Online monitoring of the size distribution of lime nodules in a full-scale operated lime kiln using an in-situ laser triangulation camera

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ABSTRACT: To maximize efficiency of the recausticizing process in a pulp mill, producing a reburned lime with high and consistent reactivity is process critical. Prior investigations have demonstrated a correlation between the reactivity of lime and its nodule size, as well as the dusting behavior of the kiln. Therefore, monitoring the nodule size produced in the lime kiln could be a promising indirect method to measure the performance of the lime kiln.

The objective of this investigation was to evaluate the utility of a laser triangulation camera for online monitoring of nodule size distribution for 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 installed at the exit conveyor to analyze the lime discharging 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 monitoring demonstrated temporal stability, and the results showed 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 they had significant impact on the specific energy demand.

The overall conclusion of the study is that the camera methodology effectively correlates lime temperature with nodule size distribution, and it advocates for the methods of implementation in automating lime temperature control, facilitating the production of consistently reactive lime at a lower specific energy consumption.

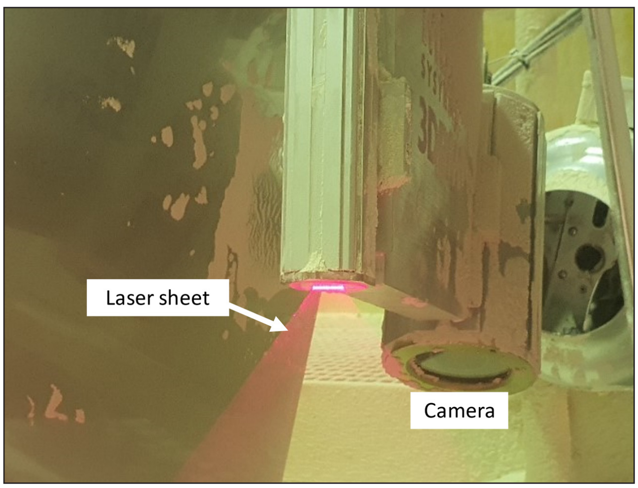
Application: Readers may use the information in this study to improve the performance of lime kiln operation. This is accomplished by learning more about how process parameters could be coupled to the nodule size of reburned lime.

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 (CaO) takes place. The process is energy demanding and, hence, making the lime kiln a major consumer of fuel. The fuels normally used include 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 substantial 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. Achieving a more precise lime dosing reduces the need for reburning lime mud, subsequently leading to lower fuel consumption. To achieve high precision in the recausticizing process, it is important that the lime quality is consistent and high. The reactivity of the lime has been shown to correlate with the size of the lime nodules (marbles) that are formed in the lime kiln. Nodules with diameters ranging from 10 to 15 mm have been shown to yield higher reactivity compared to finer lime particles [2]. To produce optimally sized 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 an overly extended residence time can cause over-calcination, which may result in a reduction of lime reactivity. Furthermore, the lime kiln may experience problems with dusting, characterized by the entrainment of small lime particles within the gas flow inside the kiln. The radiative heat 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 have been shown to influence the tendencies for dusting [4]. Experimental trials have demonstrated that a high lime temperature and a low heating rate contribute to reduced dusting [5]. Overall, these issues underscore that the importance of effective control over the lime kiln is not only crucial for the direct reduction of fuel consumption in the combustion, but it is also indirectly so by reducing the amount of dead-load of lime that is circulating through the recausticizing 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, represented by the quality of the produced lime and white liquor, is routinely assessed through manual sampling 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 setup typically lacks any direct and online 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, leading to better operation and lower energy consumption as well.

The primary objective of this study was to investigate the feasibility of online measurement of particle size distribution of the reburned lime for possible integration into the control system of a lime kiln. A specific objective was to quantify the impact of flue gas temperature, lime temperature, and residence time on the particle size distribution of the reburned lime, subsequently influencing lime reactivity and kiln 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 monitoring the particle size distribution, an automated control routine could be established to optimize optimal lime reactivity, minimize dusting, and reduce energy consumption.



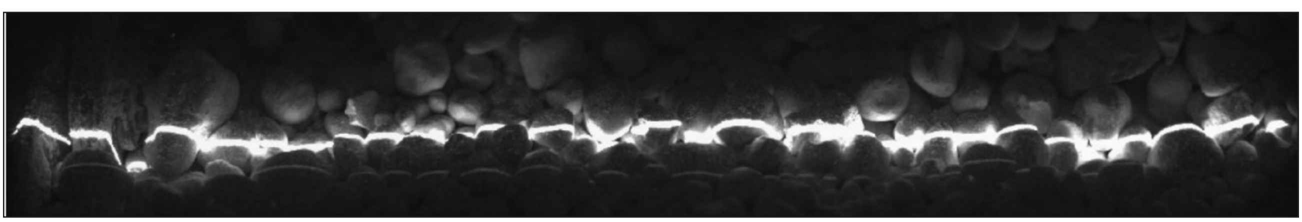
1. Measurement module showing a laser in the front and a camera in the back.

