210	6,50	1,9	0,3	0	841	591	284	Bio oil only
-High	1,1	210	7,10	1,6	0,2	0	846	662	298	

*Somewhat unstable, in the range of 720-785 C. Combustion was unstable.

**Does not reach setpoints. Lime temp sp 850C. Flue gas temp sp 610 C.

Trials 1a and 1b – Lime Temperature

The results from both trials with induced changes in the lime temperature show that there is a significant correlation between the lime temperature and the size of the nodules. The results from Trial 1a is shown in Figure 7 as online scattering of temperature and particle size values (D20,50,80), and in Table 3 as mean values of the particle size values. It can be seen that a reduction in lime temperature results in reduced nodule size and increased dust after approximately two residence time cycles. In Figure 77 it is seen that the decrease in lime temperature after at 17 hours, with a delay of eight hours, is followed by a decrease in particle size of the lime, for all three D20, D50 and D80 fractions. As the lime temperature again shifts back towards higher levels, we can see a gradual, but, somewhat unstable response towards larger nodules. It takes another 48 hours before a clear response can be seen in the nodule size. This is most probably because crude methanol containing high amounts of sulfur was co-combusted in the kiln during that period, as indicated in Figure 7. This was not planned or expected, but a consequence of the operation of

the pulp mill. Sulfur has been shown to affect the lime chemistry in the lime kiln [12] and most likely, also affected the nodule formation.

Figure 8 shows the results of manual screening of the sampled lime throughout the campaign. The results are mean values of each three samples taken during three consecutive hours. The results validate the trends that are given by the 3D camera tool, confirming that the particle size clearly decreases from the early, high temperature period into the consecutive lower-temperature. The screening results are also consequent with the 3D camera results during the later stages of the trial, showing no significant changes in particle size distribution. The analysis of the residual carbonate did not show any significant correlations with the other parameters but varied between 2,3 and 2,5%. Nor did the specific energy or other crucial parameters for the reburning change significantly, according to Table 2.

Table 3. Trial 1a. Measured values from 3D Camera for cumulative particle-size distribution of the lime.

Interval	D20 (mm)	D50 (mm)	D80 (mm)
High temperature	4,5	9	13,5
Low temperature	1,5	7,5	11,5
Medium temperature	2	7,5	12,5

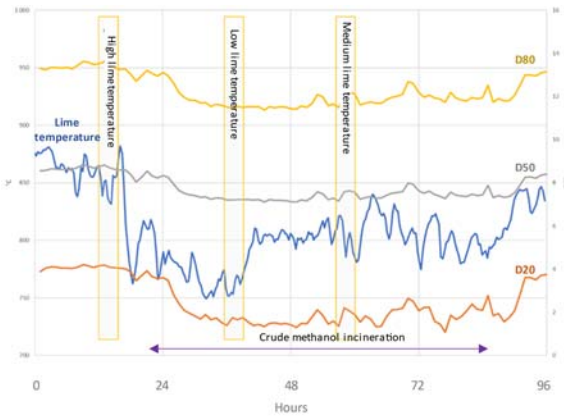


Figure 7. Trial 1a. Lime temperature (blue; left legend) and particle size distribution as D80, D50 and D20 (right legend). Crude methanol was co-combusted in the lime kiln during 50 hours, as indicated in the figure.

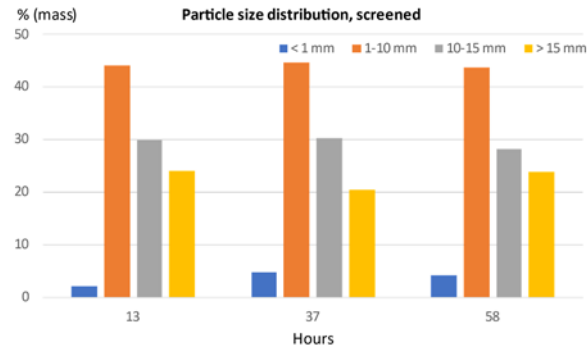


Figure 8. Validation of particle size distribution of the lime, by screening, for Trial 1a. Each value is a mean value of three measurements during three consecutive hours.

