

Computer modeling as tools to estimate the impact of fuel type on the capacity rating of lime kilns

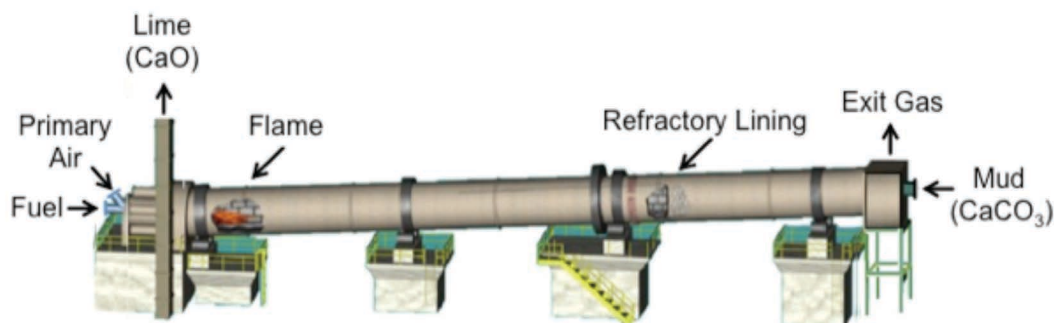
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ABSTRACT: In response to the drop in the price of natural gas, the U.S. pulp and paper industry has switched from using fuel oil to natural gas to fire kilns used to regenerate lime in the kraft process. While being financially attractive, replacing fuel oil with natural gas can be challenging. This is particularly true when the capacity rating is constrained by the temperatures of the gas exiting the kiln. In the worst case scenario, the increase in flue gas temperatures associated with switching from fuel oil to natural gas can significantly de-rate the capacity of the kiln. This paper describes a range of computational modeling tools that can be used to estimate the impacts of kiln geometry, fuel type, operating conditions, and burner design on kiln performance. Data taken from operating kilns is presented, which validates the use of these models. A detailed case study is presented showing how small amounts of torrefied wood can be co-fired with natural gas as a replacement for fuel oil without de-rating the capacity of the kiln. The visualization of the flow fields, temperature distributions, and species concentrations provided by computer models are critical to optimizing kiln operations as new fuels are being considered as replacements for more expensive, carbon intensive fuel oil.

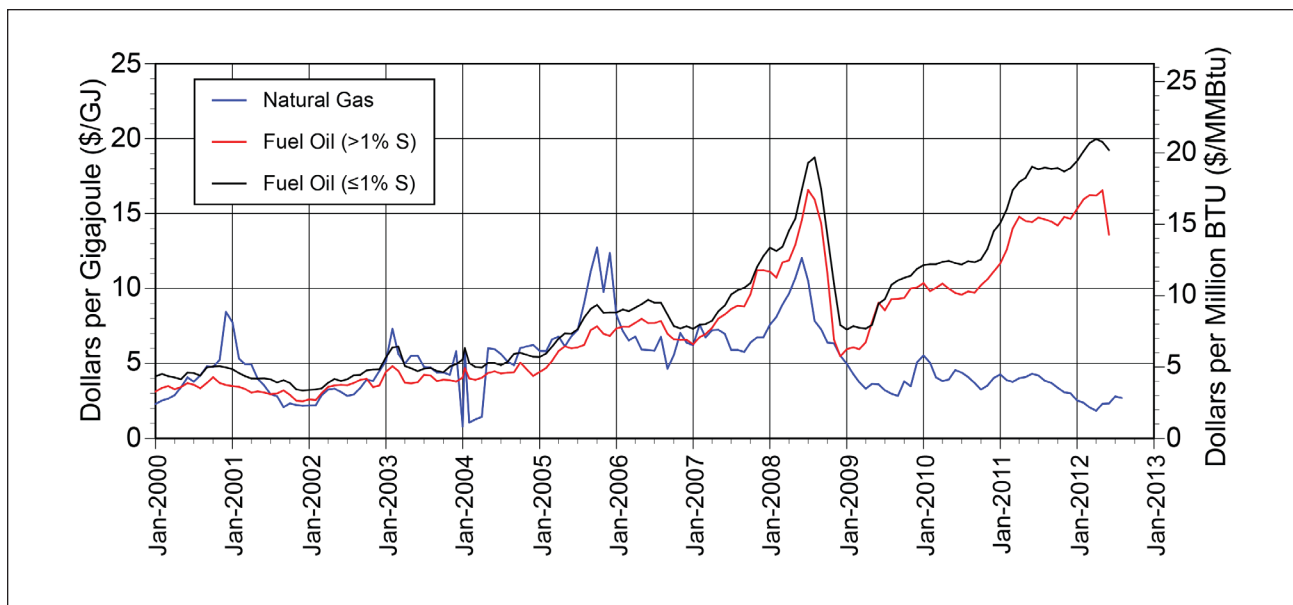
Application: The computational modeling tools described in this paper can be used by mills to explore the impact of fuel type on kiln performance. These tools can also be used to improve burner designs, to optimize the layout of chain systems and refractory linings, and for other modifications to the kiln and/or to evaluate changes in operating practices.

A rotary kiln is used to convert lime mud (mostly calcium carbonate) back into lime, for reuse in the kraft process. The kiln plays a key role in the pulp mill. It must be able to re-burn all of the mud generated by the process and produce lime to make white liquor at an acceptable quality to keep the mill running at full capacity. **Figure 1** shows a sketch of a rotary kiln [1]. Small cutaway sections reveal the flame and refractory lining. The kiln is essentially a long rotating refractory lined cylinder. Lime mud from a

filter is fed into the upper or feed-end of the kiln. The mud travels down the length of the kiln, where it is exposed to hot gases traveling in the opposite direction generated by a burner located at the lower or discharge end. As the mud travels along the kiln, it is first dried to a fine powder. The material is then heated to around 871°C (1600°F). At these temperatures, the calcination reaction drives off carbon dioxide (CO₂) from the mud, converting the calcium carbonate back to lime for reuse in the process.



1. Schematic of a rotary kiln used to re-burn calcium carbonate (CaCO₃) to produce lime (CaO) in a kraft pulp mill, with cutaway sections showing the flame and refractory brick lining.



2. Historical U.S. prices for fuel oil and natural gas used to fire kilns in kraft pulp mills.

Historically, fuel oil and natural gas have been the main fuels used to fire kilns in the U.S. **Figure 2** shows the prices of these fuels [2,3]. Beginning around 2008, due to the dramatic decline in the price for natural gas, the industry has concentrated on converting kilns firing fuel oil to natural gas. While the use of natural gas does meet the goals set by the industry to lower its cost of manufacturing and greenhouse emissions [4], its substitution in kilns that were originally designed and fired with oil can create challenges for mills. Because of differences in their combustion properties, fuel oil and natural gas are not always directly interchangeable. The increase in the volume and temperature of the flue gas exiting the kiln when switching from oil to natural gas can lower the capacity rating of the kiln.

This paper demonstrates how computational modeling tools can be used to estimate the impact of fuel type on the capacity rating of kilns. A number of case studies are presented. Despite the low price of natural gas, a case study is given showing how torrefied wood, a renewable fuel, can be used to enhance the performance of natural gas.