METHODOLOGY

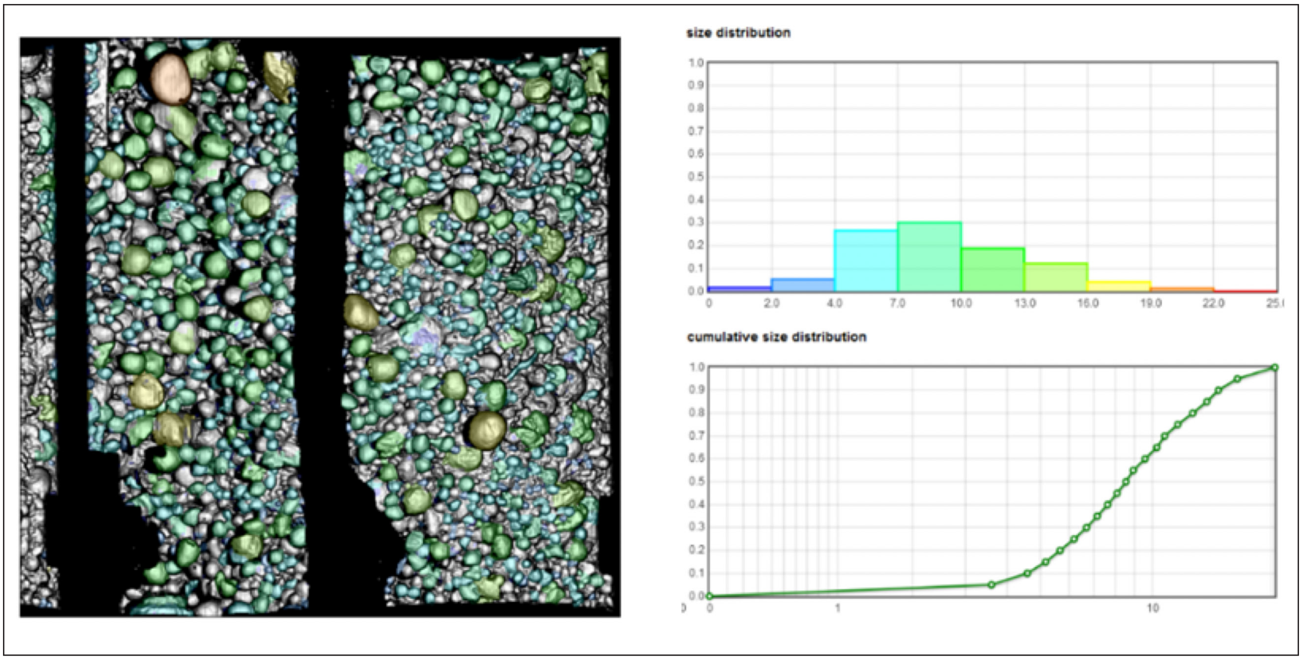
Measurement of particle size distribution of the reburned lime

The particle size distribution (PSD) of the reburned lime was measured using the 3DPM from Optimation (Piteå, Sweden), a trademarked system created for harsh environments that uses laser triangulation to collect three-dimensional data of material passing on a conveyor. Laser triangulation is a technology that uses a projected laser line to illuminate the material on the conveyor belt, providing a height profile, along with a camera that captures and extracts the laser height profile. **Fig. 1** and **Fig. 2** provide a visual representation of the laser triangulation system. **Figure 3** provides an example of the output information from the camera. The left image in Fig. 3 illustrates the belt with particles, and the charts on the right illustrate the corresponding size data. In the left image, the belt is traveling from right to left, and the full width of the belt is shown top to bottom, allowing for the measurement of size distribution across the entire belt. Calibration of the laser camera setup enables precise height information accuracy in the submillimeter range. Height profiles are collected at fixed movement intervals, determined either by time in cases of constant movement speed or by a pulse encoder/input signal in situations where 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. This capability enhances the robustness of the PSD measurement process. For instance, by excluding partially overlapped particles rather than including the smaller visible part, the risk of underestimation can be avoided [8]. The only recalibration procedure required after the initial setup is when there are modifications to either the laser or the camera. If there are changes in the relative position between the laser and the camera, recalibration is necessary to ensure accurate millimeter values, meaning a calibration must be remade to give correct millimeter values. For ex-



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



3. Example of output from the camera web interface. Left image shows laser triangulation plot; upper right image shows size distribution; and lower right image shows cumulative size distribution.

ample, this will be the case when replacing the laser. Since this is the only recalibration performed, if done correctly, it will not significantly affect any millimeter output (mean calibration error is in the range of 0.02 mm) from the camera. As a result, PSD data can be compared regardless of how far back in time a comparison is required.

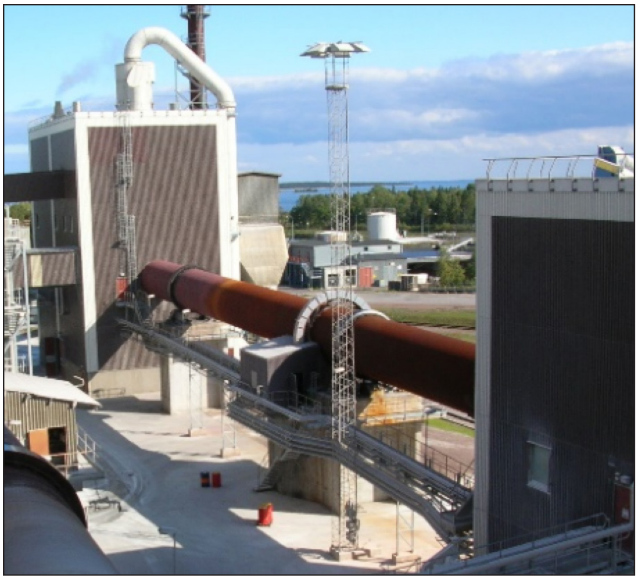
The 3D camera is a surface-based measurement tool, providing the PSD of the visible bulk surface. It is known that materials tend to segregate [9], resulting in larger particles moving toward the surface. Consequently, a PSD of the surface may overestimate the size of the material. While this information is relevant when comparing a vision-based surface PSD with manual sieve samples, it is 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 its primary application is for control purposes. In the case of converting to bulk PSD, assumptions of the bulk must be made that can become invalid due to production changes. While this 3D camera has been used to produce a patent [10] concerning surface-to-bulk conversion, employing simulations of segregation in specific process steps has been used to find an optimal conversion for all possible production variations in the recausitizing step. The primary focus of this study was not to produce a PSD equivalent to manual sieving.