To reproduce Trial 1a without any disturbances from methanol combustion, a second trial, Trial 1b, was carried out. The results from Trial 1b are shown in Figure 9 as online tracing of temperature and particle size values (D20,50,80). Table 4 presents mean values of particle size distribution (D20,50,80) during the subsequent parts of the trials. The results clearly show a correlation between the lime temperature with nodule particle size. As the lime temperature drops gradually from 850 C to 810, 780 and 760°C for four days (96 hours), the D20,50,80 fractions also decline significantly, indicating that the lime becomes characterized by smaller particles than before. However, as the lime temperature increases again, the particle size does not respond until a mean temperature around 810°C is reached. As the setpoint of lime temperature returns to 850°C, the particle size continues to increase slowly for another 24-48 hours until a stable size condition is regained. This may, however, be due to that 850°C turned out to be hard to reach, but instead stabilized at 810-830°C. Concerning the general parameters during the trial, as presented in Table 2, it should be noted that the specific energy of reburning lime can be held constant, even with increased lime temperature. This is because the temperature of the lime can efficiently be recovered in the down-stream lime cooler.

Trial 1b was not validated with manual screening samples, due to practical reasons concerning manual resources. However, the similarities with trial 1a are striking concerning the correlation between decreased lime temperature and

decreasing particle size. On the other hand, the delay in particle size increase that is seen in both trials causes uncertainties.

Table 4. Trial 1b. Measured values from 3DPM for cumulative particle-size distribution of the lime.

Lime temperature	D20 (mm)	D50 (mm)	D80 (mm)
High temperature	3,8	8,7	13,6
Lowest temperature	3,0	8,0	12,9
Minimal size	2,0	7,4	11,9
Regained size	3,4	8,2	12,9

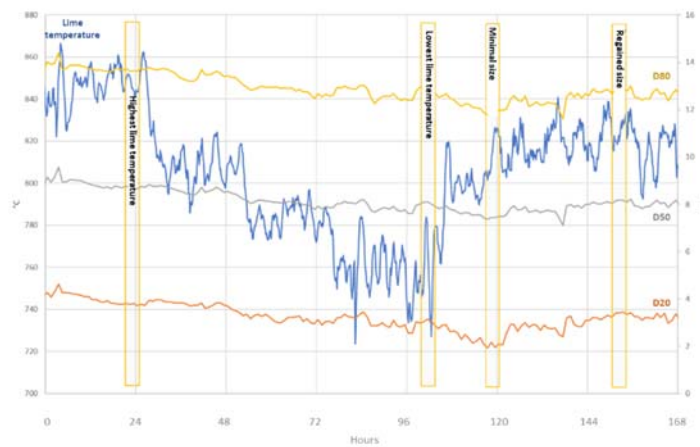


Figure 9. Trial 1b. Lime temperature (blue; left legend) and particle size distribution as D80, D50 and D20 (right-hand legend).

Trial 2 – Flue-gas Temperature

The results from Trial 2, shown in Figure 10 and in Table 5, show that operating the kiln in modes resulting in different levels of flue-gas temperature exiting the kiln does correlate with lime nodule size. There is possibly a slight trend towards larger particle size fractions with increasing temperature. But the mean values of D20-80 show less than ten percent difference. However, only small differences in flue-gas temperature was induced during the trials, which could be an explanation. Going significantly lower than 600°C started to affect the lime temperature, while a too high flue-gas temperature risked to activate the cyclone cooling.

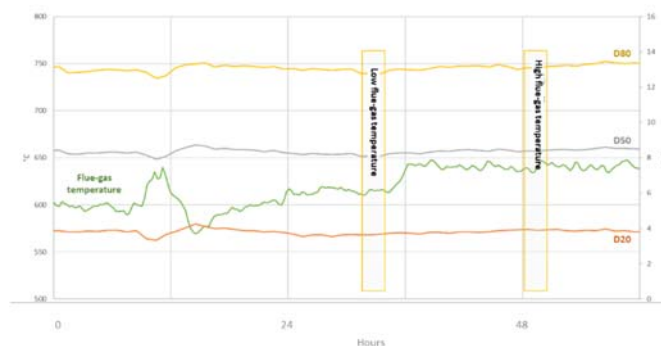


Figure 10. Trial 2. Flue-gas temperature (green; left legend) and particle size distribution as D80, D50 and D20 (right legend). The yellow boxes indicate the intervals during which lime was sampled for validation.