CAPACITY RATINGS FOR LIME KILNS

A detailed knowledge of the constraints that limit production is required to fully understand how changing fuels impacts the capacity rating of a kiln. In practice, the nominal capacity for the kiln is set to match the theoretical amount of lime required to produce white liquor for the mill. Once the capacity rating has been chosen, the kiln volume and size can be specified. The peripheral equipment is then selected to match the capacity rating. To minimize cost, the sizing of the peripheral equipment is chosen to closely match the capacity rating. For this reason, it is not surprising to see kilns in the field limited to a production rate only slightly above the nominal capacity rating.

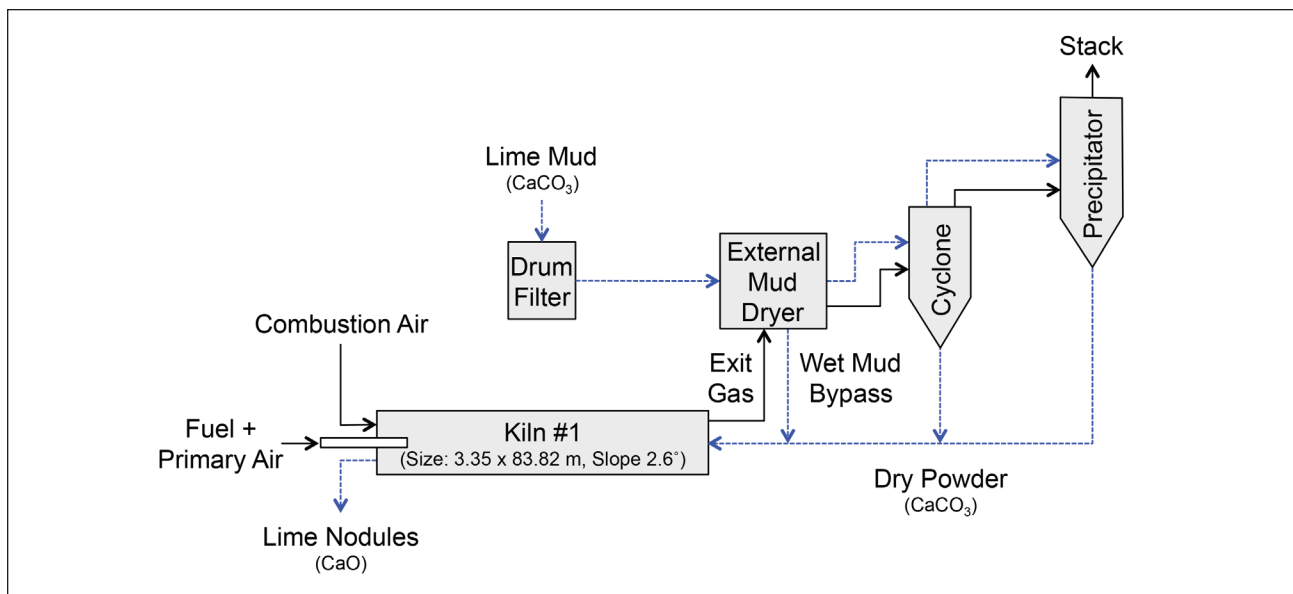
The constraints on the capacity rating of kilns are:

1. Mud flow into the kiln — mud filter, conveyors, and feed screw(s)
2. Product flow out of the kiln — lump crusher, drag conveyors, and bucket elevator
3. Gas flow out of the kiln — induced draft (ID) fan, electrostatic precipitator (ESP)
4. Fuel flow into the kiln — fuel valve train and burner
5. Air flow into the kiln — primary air fan(s), firing hood, and coolers
6. Materials temperature limits — metal shell, refractory lining, chains, ID fan, and inlet to precipitator or external mud drier
7. Emissions — dust loss, NO_x and TRS
8. Structural design — kiln shell, trunnions, tires and foundations
9. Operational problems — dust, ring formation, high residual carbonate, etc.

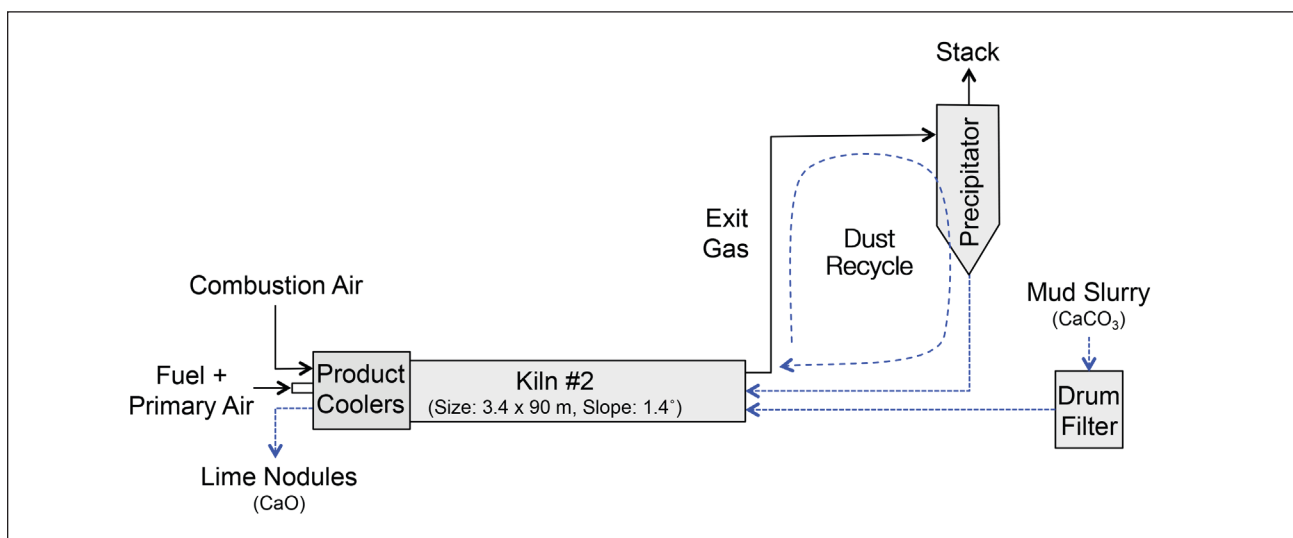
By removing one or more of the above constraints, the capacity ratings for kilns can be increased well above their original values. In all cases, the potential for increasing capacity can only be realized by carefully examining and removing the constraints on production. Ultimately, in many cases, it is the temperature and volume of the flue gas that sets the maximum capacity rating of a kiln.

KILNS SELECTED FOR THE PROJECT

In this study, two kilns, at different mills, referred to as Kiln #1 and Kiln #2, were selected to illustrate how the type of fuel used to fire the kiln impacts its capacity rating. **Fig. 3** shows a schematic of the equipment layout for Kiln #1. This kiln is equipped with an external lime mud dryer. In this design, wet mud is fed into the dryer. The dry mud is then



3. Schematic showing layout of equipment used for Kiln #1.



4. Schematic showing layout of equipment used for Kiln #2.

fed into the kiln. Based on operating experience, if the flue gas heats the mud particles in the dryer above 732°C (1350°F), they become sticky and form deposits on the walls of the dryer. When this happens, in a short period of time, the deposits can grow thick enough to plug the dryer, forcing an unscheduled outage for cleaning. In this work, it is the temperatures of flue gas entering the dryer that set the maximum capacity rating for Kiln #1.