Experimental trials in a full-scale lime kiln

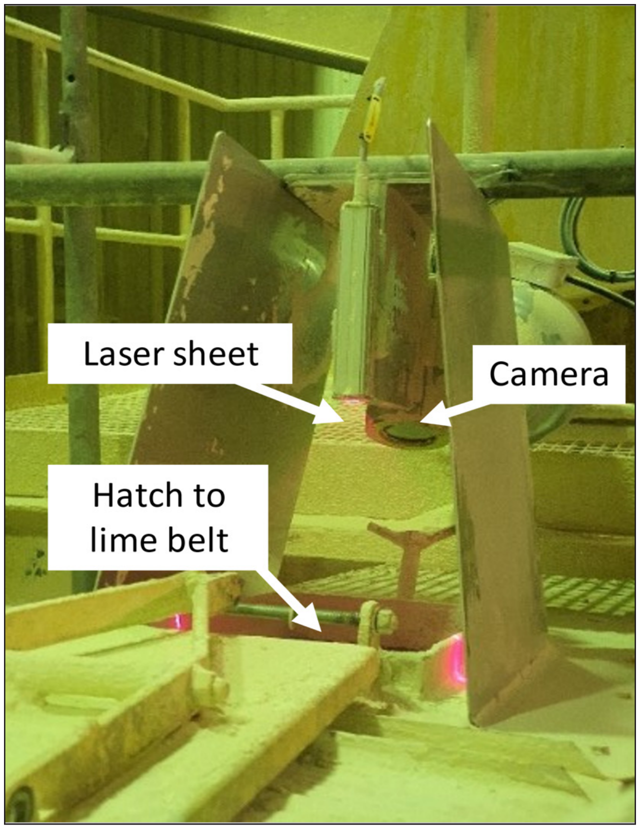
The experimental trials were performed in the No. 2 lime kiln at the Södra Mönsterås kraft pulp mill in Sweden. The mill, shown in **Fig. 4**, is situated in the southern part of Sweden on the east coast and has a production capacity of 750 air-dried (a.d.) metric tons annually of bleached kraft pulp from both softwood and hardwood feedstock operations. The lime kiln in use, shown in **Fig. 5**, is a traditional countercurrent 2.5% reclining kiln with a cyclone dryer of the lime mud. The kiln is designed to produce 275 metric tons/day of lime and is 80 m in length with an inner diameter of 2.9 m. Fuel for the kiln primarily consists of onsite dried bar that is supplemented with bio-oil and, on occasion, crude stripper-methanol for incineration.

4. The Södra kraft pulp mill in Mönsterås, Sweden.

The experimental trials were planned in a way that the operation of the lime kiln would induce variations in the quality of the produced lime, specifically focusing on changes in the PSD. Parameters that were previously indicated as important are lime temperature and heating rate



5. The No. 2 lime kiln in which the experimental trials were carried out.



6. The installation with 3DPM measurement in the trials at the Södra Mönsterås mill.

[5]. As a result, adjustments were made to the lime temperature, flue gas temperature, and kiln rotational speed during the experimental trials. The experimental plan is outlined in **Table I**. In practice, the operational conditions were achieved by introducing variations in the setpoint values of the automatic control system, enabling the system to adjust and reach new operational points that met the specified input conditions outlined in Table I.

The target parameters of the experimental trials were achieved by defining them as setpoints to the automatic control system. Since 2021, the lime kiln has been equipped with a new control system delivered by Optimation that is based on a patented strategy that can be simply described as follows: temperature level in the kiln is mainly determined by the energy supply; 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; and 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 demonstrated robustness in handling operational disturbances and can effectively be utilized 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 the excess oxygen of the flue gases, production speed, production changes, specific energy, fuel switching, and the kiln rotation speed. Detailed information about the system are available in the advanced process control (APC) patent [11].

Measurement of temperatures and validation of lime particle size distribution

Durin the experimental trials at Södra's lime kiln, the 3D camera equipment was mounted after the lime cooler, with its view directed downward into the conveyor, as illustrated in **Fig. 6**. The data from the trials was continuously transmitted to a server via internet communication. Output from

Trial No.	Variation of Condition	Duration Time	Validation
1. a. Lime temperature	850°C → 760°C → 810°C → 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°C – 640°C	2 days	Screening, residual carbonates
3. Kiln rotational speed	1.16 rpm → 0.96 rpm → 1.25 rpm	2 days	Screening, residual carbonates

I. Target parameters for the experimental trials.

the 3D camera was categorized into 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 PSD 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.

The temperature of the lime is measured at the burner side of the kiln, just before the lime exits the kiln, using three parallel pyrometers. To mitigate disturbances caused by kiln rotation, the measurement values undergo low-pass filtering, and the maximum value of the three signals is used. Typically, the difference between minimum and maximum readings is below 10°C. Prior to the trial start, the pyrometers were air cleaned. Later, automatic cleaning was installed.

The flue gas temperature was continuously measured at two positions at the end of the kiln, both before and after the cyclone. Recently installed temperature sensors were utilized in shielded positions to prevent deposition by lime mud powder. Other operational parameters were measured or calculated using standard online instruments.

The PSD was validated through manual screening of samples extracted after the cooler, essentially in the same position as the automatic 3DPM. The screening was performed manually using frames resulting in fractions categorized as < 1 mm, 1–10 mm, 10–15 mm, and > 15 mm. Sampling for screening was performed for all trials, with the exception of Trial 1b due to excessive workload, which could unfortunately not be covered. Furthermore, the residual carbonate content of the lime was analyzed and quantified for all trials.

RESULTS AND DISCUSSION

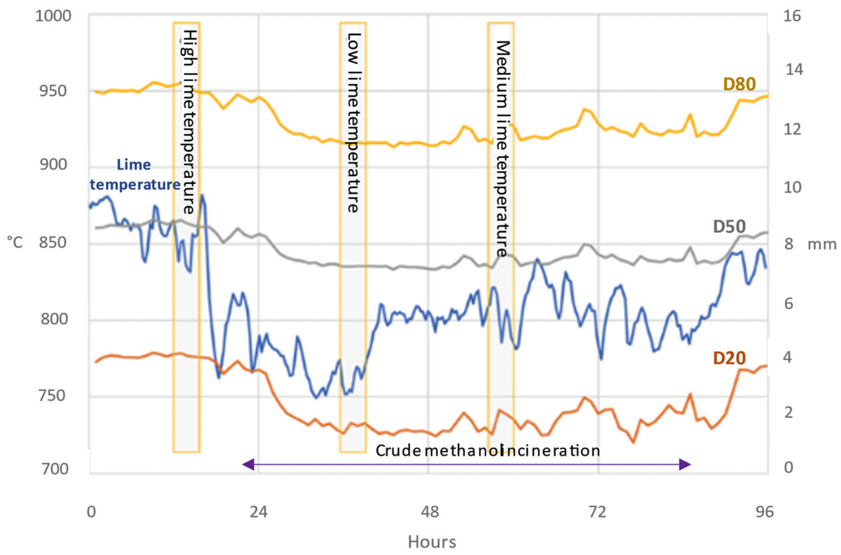
The 3DPM system was used successfully during the entire period of experimental trials for the online measurement of PSD of the reburned lime. The instrument consistently delivered stable data throughout the entire campaign and did not need any extra cleaning or servicing. As such, the instrument and method should be regarded as successfully demonstrated for use in an industrial lime kiln.