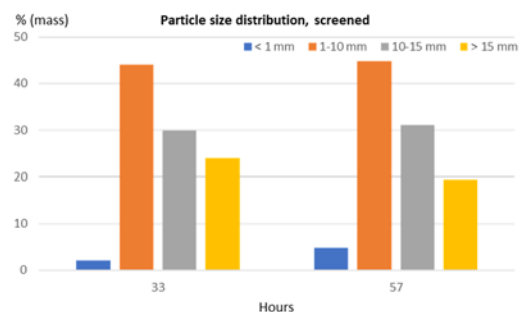


Figure 11. Validation of particle size distribution of the lime, by screening, for Trial 2. Each value is mean value of three measurements during 1.5 hours

Table 5. Trial 2. Measured values from 3DPM for cumulative particle-size distribution of the lime.

Interval	D20 (mm)	D50 (mm)	D80 (mm)
Low temperature	3,7	8,1	12,8
High temperature	4,0	8,6	13,4

Figure 11 shows the results of validation by screening of lime that was sampled Trial 2. Three consecutive samples were extracted during 1.5 hours of low and high temperature (yellow boxes in

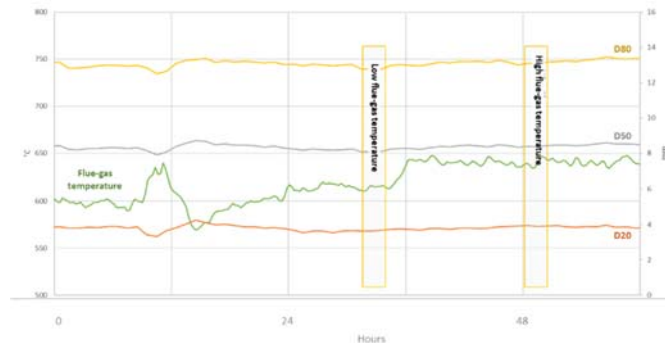


Figure 10). The results are mean values of each three samples taken during three consecutive hours. The results validate the 3D camera tool, that there was no significant difference between the periods of low and high flue-gas temperatures. Also, the analysis of the residual carbonate did not show any significant correlations with flue-gas temperature, with 2,3 and 2,8% for low and high flue-gas temperature, respectively. Nor did the specific energy or other crucial parameters for the reburning change significantly, according to Table 2.

Trial 3 – Rotational Speed of the Kiln

The results from Trial 3, shown in Figure 12 and in Table 6, indicate that there seem to be a weak correlation between the rotational speed of the lime kiln and the particle-size distribution of the produced lime. As the rotation is reduced, the particle-size distribution slowly shifts towards lower levels. However, this process is slow and does not reach a stable value before the trial switches back to higher rotational speed. Furthermore, the response seems to be only for D50 and D20. However, it cannot clearly be validated by the manual sampling and screening of lime particles, as presented in Figure 13, even if slightly higher values of the medium-size particles were seen at the higher rotational speed.

A significant effect of the rotational speed of the lime kiln was a lower flue-gas temperature and specific energy needed for the lime reburn. The specific energy was increased by 10% (0,6 MJ/kg) during the period of high rotational speed (not including the electricity for rotation). The lower specific energy at lower rotational speed could be explained by the resulting increase in level-load of lime in the kiln. Increased level-load of the kiln increases the heat transfer rate between the lime and the gas and the walls. The reduction of rotational speed from 1,25 to 1,0 rpm at 210 tonnes per day, will increase the level-load from 6,6 to 8,6%, which theoretically, increases the heat exchange rate with almost 10%, corresponding to an increase of kiln length by approximately 7 meters. The set-point of low rotational speed was maintained after the trials were finished, to maintain production and lime quality.