Figure 4 shows a schematic of the equipment layout for Kiln #2. This kiln is equipped with an ESP. Kiln #2 is currently being fired with fuel oil. The exit gas temperatures are around 400°C (752°F). At these temperatures, the mill reports seeing damage to the entrance of the precipitator indicating that it is being overheated. Moving forward, the mill is planning to switch from firing fuel oil to natural gas. The higher gas

temperatures entering the precipitator resulting from converting from fuel oil to natural gas may intensify the damage to the equipment and dramatically shorten its service life. In this work, again, it is assumed that the exit gas temperatures determine the maximum capacity rating for Kiln #2. In both kilns, for all operating conditions, the exit gas temperature must be kept at or below their current levels for all operating conditions.

FUELS SELECTED FOR THE PROJECT

A number of fuels were considered in this study. **Table I** gives the ultimate analysis and higher heating value for each fuel. The higher heating values were estimated using a modified DuLong type formula [5]. This data is to be viewed as being “typical values.” The composition and heating values must be determined on a case-by-case basis.

Fuel Type	Ultimate Analysis, wt% dry basis						HHV, MJ/kg
	C	H	O	N	S	Ash	
Heavy fuel oil	86.50	10.40	0.58	0.37	2.10	0.05	42.57
Natural gas	72.00	23.60		4.40			52.84
Methanol	37.50	12.60	49.90				22.76
Pyrolysis oil	56.00	5.80	37.90	0.10		0.20	22.44
Wood	48.00	6.50	45.20	0.10		0.20	19.72
Bark	52.00	5.51	36.21	0.56	0.04	5.68	20.76
Lightly torrefied wood	59.84	5.44	33.41	0.22	0.01	1.08	23.80
Highly torrefied wood	71.30	3.40	19.33	0.23	0.34	5.40	26.80
Torrefied hydrolysis residuals	53.30	3.46	14.36	4.03	0.31	24.54	20.64
Crude tall oil	77.90	11.20	10.60	0.10	0.20		39.29
Kraft lignin	64.30	5.82	25.23	0.90	1.57	2.18	26.78
Turpentine	83.00	12.20		1.60	3.20		43.62
Tall oil pitch	81.90	11.40	6.00	0.10	0.30	0.30	41.40

I. Typical values for ultimate analysis and higher heating values of kiln fuels (C = carbon, H = hydrogen, O = oxygen, N = nitrogen, S = sulfur, HHV = higher heating value).

Ranking	Fuel	Moisture, wt% wet basis	AFR	RNHVCP, MJ/kg
1	Fuel Oil		13.4	2.34
2	Highly torrefied wood	3.1	8.6	2.32
3	Tall oil pitch		13	2.30
4	Turpentine		13.8	2.30
5	Kraft lignin	2.6	8.3	2.29
6	Crude tall oil	1.1	12.3	2.29
7	Lightly torrefied wood	3.2	7.3	2.28
8	Natural gas		16.2	2.21
9	Torrefied hydrolysis residuals	5	6.6	2.20
10	Bark	5	6.3	2.20
11	Wood	5	5.8	2.18
12	Pyrolysis oil	25	6.8	2.12
13	Methanol	15	6.5	2.01

II. Ranking of fuels based on Reduced Net Heating Value per unit mass of Combustion Products (RNVHCP). (AFR = stoichiometric air-to-fuel ratio.)

Torrefied wood and hydrolysis residuals were selected for use in this work. Torrefaction is a thermal pretreatment that involves heating biomass in the absence of oxygen. The process drives off the moisture and some of the volatile components of the wood. It also degrades the fibrous structure of the wood, making it easier to grind. The final torrefied product retains approximately 70% of the initial dry weight and 80% to 90% of the energy content of the original wood. The hydrolysis residuals used in this study were generated as by-products from the enzymatic treatment of corn stover used to produce ethanol. These residuals contain primarily lignin with some unreacted cellulose and ash. In a similar manner to wood, torrefying the residuals degrades the remaining cellulose, making them easier to grind.

IMPACT OF FUEL TYPE ON KILN CAPACITY

In this work, the impact of fuel type on kiln capacity was examined using these computational tools:

1. Adiabatic flame temperatures (Reduced Net Heating Value of Combustion Products)
2. One-dimensional (1-D) plug flow model
3. Three-dimensional (3-D) computational fluid dynamics (CFD) model

The adiabatic flame temperature is related to the energy content of the fuel divided by the thermal capacity of the combustion products. As such, it is a measure of the potential of a fuel to reach high temperatures. By treating the kiln as a simple heat exchanger, in most cases, increasing the flame tempera-

Operating Variable	Case #1	Case #2
Fuel type	Fuel Oil	Natural Gas
Feed temperature	82°C	82°C
Mud solids (off-filter)	69.4%	70.5%
Effect mud solids (to kiln)	87%	87%
Dust loss	Nil	Nil
Kiln speed	1.25 rpm	1.25 rpm
Production rate	276 metric tons/day	236 metric tons/day
Lime availability	86.5%	85.5%
Residual carbonate	1.7%	1.8%
Flame length (visual observation)	16.8 m	18.8 m
O ₂ exit gas, % wet basis	1.7%	1.7%

III. Operating conditions for Kiln #1 firing natural gas and fuel oil.

ture will increase both its efficiency and capacity [6]. The adiabatic flame temperature represents the simplest way to compare fuels. Fuels with higher adiabatic flame temperatures make better kiln fuels.

While the adiabatic flame temperature can be used to rank a fuel relative to others, it cannot be used to directly calculate the capacity rating of a kiln for a given fuel. For this, more detailed models are required. As a next step, a 1-D flow model [7] is used to predict the temperature profiles, the compositions of the gas and solids along the length of the kiln, and the capacity rating for the kiln. In this approach, the velocities of the gas and solids are assumed to be constant across any cross-section of the kiln and are perfectly mixed in the radial direction. Also, it is assumed that the heat transfer to the solids, not the kinetics, controls the overall rate of these reactions. A detailed description of heat transfer may be found in a number of papers [8-13]. The total execution times for this model are short, making it very easy to evaluate a wide range of operating conditions.

A 3-D CFD model is required to fully describe the combustion and heat transfer for a given fuel and burner design. The CFD model selected for use in this work has been extensively tested in a wide range of industrial applications [14,15]. In this model, the flow field is assumed to be a steady state, turbulent, reacting continuum field that can be described locally by general conservation equations. The governing equations for gas-phase fluid mechanics, heat transfer, thermal radiation, and scalar transport are solved in an Eulerian framework. The governing equations for particle-phase mechanics are solved in a Lagrangian reference frame. The overall solution scheme is based on a particle-source-in-cell technique.

The methodology used in this work to evaluate the impact of switching fuels on the capacity rating of a kiln starts by calculating the adiabatic flame temperature for each fuel. This provides insights into how the new fuel(s) compare to those currently being used. Next, the capacity ratings are calculated for each fuel using a 1-D plug flow model. If needed, a 3-D CFD

model is used to fully optimize the burner design and kiln operations to maximize the capacity rating for the fuel(s) selected by the mill for implementation in the kiln.