A summary of the ordinary operational parameters from the trials is given in **Table II**, presenting mean values for the period under consideration.

Trial No.	Rotation, rpm	Production, metric tons/h	Specific Energy, MJ/kg	O_2, % vol	H_2S, ppm	CO, ppm	Lime Temp., °C	Flue Gas Temp., °C	Temp. to Cyclone, °C	Comments
1a. Lime temperature										
-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	
1b. Lime temperature										
-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	
2. Flue gas temperature										
-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	
3. Kiln rotational speed										
-Low	0.96	210	6.50	1.9	0.3	0	841	591	284	Bio-oil only
-High	1.25	210	7.10	1.6	0.2	0	846	662	298	

O_2: oxygen; H_2S: hydrogen sulfide; CO: carbon monoxide.
* Somewhat unstable, in the range of 720°–785°C. Combustion was unstable.
** Does not reach setpoints. Lime temperature setpoint 850°C. Flue gas temperature setpoint 610°C.

II. Summary of operational conditions during the trials. Note that target values are automatically controlled by the kiln's advanced process control (APC) as shortly described in section "Experimental trials in full-scale lime kiln."



7. Trial 1a data showing lime temperature (blue; left legend) and particle size distribution (PSD) at D80, D50, and D20 (right legend). Crude methanol was co-combusted in the lime kiln for 50 h, as indicated in the figure.

Trials 1a and 1b – Lime temperature

The results from both trials involving induced changes in the lime temperature reveal a significant correlation between the lime temperature and the size of the nodules. Trial 1a's results are depicted in **Fig. 7**, illustrating the online scattering of temperature and particle size values (D20, D50, D80), which are summarized in **Table III** as mean values of the particle size values. It is evident that a reduction in lime temperature leads to a decrease in nodule size and an increase in dust after approximately two lime kiln residence times have elapsed. In Fig. 7, it is seen that the decrease in lime temperature at 17 h, with a delay of 8 h, is followed by a decrease in particle size of the lime across 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 h before a clear response in the nodule size can be observed. This delay is likely due to the co-combustion of crude methanol containing high amounts of sulfur used in the kiln during that period, as indicated in Fig. 7. This was not planned or expected, but was a consequence of the operation of the pulp mill. Sulfur has been shown to affect the lime chemistry in the lime kiln [12], and it 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 presenting mean values of each of the three samples taken over three consecutive hours. These results validate the trends that are observed with the 3D camera tool, confirming that the particle size clearly decreases from the earlier high temperature period into the consecutively lower temperature periods shown in Fig. 7. The screening results are consistent with the 3D camera results during the later stages of the trial, indicating no significant changes in PSD. The analysis of the residual carbonate did not reveal any significant correlations with the other parameters but exhibited variations between 2.3% and 2.5%. Similarly, the specific energy or other crucial parameters for reburning did not change significantly, as indicated in Table II.

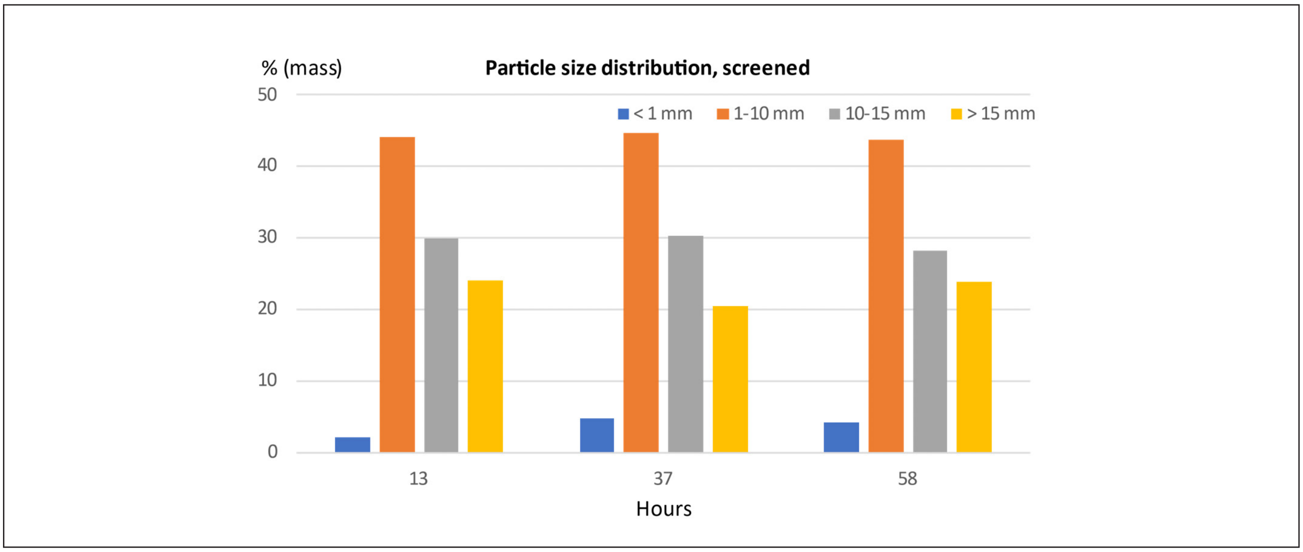
To reproduce Trial 1a without any disturbances from methanol combustion, a second trial, Trial 1b, was carried out. The results from Trial 1b are shown in **Fig. 9** as online

