REDUCED ORDER MODEL OF A LIME KILN FOR FUEL SWITCHING

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ABSTRACT

The lime kiln is an essential part of the causticizing loop in the kraft pulp mill. It is also the last operating unit that routinely fires fossil fuels like natural gas and fuel oil. Displacing these fossil fuels with biomass like bark or sawdust is done, as is firing lignin extracted from black liquor. Air-blown gasification and fast pyrolysis are thermal conversion technologies to produce a higher quality biofuel.

A reduced-order model has been developed to model both the gas phase and particle phase in a lime kiln. The objective of the model is to study the effect of fuel switching on the performance of the lime kiln and the quality of the solid product. Initial results of the model are in the expected range, but industrial data are needed for validation. The first application of the model will be to a full-scale trial co-firing natural gas with sawdust or kraft lignin.

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INTRODUCTION

The lime kiln is a rotary kiln that is part of the chemical recovery process within the kraft pulp mill. Its purpose is to take the wet lime mud (primarily calcium carbonate) from the causticizing plant and produce lime (primarily calcium oxide). The lime is hydrated to produce calcium hydroxide to react with green liquor (primarily sodium carbonate) to produce white liquor (primarily sodium hydroxide) and lime mud. The white liquor is used to digest the wood to produce pulp. The lime kiln and causticizing plant form a closed loop.

There are 475 rotary kilns in kraft pulp mills globally. In the past fifty years the thermal efficiency of the lime kilns has improved from 23 GJ/tonne to around 7 GJ/tonne. In Canada, the lime kilns process from 115 tonnes CaO/day to 430 tonnes CaO/day. The burners have a thermal rating from 10 MW to 23 MW. The lime kiln, at least in Canada, is the last unit within the kraft pulp mill that regularly fires fossil fuel, either natural gas or #6 fuel oil.

The carbon dioxide emissions from the lime kiln are from the calcination of the lime mud and from the fuel being fired. The former are biogenic, coming from the chemical process of the wood to make pulp. If a biofuel were used in the place of fossil fuels, then the carbon dioxide emissions would be completely biogenic. If, in addition, those emissions would be captured and sequestered, the pulp industry would be a source of negative emissions, aiding Canada in reaching the goal of carbon neutrality by 2050. Oxy-firing with recycling of carbon dioxide is a possible way of producing a high-concentration CO_2 stream for sequestration or utilization.

However, the lime kiln is a crucial unit in the pulp mill and the primary purpose is the production of high-quality lime for the causticizing plant. Switching to biofuels can cause problems like insufficient calcination due to low flame temperature and deposition of non-process elements (NPE) into the lime that contaminate the causticizing loop.

REDUCED ORDER MODELS

Reduced order models (ROMs), also known as reactor network models (RNMs) use networks of simple reactors (plug flow, stirred tank) to reproduce the main features of a reacting flow without the computational intensity of a full computational fluid dynamics model. Such models reduce the computational cost of studying the dominant behaviours, or permit incorporation of detailed kinetics for reactions that do not have a strong impact on the main flow and combustion reactions, such as NOx formation and reduction. Proponents of ROMs have used them for:

- Design optimization and shortening the design cycle;
- Components in large systems simulations;
- Testing control software; and
- Foundation for digital twins.

The scientific literature has instances of ROMs and RNMs applied to different high temperature combustors and reactors. Sahraei et al. [2015] developed a ROM for entrained flow gasifiers. Fichet et al. [2010] used a RNM to predict the NOx emissions from a gas turbine. Agizza et al. [2017] used residence time distribution with the CFD simulation for a pilot-plant combustor to construct a RNM for parametric studies on the furnace. Trespi et al. [2021] used an RNM to study the carbon monoxide emissions for the same pilot-scale combustor operating in oxy-fired configuration, starting from a Large-Eddy Simulation (LES) of the unit. Numerous other examples can be found of the application of ROMs and RNMs to combustion systems.

PARTICLE BED MODEL

The particle motion in the kiln is assumed to be in the rolling mode where the rotational speed brings the particles up the side of the kiln until they roll back down along the top of the bed. This sets up a zone of mobile particles on the outside of the bed in contact with the wall and along the top exposed to the kiln gases. There is also a core zone inside the bed that is much less mobile. There is exchange of particles between the two zones. This division into two zones follows the work of Boateng and Barr [1996]. The core zone makes up a third of the axial cross-section and the shell is the remaining two-thirds.