Adiabatic flame temperature

A general expression for Reduced Net Heating Reduced Net Heating Value per unit mass of Combustion Products (RNHVCP) that includes the influence of fuel moisture, excess air, and air preheat is given in Eq. (1). A complete derivation may be found elsewhere [16]. Two fuels with equal RNHVCP will have equal adiabatic flame temperatures and equal velocities at the same firing rate in any particular kiln.

$$\text{RNHVCP} = \frac{\{\text{HHV} \cdot 2.44(9\text{H} + \text{M})\} + \{1.13 \times 10^{-3} \text{AFR}(1 + \text{E}/100)(T_{\text{air}} - T_0)\}}{\{1 + \text{M} + \text{AFR}(1 + \text{E}/100)\} \{1 + y_{\text{H}_2\text{O}} + 0.03 y_{\text{CO}_2}\}} \quad (1)$$

where:

HHV	=	higher heating value of the fuel, MJ/kg
H	=	mass fraction of hydrogen in the fuel, dry basis
C	=	mass fraction of carbon in the fuel, dry basis
m	=	water in the fuel, % wet basis
M	=	m/(100-m) mass fraction water in the fuel, dry basis
E	=	percent stoichiometric air, excess air
$y_{\text{H}_2\text{O}}$	=	$(9\text{H} + \text{M}) / \{1 + \text{M} + \text{AFR}(1 + \text{E}/100)\}$
$y_{\text{C}_2\text{O}}$	=	$(44\text{C}/12) / \{1 + \text{M} + \text{AFR}(1 + \text{E}/100)\}$
T_{air}	=	temperature of the combustion air entering kiln, °C
AFR	=	stoichiometric air to fuel ratio

For Kiln #1, the level of excess air and the temperature of the combustion air were held constant at 13%, e.g., E=113%, of the stoichiometric air requirement, and 32°C (90°F), respectively. The stoichiometric air-to-fuel ratio (AFR) and the cor-

LIME KILN

responding value for RNHVCP for each fuel under consideration are given in **Table II**. Compared to the other fuels, fuel oil has the highest RNHVCP. For the most part, the RNHVCPs for the other fuels fall between the values for fuel oil and natural gas. Methanol and pyrolysis oil are the major exceptions. The high moisture contents significantly reduce the RNHVCP for both of these fuels. The high ash content of the torrefied hydrolysis residuals significantly reduces the RNHVCP. Both torrefied wood and kraft lignin look promising as replacements for fuel oil.

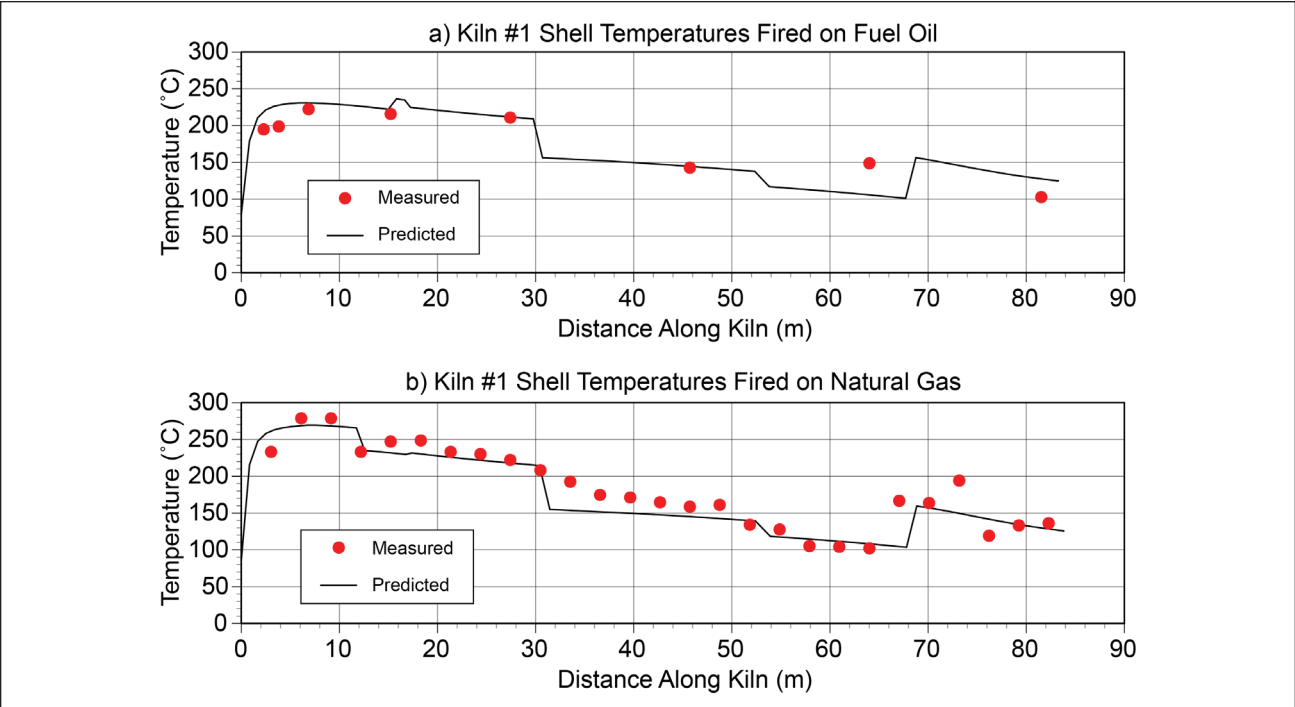
1-D flow model

Data collected from Kiln #1 firing both fuel oil and natural gas are summarized in **Table III**. **Figures 5a** and **5b** compare

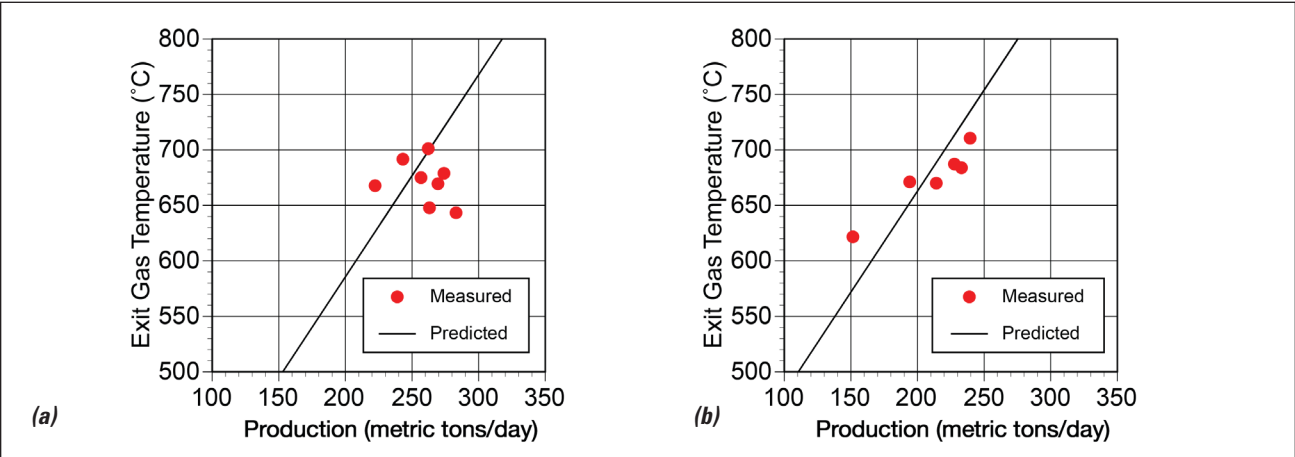
shell temperatures predicted by the 1-D model to the measured values for both fuel oil and natural gas, respectively.