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

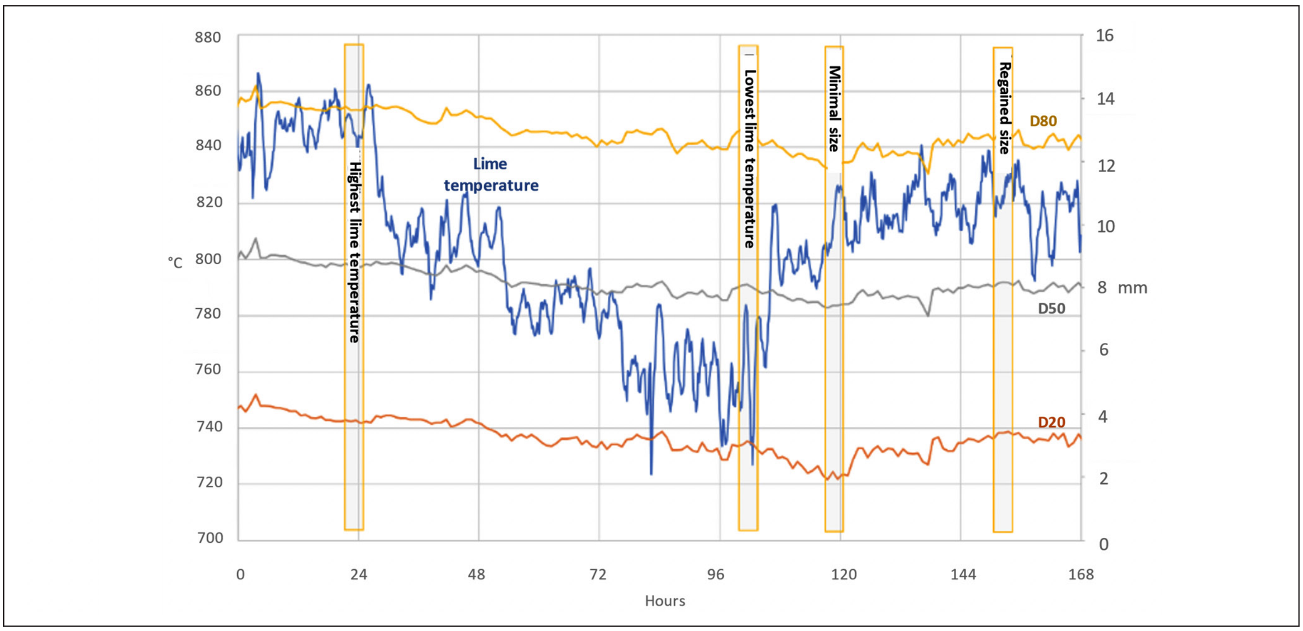
III. Trial 1a measured values from 3DPM system for cumulative particle size distribution (PSD) of the lime.

Interval	D20, mm	D50, mm	D80, mm
High temperature	3.8	8.7	13.6
Low temperature	3.0	8.0	12.9
Minimal size	2.0	7.4	11.9
Regained size	3.4	8.2	12.9

IV. Trial 1b measured values from 3DPM system for cumulative PSD of the lime.



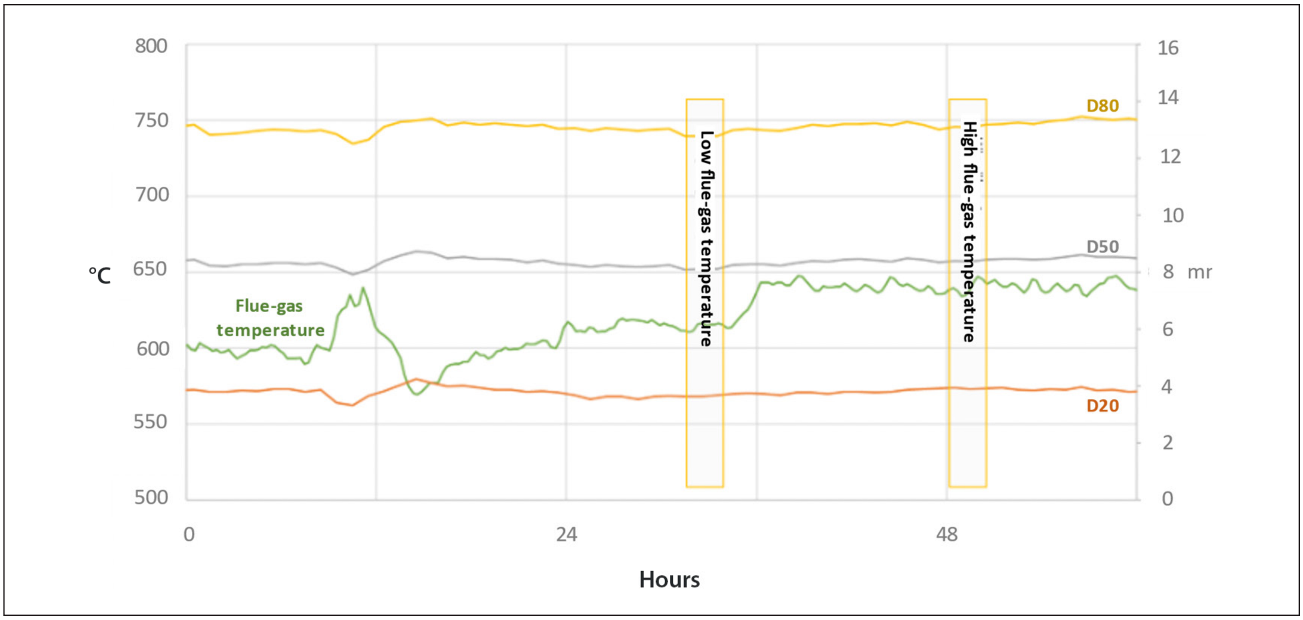
8. Validation of lime PSD, by screening, for Trial 1a. Each value is a mean value of three measurements during three consecutive hours.



9. Trial 1b data showing lime temperature (blue; left legend) and PSD at D80, D50, and D20 (right legend).

tracking of temperature and particle size values (D20, D50, D80). **Table IV** presents mean values of particle size distribution (D20, D50, D80) during the different phases of the trials. The results clearly show a correlation between the lime temperature and nodule particle size. As the lime temperature drops gradually from 850°C to 810°C, 780°C, and 760°C for four days (96 h), the D20, D50, and D80 fractions also decline significantly, indicating a shift toward smaller particles. However, as the lime temperature increases again, the particle size does not respond until a mean temperature of around 810°C is reached. Upon returning to the setpoint of 850°C for lime temperature, the particle size continues to increase slowly for another 24–48 h until a stable size condition is regained. It is worth noting that achieving 850°C proved challenging, but instead the temperature stabilized at 810°C–830°C. Regarding the general parameters observed during the trial, as presented in Table II, 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 downstream lime cooler.