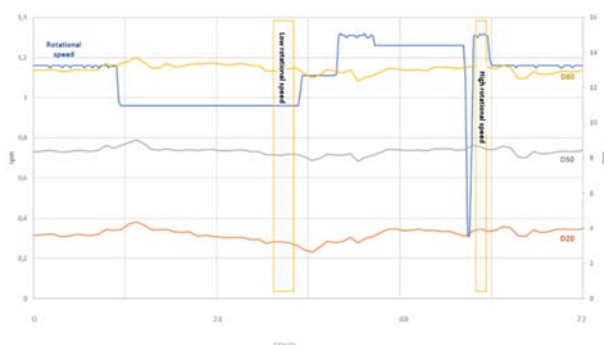


Figure 12. Trial 3. Rotational speed of the lime kiln (blue; left legend) and particle size distribution as D80, D50 and D20 (right legend). The yellow boxes indicate the intervals during which lime was sampled for validation.

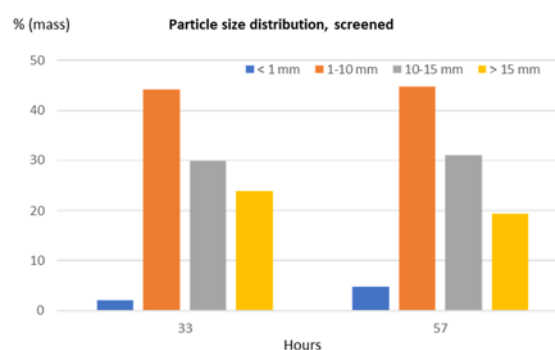


Figure 13. Validation of particle size distribution of the lime, by screening, for Trial 2. Each value is mean value of three consecutive measurements during 1.5 hours, indicated by the yellow boxes in Figure 12.

Table 6. Trial 3. Measured values from 3D camera for cumulative particle-size distribution of the lime.

Interval	D20 (mm)	D50 (mm)	D80 (mm)
Low rotational speed	3,3	8,2	13,1
High rotational speed	3,8	8,6	13,2

CONCLUSIONS

The overall results concluded that the online measurement using 3D camera for identifying particle size groups, can be used as a stable tool for the monitoring of particle-size distribution of the reburned lime from a lime kiln. The instrument system acquired and delivered the data throughout the entire campaign and there was no need for any extraordinary maintenance. Furthermore, the measurement campaign was successfully performed with the variation of three different parameter in the industrial lime kiln of Södra's kraft pulp mill in Mönsterås, Sweden. The set values of lime temperatures and rotational speed of the kiln were achieved according to the experimental plan. However, a second trial with variable lime temperature was performed to rule out the possible effect of the combustion of high-sulfur crude methanol that was initiated during the latter part of the first trial. Furthermore, the trial with variable flue-gas temperature did not reach the span of the defined set-points, which gives the trial less significance of the results than the other trials.

The results from the trials in the lime kiln conclude that the lime temperature had a significant effect on the nodule particle-size distribution of the reburned lime. This was identified by the continuous measurement by 3DPM and validated by the screening of manual lime samples. The increase in lime temperature could be achieved at basically constant specific energy consumption since the lime cooler could recover the increase in excess heat. On the other hand, the rotational speed of the lime kiln turned out to have significant effect on the specific energy consumption. This was coupled to the fact that low rotational speed increases the level-load of lime in the kiln, due to increased heat transfer between the lime and both the gas and walls. A theoretical comparison of the expected change in heat transfer coincided well with the measured change of approximately 10%. The set-point of low rotational speed was maintained after the trials were finished, with maintained production and lime quality. The rotational speed of the lime kiln, as well as the flue-gas temperature at the end of the kiln, did not have any significant effect on the particle-size distribution. It is noted that the flue-gas temperature experiment had limited span, thus, leaves limited possibilities to draw conclusions on the possible correlation with particle-size distribution of the lime.

Altogether, the successful experimental trials using the on-line measurement tool for particle-size distribution, together with the prior known correlation of lime nodule size to lime quality, open new possibility to perform and monitor long-term trials in real lime kilns.