Figure 6 compares the predicted exit gas temperatures and measured values for both fuel and natural gas as a function of production rate. **Table IV** compares the measurements and model predictions for fuel oil and natural gas.

Figure 7 shows the production curves predicted by the 1-D model for Kiln #1 firing both fuel oil and natural gas. As previously stated, to avoid overheating the solids in the dryer, the exit gas temperatures must be maintained at or below 732°C (1350°F). The model predictions show that switching from fuel oil to natural gas drops the capacity rating of the kiln from 279 metric tons/day (307 tons/day) to 239 metric tons/day (263 tons/day), which is a 15% decrease in the capacity



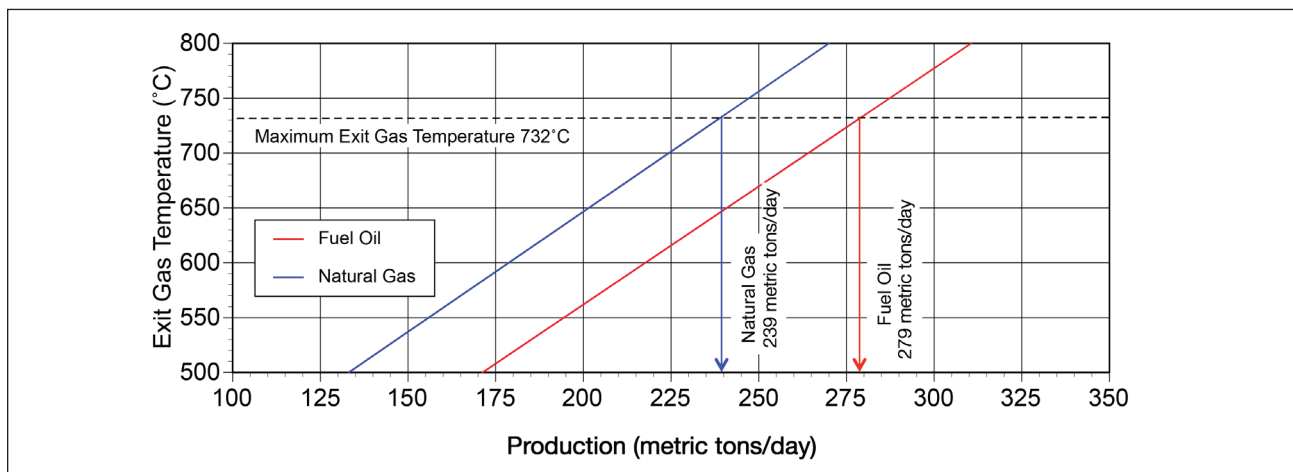
5. Measured and predicted shell temperatures for Kiln #1 fired on a) fuel oil, and b) natural gas.



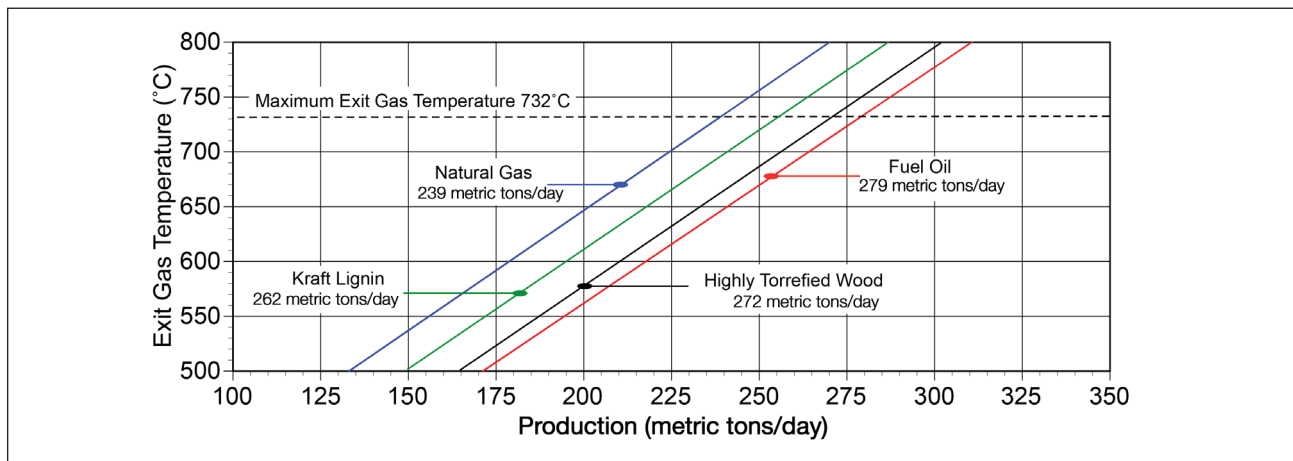
6. Production curves for Kiln #1 fired with a) fuel oil, and b) natural gas.

Operating Variable	Case #1		Case #2	
	Measured	Predicted	Measured	Predicted
Fuel type	Fuel Oil	Fuel Oil	Natural Gas	Natural gas
Production, metric tons/day	276	276	236	236
Exit gas temperature, °C	674	704	681	713
Fuel flow, l/min	40.1	38.2	38.8	34.8

IV. Comparison of measured and predicted operating variables for Kiln #1 using the 1-D model.



7. Exit gas temperatures for Kiln #1 firing natural gas and fuel oil as a function of production.



8. Production curves for Kiln #1 comparing fuel oil, highly torrefied wood, kraft lignin, and natural gas.

rating. Based on these calculations, at up to 239 metric tons/day, Kiln #1 can be fired with 100% natural gas. Above this production rate, fuel oil must be co-fired with natural gas to keep the exit gas temperatures below 732°C (1350°F).

The lime reports they are not able to produce much more than 236 metric tons/day (260 tons/day) when firing 100% natural gas. Fortunately, since making the conversion from fuel oil to natural gas, they have reduced white liquor consumption and are able to meet their current requirements for lime without co-firing fuel oil. Overall, the 1-D model does a good job predicting the performance of Kiln #1.