Trial 1b was not validated with manual screening samples due to practical reasons concerning manual resources. Nevertheless, the similarities with Trial 1a are noteworthy, particularly regarding the correlation between decreased lime temperature and decreasing particle size. However, the observed delay in particle size increase in both trials introduces uncertainties.



10. Trial 2 data showing flue gas temperature (green; left legend) and PSD at D80, D50, and D20 (right legend). The yellow boxes indicate the intervals during which lime was sampled for validation.

Trial 2 – Flue-gas temperature

The results from Trial 2, shown in **Fig. 10** and in **Table V**, indicate a correlation between operating the kiln under varying levels of flue gas temperature exiting and the size of lime nodules. There is possibly a slight trend towards larger particle size fractions with increasing temperature, although the mean values of D20–D80 show less than 10% difference. However, it is important to note that only minor variations in flue gas temperature were induced during the trials, which could account for these findings. Lowering the temperature significantly below 600°C started to affect the lime temperature, while excessively high flue gas temperature risked activating the cyclone cooling mechanism.

Figure 11 shows the validation results obtained through screening lime samples collected during Trial 2. Three consecutive samples were extracted during 1.5 h under conditions of low and high temperature (yellow boxes in Fig. 10). The results are mean values of each of the three samples taken during three consecutive hours. The results confirm the reliability of the 3D camera tool, as there was no significant difference observed between periods of low and high flue gas temperatures. Additionally, analysis of the residual carbonate did not show any significant correlations with flue gas temperature, measuring 2.3% and 2.8% for low and high flue gas temperature, respectively. Similarly, specific energy or other crucial parameters for the reburning remained unchanged, as indicated in Table II.

Trial 3 – Rotational speed of the kiln

The results from Trial 3, shown in **Fig. 12** and summarized in **Table VI**, suggest a subtle correlation between the rotational speed of the lime kiln and the particle size distribution of the produced lime. As the rotational speed of the lime kiln 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, validation through manual sampling and screening of lime particles, as depicted in **Fig. 13**, doesn't offer a clear confirmation, despite slightly higher values of medium-sized particles being observed at higher rotational speeds.

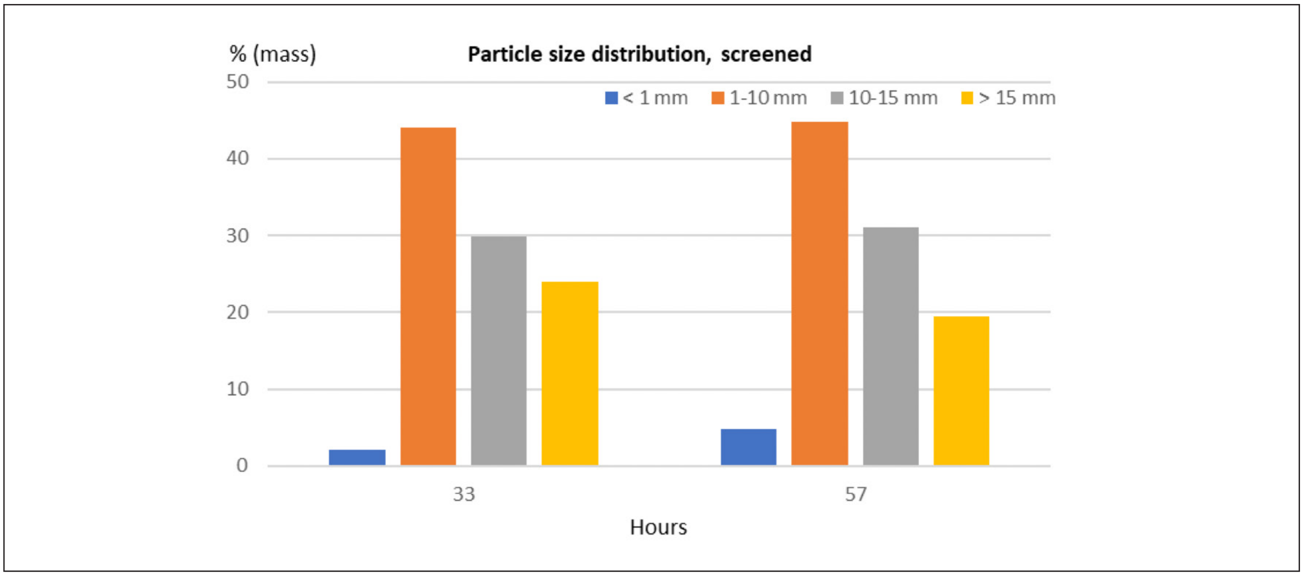
The variation in rotation speed of the lime kiln had a notable impact on both flue gas temperature and specific energy required for lime reburning. Specifically, during periods of high rotational speed, the specific energy increased by 10% (0.6 MJ/kg), excluding the electricity need-

Interval	D20, mm	D50, mm	D80, mm
Low gas exit temperature	3.7	8.1	12.8
High gas exit temperature	4.0	8.6	13.4