The axial motion is assumed to be plug flow for both zones. The cold model data of Sai et al. [1990] was analysed and a dimensionless correlation for the mean residence time developed (Gogolek 2022). With the solid feed rate this gives the solid hold up and the mean axial velocity. The bed height is assumed to be constant for 80% of the bed from the feed end, at which point the bed height decreases linearly to the dam height at the solids exit.

The particles are composed of calcium carbonate, calcium oxide, water, and an inert fraction for the non-process elements. The drying of the solids is modelled as a kinetic process after Paul

[2004]. Similarly, the calcination process is a kinetic process (Paul 2004). The gases evolved by drying and calcination in the particle bed, in either zone, is passed directly to the gas phase.

COMBUSTION MODEL

ROM for the combustion side of a rotary kiln starts with a qualitative analysis of the flow pattern calculated using CFD to identify the major flow patterns. In this case a CFD study (Runstedtler et al. 2021) was done on a representative lime kiln to understand the effect of changing the composition of the fuel gas from natural gas to various biomass derived gases, product gases from different gasification technologies. The temperature profiles for these calculations are shown in Figure 1.

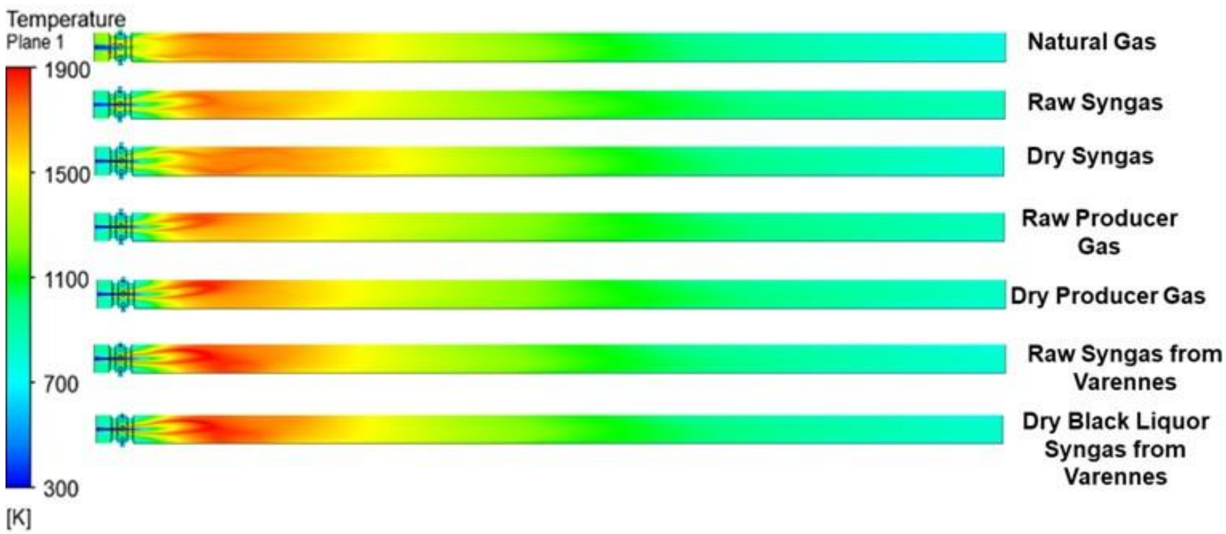

Figure 1 - Temperature profiles for an axial cross-section of the lime kiln studied in Runstedtler et al. 2021.

Inspection of the burner zone shows the presence of a low temperature core surrounded by an envelope of flame. Around the flame is the secondary air entering the kiln around the burner. The flame expands to incorporate the secondary air as well as part of the core. Finally, the core is incorporated into the flame and a near-uniform flow of post-combustion hot gases is produced.

Following those observations, the following four zones are used to develop the ROM for the gas phase.

Zone I is the near burner zone. The length of the zone is equal to the outer diameter of the burner. The burner design is assumed to have a central flow of the fuel and an annulus around the fuel for the primary air. The outer diameter of the secondary air is smaller than the burner outer diameter, providing a gap between the burner flow and the secondary air. It is assumed that the flows out of the burner are resolved into a uniform flow at the exit of the zone that is split into two reactors: a core composed of the fuel, and the flame. A small fraction of the fuel reacts in Zone I to provide the initial conditions for the flame. The secondary air flow in Zone I is a plug flow reactor with some heat and carbon dioxide is taken from the particle bed. There is convective heat transfer between the bed and the secondary air, using the correlation in Watkinson and Brimacombe [1978] as described by Barr [1986]. There is no interaction between the near-burner and the secondary air in Zone I because of the physical gap.