To further examine the impact of fuel type on the capacity rating of Kiln #1, a set of simulations were performed using the 1-D model, varying only the production rate for the fuels listed in Table I. For each fuel, the maximum capacity rating was set at the production rate at which the exit gas temperature equals 732°C (1350°F). **Figure 8** compares the production curves for fuel oil, highly torrefied wood, kraft lignin, and natural gas. Based on this approach, the capacity ratings for fuel oil, highly torrefied wood, kraft lignin, and natural gas are 279, 272, 265 and 239 metric tons/day (308, 300, 292 and 263 tons/day), respectively. The capacity ratings for all of the

Ranking	Fuel	RNHVCP, MJ/kg	Heat Rate, GJ/metric ton	Capacity, metric tons/day
1	Fuel oil	2.34	8.38	279
2	Highly torrefied wood	2.32	8.51	272
3	Tall oil pitch	2.3	8.6	265
4	Turpentine	2.3	8.67	263
5	Kraft lignin	2.29	8.71	262
6	Crude tall oil	2.29	8.74	260
7	Lightly torrefied wood	2.28	8.77	259
8	Natural gas	2.21	9.22	239
9	Torrefied lignin residuals	2.2	9.3	238
10	Bark	2.2	9.33	237
11	Wood	2.18	9.4	235
12	Pyrolysis oil	2.12	9.85	219
13	Methanol	2.0	10.46	208

V. Impact of fuel type on capacity ratings and heat consumption.

fuels are given in **Table V**. There is very good agreement between the ranking of these fuels based on the RNHVCP and the model predictions. As expected, the capacity rating and energy efficiency improve with RNHVCP. Based on this analysis, highly torrefied wood and kraft lignin both appear to be very good choices as replacements for fuel oil. The decreases in the capacity ratings for these fuels compared to fuel oil are less than 5%.

3-D computational fluid dynamics model

A comprehensive CFD model was used to analyze the impacts of the burner design and fuel type on the capacity rating for Kiln #2. With this in mind, a series of simulations were set up with the goal of replacing fuel oil with natural gas and/or torrefied wood. The decision to use torrefied wood was based on the following factors.

1. The results from the modeling work on Kiln #1 suggest that natural gas alone may not be able to replace 100% of the fuel oil currently being fired without decreasing the capacity rating of Kiln #2.
2. Both the RNHVCP and the results of the 1-D modeling of Kiln #1 suggest that torrefied wood is a good replacement for fuel oil.
3. Torrefied wood is currently being commercially produced in the U.S.
4. While the price for torrefied wood will be higher than natural gas, it is much lower than the current price of fuel oil.
5. While the level of ash in torrefied wood will increase the lime mud purge required to prevent the buildup of nonprocess elements, it does not contain the high levels of sulfur and alkali associated with pet coke and kraft lignin. On this basis, it is expected to be more compatible with the process.

A new multi-fuel burner capable of firing fuel oil, natural gas and torrefied wood was designed specifically for Kiln #2. This burner includes an atomizer for fuel oil, openings for radial and axial natural gas, and openings for radial and axial primary air. The layout and exact dimensions for the burner are not included in this paper.

Data collected from Kiln #2 for the current operating conditions firing fuel oil at a production rate of 367 metric tons/day (404 tons/day), Case #3, are summarized in **Table VI**. A list of the cases run using the CFD model is given in **Table VII**. Only the production rate, fuel type, and burner were changed in these simulations. All of the remaining operating variables were maintained at their current values.

Figure 9 shows the predicted peak gas, average gas, and solids temperature profiles, together with the temperature distribution of the gas along the centerline of the kiln for the current operating conditions, for Case #3. The predicted and measured shell temperatures are plotted in **Fig. 10**. The predicted shell temperatures from 50 to 70 m (164 to 230 ft) are higher than the measured values. The coating on the inner wall of the refractory lining was not taken into account in the model. Kiln #2 typically runs with a thick buildup or ring in this area. The error introduced by not including the insulating effect of this ring is negligible. The measured and predicted values for the oil flow rate and the average exit gas temperatures for Case #3 are given in **Table VIII**. Overall, the CFD

	Measured	Predicted
Oil flow, l/min	43.4	43.5
Average exit gas temperature, °C	395	419

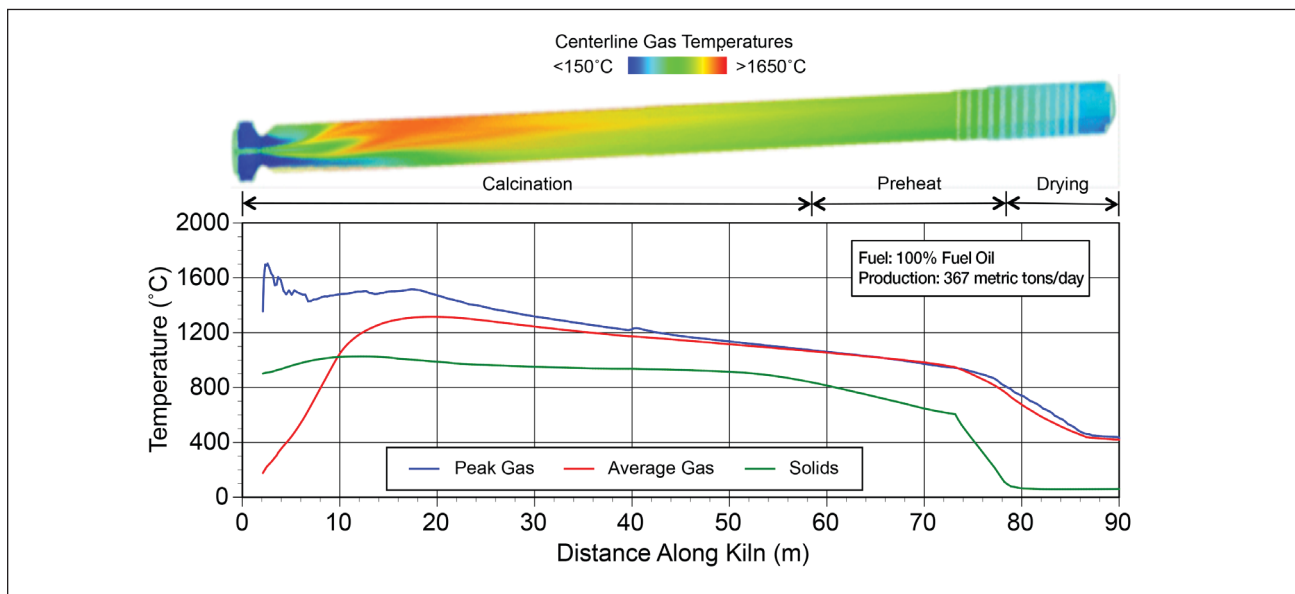
VIII. Comparison of measurements and CFD model predictions for Kiln #2 operating at 367 metric tons/day, Case #3, the current operating conditions.

Operating Variable	Value	Operating Variable	Value
Feed temperature, °C	60	Production, metric tons/day	367
Mud solids, % off-filter	69.4	Availability, %	86.5
Effect mud solids, % to kiln	87	Residual carbonate, %	1.7
Dust loss, %	nil	O ₂ in exit gas, % wet basis	1.79

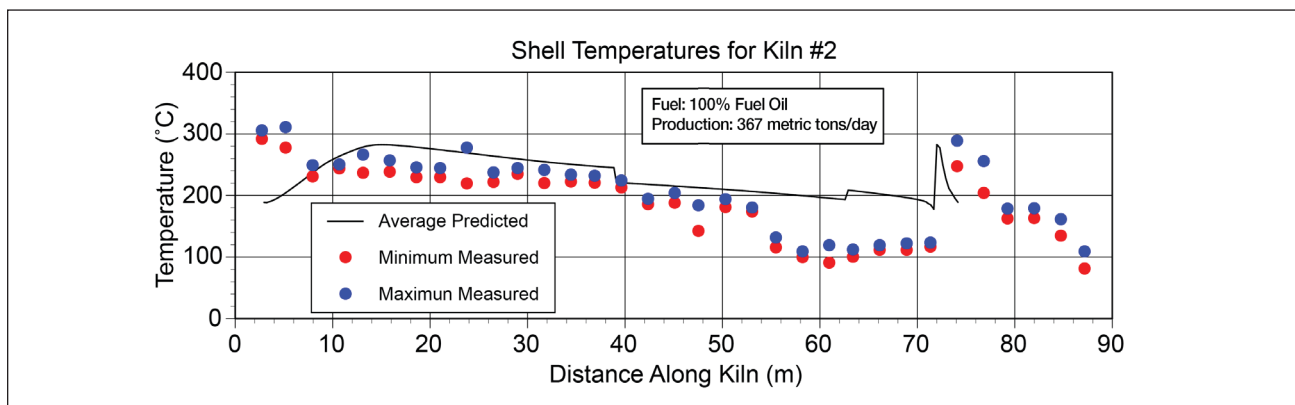
VI. Current operating conditions for Kiln #2, Case #3.