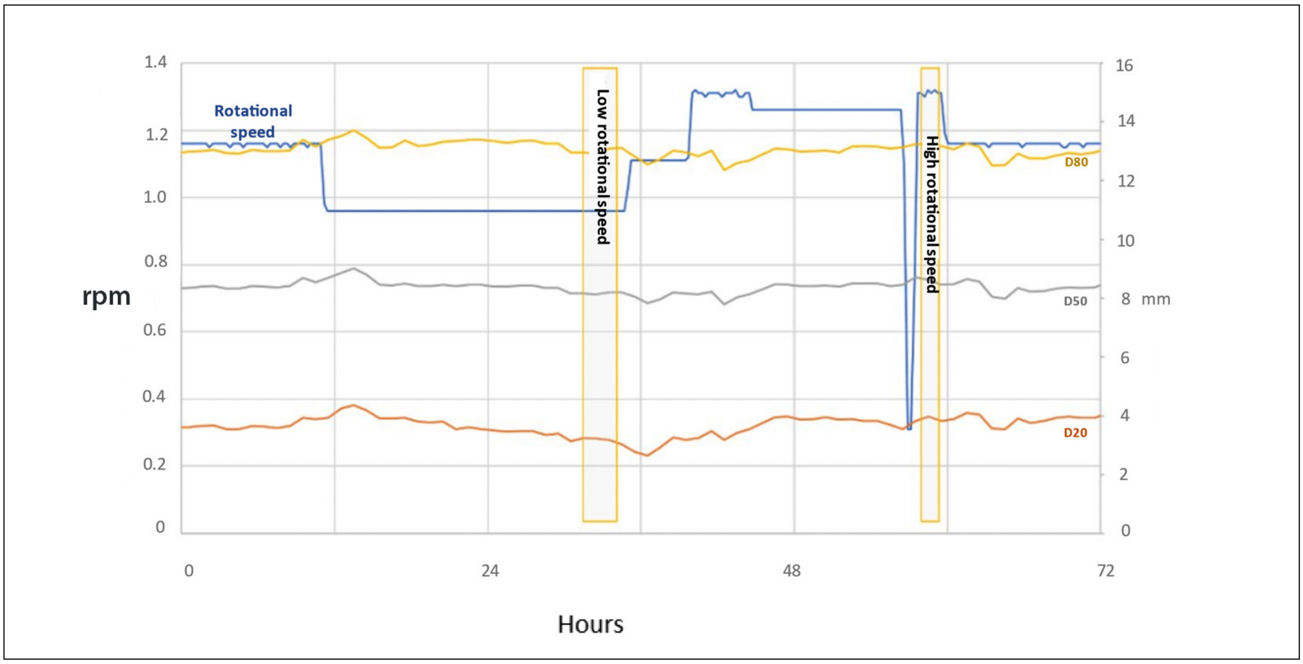
V. Trial 2 measured values from 3DPM system for cumulative PSD of the lime.

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

VI. Trial 3 measured values from 3DPM system for cumulative PSD of the lime.



11. Validation of lime PSD, by screening, for Trial 2. Each value is the mean value of three measurements during 1.5 h.

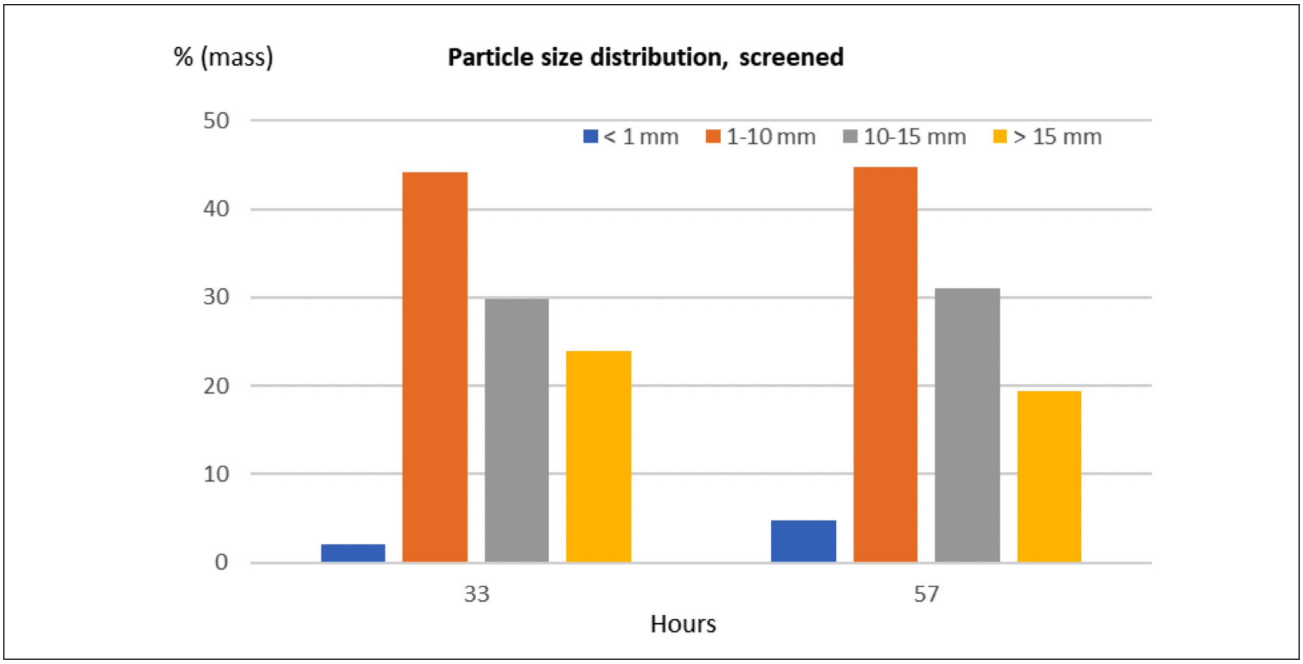


12. Trial 3 showing rotational speed of the lime kiln (blue; left legend) and PSD at D80, D50, and D20 (right legend). The yellow boxes indicate the intervals during which lime was sampled for validation.

ed for rotation. This phenomenon can be explained by the resulting increase in the level load of lime in the kiln. Increased level load of the kiln enhances the heat transfer rate between the lime, gas, and kiln walls. For instance, reducing the rotational speed from 1.25 to 1.0 rpm at 210 metric tons/day increased the level load from 6.6% to 8.6%, theoretically enhancing the heat exchange rate by almost 10%. This increase in heat exchange is akin to extending the kiln length by approximately 7 m. Subsequently, the setpoint for low rotational speed was retained after the trials to uphold production and maintain lime quality.