RECOMMENDATIONS

Continued investigations of the influence of operational conditions of a lime kiln on the resulting lime quality is recommended. The on-line measurement of lime-particle size-distribution could serve as;

A soft sensor for the lime composition. It has been suggested that non-process elements, such as Na, P and Cl, play important roles in the chemistry of the lime calcining. The authors of this paper have qualitatively experienced that there seems to be a correlation between the amount of virgin (fresh) lime that has been purged recently and the dusting in a lime kiln along with the nodule size. Such effects could be caught by the demonstrated nodule-size measurement system. On one occasion, high dusting and small nodules were noticed during a period of high purging, which took approximately one month to recover. This is an example of effects from non-process elements that could be automatically tracked by particle-size measurement.

Evaluation tool for the firing of biomass powder in lime kilns. Lime temperature could, in this study, be correlated to the nodule sizes. To get the right lime temperature and, hence, optimal nodule sizes with minimal dusting, it is important to understand the heat transfer from the flame to the lime bed, and how this is affected by properties of the fuel and operational conditions. Here, online particle-size measurement could be a useful tool.

Evaluation tool of the firing of sulfuric fuels in lime kilns. Crude methanol of high sulfur content was combusted in the lime kiln partly during one of the trials. The results indicate that this caused a drop in the nodule size and lime temperature, as well as an increase in specific energy need. Could it be so that sulfur interfered with the sodium chemistry that is important for nodule formation? Here, on-line measurement of nodule size may serve as an efficient tool, alongside chemical analysis of lime samples, in further investigations when firing fuels of high sulfur content, e.g. crude methanol and kraft lignin.

ACKNOWLEDGEMENTS

The project was funded in part by the Swedish industrial research program Energiforsk (Skogsindustriella programmet, eng: the Research Program for Forest Industry) and in part by Södra Skogsägarna Research Foundation.

Henric Dernegård initiated the idea of performing this kind of trial, as a spin-off from his research, and he also took part in the early planning to make the project possible. For this important contribution, the authors would like to extend an acknowledgement. Furthermore, the authors would like to acknowledge the operational team of the lime kiln, as well as the lab technicians, at the Södra Mönsterås mill for the engagement during the project trials.

REFERENCES

1. Dernegård, H. (2019). Dusting in a lime kiln. Göteborg: Chalmers tekniska högskola.
2. Dernegård, H., Brelid, H., & Theliander, H. (2017). Characterization of a dusting lime kiln - A mill study. Nordic Pulp and Paper Research Journal Vol 32 (1), 25-34
3. Tran, H., & et.al. (2007). Correlation between nodule sizes and residual carbonate content in lime kilns. Tappi Journal vol. 6(4), 9-15
4. Fardadi, M. (2010). Modeling Dust Formation in Lime Kilns. Toronto: University of Toronto
5. Richards, T., & Joseph, J. (2019). Lime Kiln Dusting. Energiforsk
6. Järvensivu, M., Saari, K., & Jämsä-Jounela, S.-L. (2001). Intelligent control system of an industrial lime kiln process. Control Engineering Practice
7. Villarroel, R., & Tran, H. (2015). Operating experience of the world's largest lime kiln. The 7th international Collegium of Eucalyptus Pulp. Vitoria, Brazil
8. Thurley, M J, Degerfeldt, D, Nystrom, J, Nordenskjöld, R and Lindqvist, L, (2018). Automated, online measurement of bulk material size distribution on conveyor using 3D profile imaging at Boliden Mines, in Proceedings 14th AusIMM Mill Operators' Conference 2018, pp 641-652 (The Australasian Institute of Mining and Metallurgy: Melbourne)
9. A. Rosato, K. J. Strandburg, F. Prinz, and R. H. Swendsen, (1987) Why the brazil nuts are on top: Size segregation of particulate matter by shaking, Physical Review Letter, vol. 58, pp. 1038 – 1040.

10. Nordenskjold, R. et.al (2022). Method and arrangement for determining an estimated bulk particle-size distribution (SE545201 C2, SE2251592 A1, WO2022010399A1).
11. Berg, E., Eriksson, T., Optimization of control of rotary kiln, (2019), SE1850477A1, EP3784971A1, WO2019209156A1.
12. Francey, S., Tran, H. Impacts of burning high-sulfur fuels in lime kilns (2012), Journal of Science & Technology for Forest Products and Processes: VOL.2, NO.3