Case	Fuel	Burner	Production, metric tons/day	Comments
#3	100% fuel oil	Existing	367	Current operating conditions
#4	100% fuel oil	Multi-fuel	367	Current operating conditions
#5	100% fuel oil	Multi-fuel	386	Maximum production firing fuel oil
#6	100% natural gas	Multi-fuel	340	Maximum production firing natural gas
#7	Natural gas + Torrefied wood	Multi-fuel	367	100% replacement of fuel oil

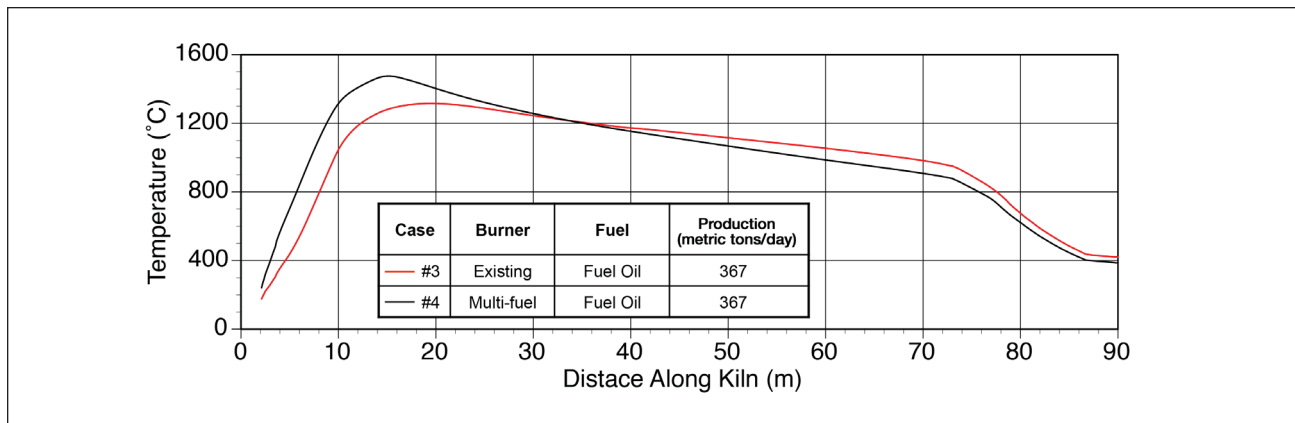
VII. Summary of cases run using the CFD model.



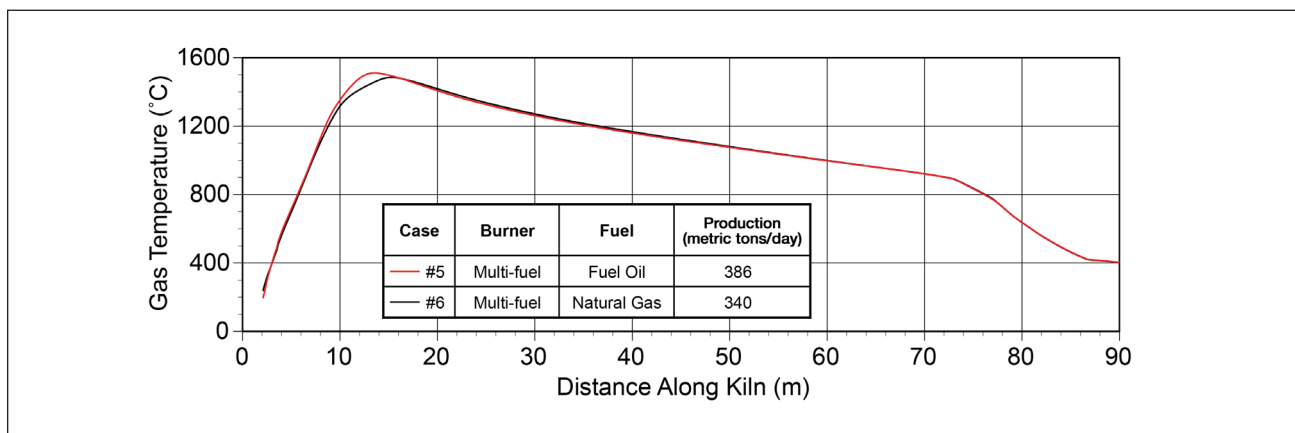
9. Predicted gas and solids temperature profiles for Case #3, the current operating conditions, for Kiln #2.



10. Predicted and measured shell temperatures for Case #3, the current operating conditions, for Kiln #2.



11. Average gas temperature profiles for the existing and new multi-fuel burners firing fuel oil at a production rate of 367 metric tons/day, Case #3 and Case #4.



12. Average gas temperature profiles for the maximum production rates for the multi-fuel burner firing fuel oil and natural gas, Case #5 and Case #6.

model does a good job predicting both the temperatures and firing rate for Kiln #2.

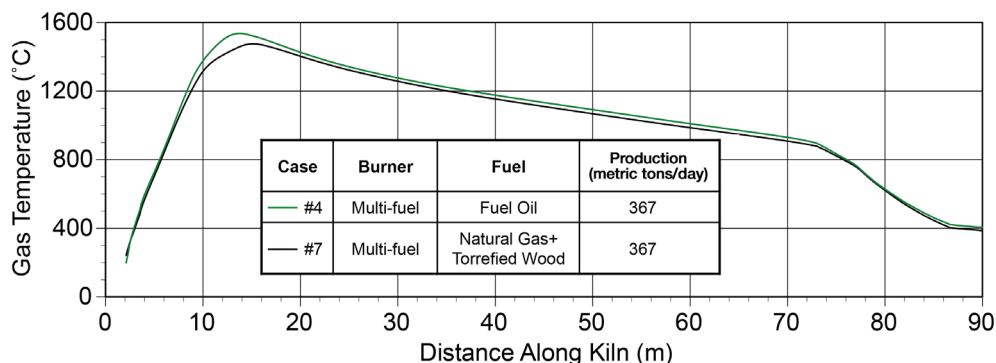
Figure 11 compares the gas temperature profiles for the existing and the new multi-fuel burner, Cases #3 and #4. The smaller oil droplets generated by the atomizer by the multi-fuel oil burner reduce the time required to evaporate and burn the oil. As a result, the multi-fuel burner increases the peak gas temperature when firing oil from 1316°C to 1475°C (2401°F to 2687°F). Due to the increase in gas temperatures in the front of the kiln, more energy is transferred to the solids in the calcination zone, with less energy being lost with the gas leaving the kiln. At the current production rate of 367 metric tons/day, when firing oil, replacing the existing burner with the new multi-fuel burner reduces the temperature of the exit gas from 419°C to 387°C (786°F to 729°F). The drop in exit gas temperature allows for an increase in production. The CFD model predictions indicate the maximum capacity rating for the new multi-fuel burner, Case #5, is 386 metric tons/day (425 tons/day). This is a 5% increase in production.