Zone II is composed of three plug flow reactors. The outer reactor has the secondary air that is being entrained into the flame. The inner core is a plug flow reactor with the fuel. The stoichiometric amount of fuel is entrained to react with the amount of secondary air that is entrained into the flame. The entrainment rate is that for a free turbulent jet except that the jet momentum flux is replaced by the difference between the total initial momentum flux of the burner and the initial momentum flux of the secondary air. The flame is a plug flow reactor in which the entrained air and fuel is assumed to react instantly and completely. The flame zone radiates to the kiln walls and the particle bed based on the concentrations of carbon dioxide and water vapour in the flame. The emissivity of the hot gas is estimated using the method outlines in Baukal [2004], with the graphs for the water vapour and carbon dioxide approximated for the temperature range of 1300°C to 2200°C and pressure-beam lengths from 5 bar-cm to 100 bar-cm. The secondary air is assumed to be transparent to the radiation, even though it can contain a significant concentration of carbon dioxide released from the particle bed. Similarly, the fuel core is not heated by the flame, even though some product gases from biomass gasification can have significant water vapour and carbon dioxide. The area of the kiln cross-section occupied by the three reactors changes along the length of Zone II, with the decrease in area for the secondary air and the fuel core corresponding to the amount of material transferred to the flame.

The secondary air is completely entrained into the flame zone by the end of Zone II. Zone III has two plug flow reactors – the flame and the fuel core. The flame continues to entrain the fuel from the core along the length of Zone III, which ends when all the fuel has been entrained. There is heat transfer from the flame to the kiln wall and the particle bed by radiation and by convection. The gases evolved from the particle bed, carbon dioxide and water, are transferred to the flame in Zone III. Zone III ends when all the fuel from the core has been entrained into the flame.

Zone IV has no combustion reactions since all the fuel has been consumed in Zone III. Zone IV continues for the remainder of the length of the kiln with a single plug flow reactor that receives carbon dioxide and water vapour evolved from the particle bed. The heat transfer from the hot gases to the wall and the particle continues by radiation and convection.

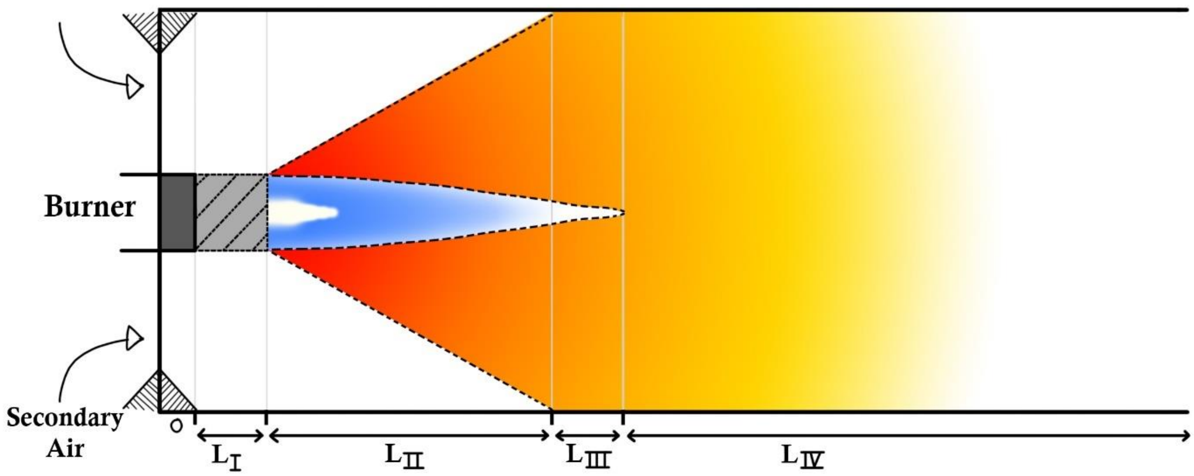

Figure 2 - A schematic of the zones for the lime kiln gas phase combustion.

PRELIMINARY RESULTS

The first calculations with the model were performed for the same kiln as in Runstedtler et al. [2021] firing natural gas. The internal diameter of the kiln is 3.8 m and it is 115 m long. The burner geometry is simplified to be an inner fuel nozzle with 10 cm diameter surrounded by a primary air annulus with outer diameter of 60 cm. The natural gas feed rate is 0.8 kg/s (40 MW) with primary air of 2.2 kg/s and secondary air of 12.7 kg/s. The kiln rotates at 1.36 rpm. The solids feed rate is 39.6 T/h on a dry solids basis, with initial water content of 20%.