CONCLUSIONS

The findings of this study indicate that the online measurement using the 3D camera for particle size characterization can serve as a reliable tool for monitoring the particle size distribution of reburned lime from a lime kiln. Throughout the entire campaign, the instrument system consistently acquired and delivered data without the need for significant maintenance. Furthermore, the measurement campaign was successfully performed with the variation of three different parameters in the industrial lime kiln of Södra's kraft pulp mill in Mönsterås, Sweden. The set values of lime tem-



13. Validation of lime PSD, by screening, for Trial 2. Each value is the mean value of three consecutive measurements during 1.5 h, as indicated by the yellow boxes in Fig. 12.

peratures and rotational speed of the kiln were achieved according to the experimental plan. A second trial involving variable lime temperature was performed to rule out the possible effect of high-sulfur crude methanol combustion that was initiated during the latter part of the first trial. For this particular lime kiln, use of this high sulfur content methanol has proven difficult. Furthermore, the trial with variable flue gas temperature did not reach the span of the defined setpoints, which gives the trial less significance than the other trials.

The results from the trials in the lime kiln conclude that the lime temperature had a significant effect on PSD of the reburned lime nodules. This was identified by the continuous measurements using 3DPM and validated through screening of manual lime samples. Increasing lime temperature could be achieved at relatively constant specific energy consumption, as excess heat could be recovered in the lime cooler. Conversely, the rotational speed of the lime kiln turned out to have significant impact 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 setpoint of low rotational speed was retained after the trials were finished, ensuring sustained production and consistent lime quality 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 exhibit any significant impact on the particle size distribution. However, it is worth noting that the flue gas temperature experiment had a limited span, which restricts the ability to draw conclusive correlations with the PSD of the lime.

In conclusion, the successful experimental trials utilizing the online measurement tool for PSD, along with the established correlation between lime nodule size and lime quality, present new opportunities for conducting and monitoring long-term trials in lime mud kilns.

RECOMMENDATIONS

Continued investigations into the impact of operational conditions on lime quality in lime kilns is recommended. The online measurement of lime particle size distribution can serve as a valuable tool in this regard.

A soft sensor for the lime composition

The measurement of lime particle size distribution could function as a soft sensor for lime composition. Non-process elements like sodium, potassium, and chlorine may influence lime calcining chemistry. The observed correlation between purging of fresh lime and dusting in the kiln can be automatically tracked through particle size measurement. These effects could potentially be detected using the demonstrated nodule-size measurement system. For instance, during a period of high purging characterized by high dusting and small nodules, it took approximately one month for the system 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 correlated with nodule size in this study. Understanding heat transfer from flame to lime bed, influenced by fuel properties and operational conditions, is crucial for optimal nodule sizes and minimal dusting. Online particle size measurement can facilitate this analysis.

Evaluation tool for the firing of sulfuric fuels in lime kilns

Combustion of high-sulfur fuels like crude methanol affected nodule size, lime temperature, and specific energy demands in the kiln. Could sulfur have disrupted the sodium chemistry crucial for nodule formation? Here, online measurement of nodule size could prove invaluable, complementing chemical analyses of lime samples in further investigations involving high-sulfur fuels like crude methanol and kraft lignin. **TJ**

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ABOUT THE AUTHORS

This research topic was chosen due to the vital role efficient recausticizing plays in pulp mill performance. Previous studies highlighted nodule size as crucial, yet its online measurement remained a challenge. Our aim was to address this gap, enabling real-time monitoring to enhance recausticizing efficiency and overall mill performance. The research builds upon previous work by further elucidating the relationship between operational parameters and particle size distribution (PSD) in lime kilns.

The most challenging aspect of this research revolved around conducting experimental measurements within the factory environment. These measurements were inherently complex and time consuming due to the intricacies of industrial processes and the need for precision in data collection. To address this challenge, a collaborative team effort was essential.

Through this study, we discovered the limited influence of flue gas temperature on PSD. The most interesting and surprising finding was the stability of the online measurement tool.

For mills, the successful use of online measurement tools for PSD opens up the possibility of long-term monitoring in lime kilns. Our next step is to develop a soft sensor for the lime composition.

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Lingman

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LITERATURE CITED

1. Dernegård, H., "Dusting in a lime kiln," Lic.Eng. thesis, Chalmers University of Technology, Gothenburg, Sweden, 2019.
2. Dernegård, H., Brelid, H., and Theliander, H., *Nord. Pulp Pap. Res. J.* 32(1): 25(2017). https://doi.org/10.3183/npprj-2017-32-01-p025-034.
3. Tran, H., Vollicks, S., Gauthier, M., et al., *TAPPI J.* 6(4): 9(2007). https://doi.org/10.32964/TJ6.4.9.
4. Fardadi, M., "Modeling dust formation in lime kilns," Ph.D. thesis, University of Toronto, Toronto, 2010.
5. Richards, T. and Joseph, J., *Lime Kiln Dusting*, Report 2019:628, Energiforsk, Stockholm, 2019.
6. Järvensivu, M., Saari, K., and Jämsä-Jounela, S.-L., *Control Eng. Pract.* 9(6): 589(2001). https://doi.org/10.1016/S0967-0661(01)00017-X.
7. Villarroel, R. and Tran, H., "Operating experience of the world's largest lime kiln," *7th Int. Colloq. Eucalyptus Pulp*, International Colloquium on Eucalyptus Pulp, São Paulo, 2015.
8. Thurley, M.J., Degerfeldt, D., Nystrom, J., et al., "Automated, online measurement of bulk material size distribution on conveyor using 3D profile imaging at Boliden Mines," *14th AusIMM Mill Operators' Conf., Proc.*, Australasian Institute of Mining and Metallurgy (AusIMM), Melbourne, 2018, pp 641-652.
9. Rosato, A., Strandburg, K.J., Prinz, F., et al., *Phy. Rev. Lett.* 58: 1038(1987). https://doi.org/10.1103/PhysRevLett.58.1038.
10. Nordenskjöld, R., Lindqvist, L., Lingman, P., et al., "Method and arrangement for determining an estimated bulk particle size distribution," WIPO pat. WO2022010399A1 (Jan. 13, 2022).
11. Berg, E. and Eriksson, T., "Optimization of control of rotary kiln," WIPO pat. WO2019209156A1 (Oct. 31, 2019).
12. Francey, S. and Tran, H., *J-FOR* 2(3): 32(2012).