Figure 12 plots the gas temperature profiles at the maximum production rates for fuel oil and natural gas for the new

burner, Case #5 and Case #6. The CFD modeling suggests that switching from fuel oil to natural gas will reduce the capacity rating from 386 metric tons/day (425 tons/day) to 340 metric tons/day (375 tons/day), which is a 12% drop in production. Recognizing this situation, instead of co-firing fuel oil with natural gas, to increase the capacity rating of Kiln #2, a series of simulations were performed in which torrefied wood was co-fired with the natural gas. **Figure 13** compares the predicted gas temperatures for co-firing 23% torrefied wood and 77% natural gas, Case #7, to those for the new burner firing fuel oil at the same production, Case #4.

RESULTS AND DISCUSSION

This paper describes a number of modeling tools that can be used to determine how the type of fuel used to fire a kiln impacts its capacity rating. For the purpose of illustration, it was assumed that the capacity ratings of the kilns in this study are constrained by the exit gas temperatures. This means, without modifying the equipment, when switching fuels the exit gas temperatures must be maintained at or below their current levels so as to not further constrain or reduce the capacity rating of the kiln. Working against this constraint, it was shown



13. Average gas temperature profiles for multi-fuel burner firing fuel oil and co-firing torrefied wood natural gas, Case #4 and Case #7.

that switching from firing 100% fuel oil to 100% natural gas can decrease the capacity rating by as much as 15%. In the case of Kiln #1, the mill was able to significantly reduce its requirement for lime. As a result, they were able to replace all of the fuel oil with natural gas and still meet their production requirements for lime. In the case of Kiln #2, unless the mill is able to reduce the requirement for lime, less than 50% of the fuel oil can be replaced with natural gas. Based on the results of the modeling, it was determined that 100% of the fuel oil could be replaced by co-firing small amounts of torrefied wood with the natural gas. The use of torrefied wood offsets the increases in the volume and temperature of the exit gas associated with the switch from fuel oil to natural gas.

CONCLUSIONS

This work demonstrates the value of computer modeling as a means to provide input in making decisions around switching fuels and their impact on the capacity rating of kilns used to regenerate lime in the kraft process. The methodology developed in this work uses a series of modeling tools that range from being relatively simple to quite complex. The time and effort involved in applying these tools can be tailored to match the specific needs of a project. The tools used in this work are:

- A relatively straightforward approach based on Reduced Net Heating Value per unit mass of Combustion Products (RHHVCP) can be used to provide qualitative comparisons of fuels. The model can be prepared relatively quickly in that it requires a minimum amount of data. The calculations are nearly instantaneous on simple computing platforms.
- A slightly more complex approach based on a 1-D flow model can be used to provide estimates of fuel mass flow rates, axial gas, solids, and shell temperature profiles, and the capacity rating for a given kiln geometry and set of operating conditions. Calculations can be performed in minutes using an inexpensive desktop computer, allowing for a wide range of operating conditions to be studied.
- The most sophisticated approach based on a detailed

CFD model can be used to examine a variety of multi-phase physical and chemical phenomena, including details involving the location and shape of the flame, local heat transfer, and temperatures. The detailed results from these simulations using this model can also be helpful in providing insight associated with graphical depictions of properties and flow fields inside the kiln. This model requires considerable preparation time involving the collection of operating data and preparation of a computational mesh. It may take several days to complete a single simulation on a high-end desktop computer.

Comparisons between the data collected from the kilns in this study over a broad range of operating conditions and the model predictions validate the use of these tools. In particular, the 1-D and CFD models do a very good job predicting the mass flow rates of fuel oil and natural gas, along with the axial gas, solids, and shell temperature profiles. These are the key variables that must be considered when examining the impact of fuels on the capacity rating of a kiln.

In addition to providing detailed descriptions of the modeling tools, the paper demonstrates the value of modeling to help in making decisions around replacing fuel oil with natural gas and other fuels. More specifically, the results of the simulations show, for Kiln #2, where the capacity rating is constrained by exit gas temperatures; 100% of the fuel oil currently used to fire the kiln can be replaced by co-firing small amounts torrefied wood and natural gas without increasing the temperature or volumetric flow rate of the exit gas, thereby allowing the capacity rating to be maintained at its current level. It is interesting to note that even in presence of cheap and abundant natural gas, this work builds a strong case for the use of biomass as a replacement for fuel oil. The risks associated with making this change appear manageable. The obvious next step is to conduct a full-scale trial on an operating kiln, a step for which this project provides a ready foundation.

Finally, it must be noted that while this paper is specifi-

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cally focused on the use of modeling tools to quantify how the fuel used to fire a kiln impacts its capacity rating, the same tools can be used to address other needs. The enhanced understanding of the aerodynamics and its impact on combustion and flame shape, the axial gas, solids, and shell temperature profiles, and the compositions of the gas and solids along the length of the kiln provided by the tools described in this paper can be tailored to assist in optimizing operating conditions, as well as kiln modifications such as the design of chain systems and layout of the refractory lining. **TJ**

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ABOUT THE AUTHORS

We chose this topic for research because the pulp and paper industry has switched from using fuel oil to natural gas to fire lime kilns, due to the drop in the price of natural gas and the growing pressures to reduce greenhouse gas emissions. Also, there is a growing interest in using lignin and other biofuels to fire kilns, and the U.S. Department of Energy funded a project with us to look at renewable fuels as a replacement for fossil fuels in lime kilns.

Computational modeling tools can be very helpful in determining the impacts of changing fuels on kiln performance. Over the years, we have done a considerable amount of work using both physical and computational models to improve combustion. This work extends the use of these tools to examine the impact of fuel type on kiln performance and brings together in a unique way a number of computational tools the industry can use to evaluate the impacts of fuels. Based on this work, you can match the modeling tools and cost to a specific need.

Gathering the operating data needed to validate model predictions is very challenging. Most kiln operators and owners believe all fuels are equal. This work shows that natural gas and fuel oil behave differently when used to fire kilns. It was interesting to find that, even with very low prices for natural gas, small amounts of more expensive renewable fuels such as torrefied wood can be economically



Gorog



Leary



Wang



Davis

used to enhance the performance of natural gas.

The computational modeling tools described in this paper can be used by mills to explore the impact of fuel type on kiln performance. These tools can also be used to improve burner designs, optimize the layout of chain systems and refractory linings, and other modifications to the kiln. Also, these modeling tools can be used to evaluate changes in operating practices. Finally, the visualization of fluid flow and temperatures generated by these modeling tools can be helpful for operator training.

Our next step is to further improve the speed and accuracy of the modeling tools. We are also currently working to incorporate the results from this work into a new design for gas burners.

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