Because the kiln is a counter-flow system, the solution method requires iteration between the particle bed model and the combustion model. The heat flux calculated by the CFD model is used for the initial calculation of the particle bed model. The results for the particle bed model with the CFD heat flux are presented in Figure 3. These data show 65% calcination was obtained but this is significantly less than that expected from an operating kiln. Drying the lime mud takes almost

60% of the kiln length, which is also longer than would be observed in an actual kiln. However, the shell and core division does give the expected behaviour with respect to heating and calcination.

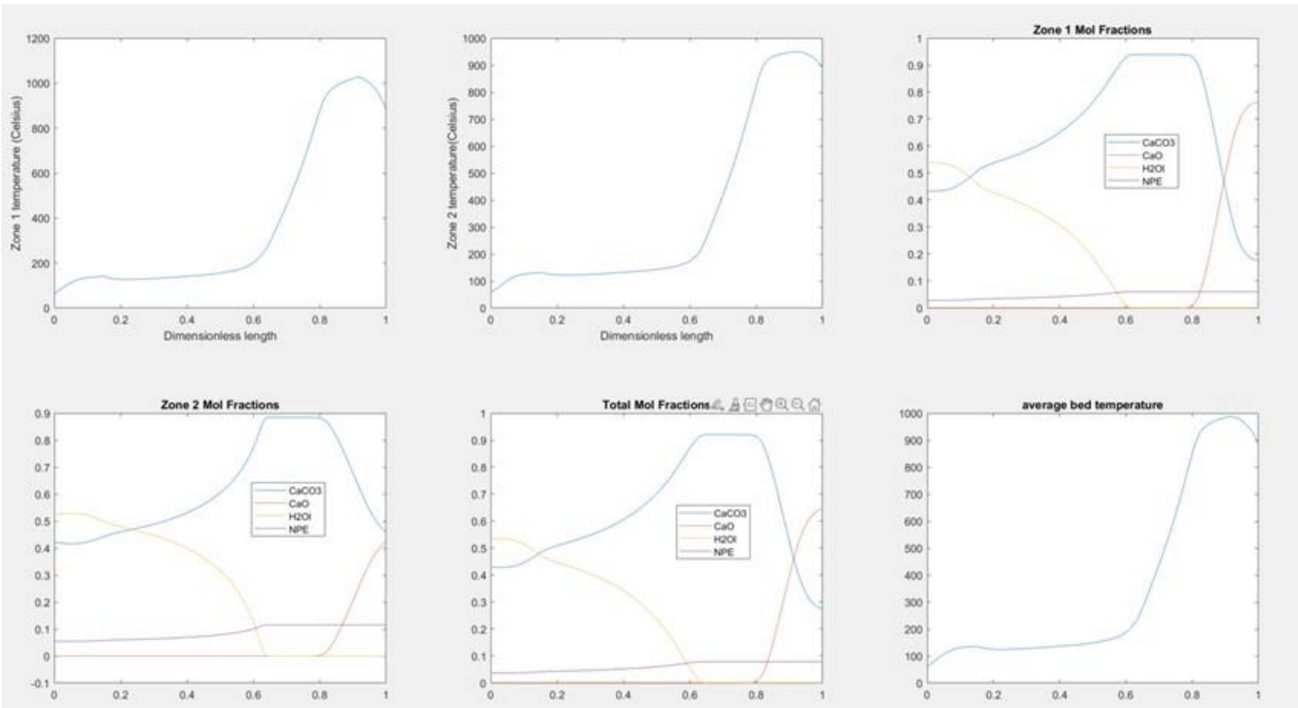

Figure 3 - Results from the particle bed model using the heat flux from the CFD simulation of the gas phase.

The temperature profile and gas efflux from the particle bed model are then passed to the combustion ROM. The combustion model gives the heat flux to the bed that is compared to the heat flux from the CFD calculation in Figure 4. The shape of the ROM heat flux curve has the same general profile as the CFD heat flux but it is significantly lower. This discrepancy does not have an easy explanation.

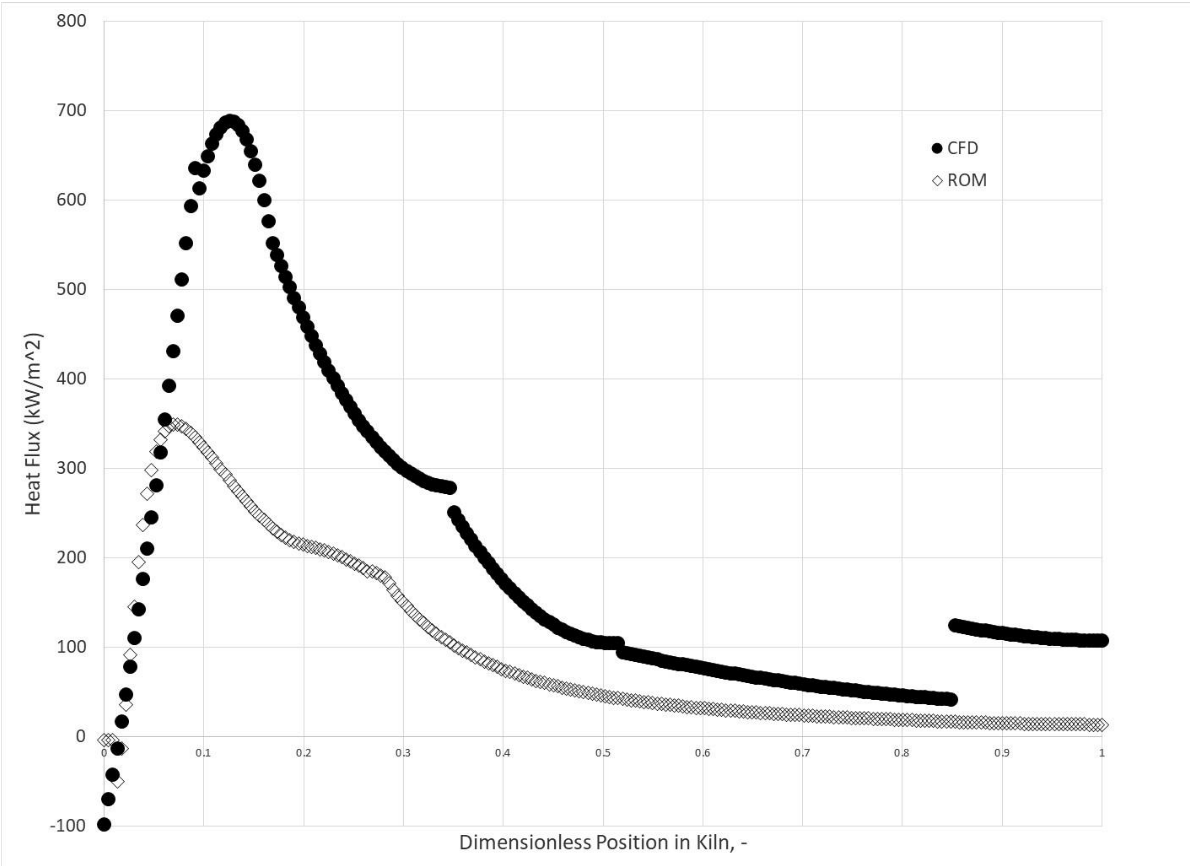

Figure 4 - Comparison of the heat flux to the particle bed from the CFD and ROM combustion models.

NEXT STEPS

The particle bed model provides the expected results using the heat flux calculated using the CFD model. However, the ROM for combustion only reproduces the general shape of the heat flux to the bed as calculated by CFD. The reason for the discrepancy needs to be explained.

The next iteration of the combustion model will be validated with actual data from operating industrial facilities, as well as comparison to the CFD results. There are published data from some European lime kilns firing natural gas and then co-firing with solid biomass, with natural gas firing being the baseline case.

The initial CFD study investigated the effect of using different gaseous fuels, switching from natural gas to product gases from various gasification technologies. This investigation will be repeated with the ROM to confirm the conclusions.

Solid and liquid biomass-derived fuels, like sawdust, lignin, fast pyrolysis liquids, need to be included among the capabilities of the model. This will be accomplished by incorporating drying, devolatilization and char combustion steps based on rate parameters from thermogravimetric analyses (TGA) of the candidate fuels.

The ultimate objective is to be able to model oxy-firing for the kiln. This will involve significant changes to the particle bed model since the elevated concentration of carbon dioxide will inhibit calcination, requiring higher kiln temperatures. The inhibition of onset of calcination and the effect of ambient carbon dioxide on the rate of calcination is being studied using the TGA. This work has been started with laboratory grade calcium carbonate and a sample limestone. Lime mud samples from operating kraft mills are needed to confirm the results.

CONCLUSION

A reduced order model for a lime kiln, including both combustion and particle bed, has been developed. The particle bed model, composed of a shell and a core treated as plug flow reactors, shows promise when the heat flux from the CFD model is used. The ROM combustion model provides a heat flux to the bed that is qualitatively similar to that from the CFD model, but it is significantly less over most of the length of the kiln. This discrepancy needs to be corrected before the model can be used to predict the changes in lime kiln operation with changes in fuel or oxy-firing, which are the objectives of this project.

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