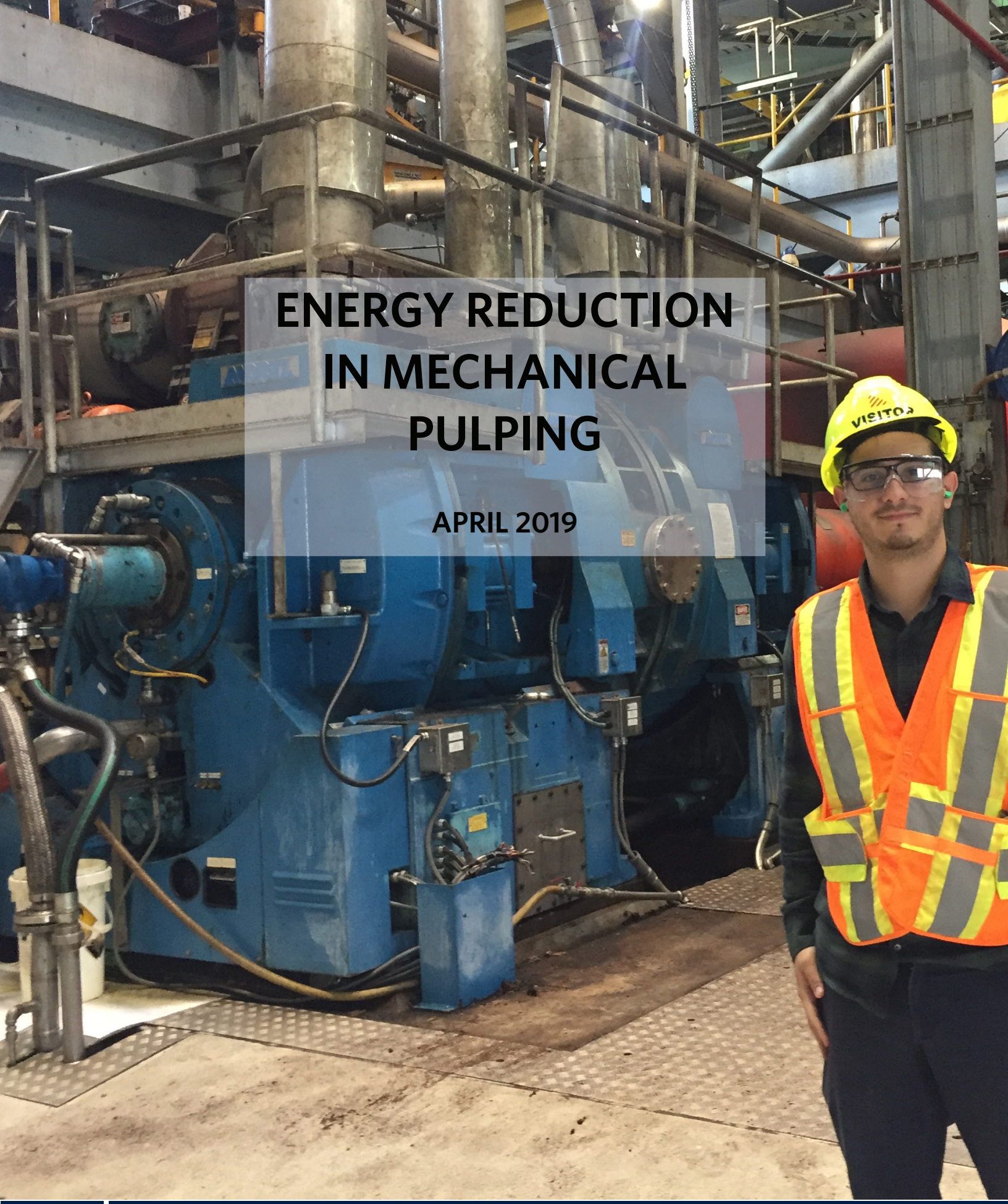
ENERGY REDUCTION IN MECHANICAL PULPING

APRIL 2019



THE UNIVERSITY OF BRITISH COLUMBIA

WELCOME MESSAGE

Dear partners in the Energy Reduction in Mechanical Pulping research program,

Twelve years ago, we formed this globally unique partnership with the aim of reducing electrical energy use in mechanical pulping processes. We initiated a five-year research proposal and in 2013—building on our accomplishments—we renewed the consortium with another round of projects. As those projects are now concluding, it is again time to renew our partnerships for a third phase of the ERMP program, with an increased scope that reflects the need to expand the markets for mechanical pulp.

Professor Mark Martinez will be leading the next stage of the consortium, and has been working with interim Program Manager Sona Kazemi and eleven other professors to develop a research proposal focused on system design for low energy pulps, valorization of mechanical pulp fines, and enhancing properties of fines-free furnishes. The strong proposal was made possible by all of your financial and in-kind commitments. Thanks to your continued support, we are very optimistic about the program being extended. In personnel news, Meaghan Miller has returned as Program Manager, while Sona has begun a new role as Innovation Development Officer at UBC's Vice President Research and Innovation Office.

Since our last newsletter, we held a successful Steering Committee meeting at UBC on October 2, 2018, where several students presented their project updates for the final time. Jorge Rubiano, Miguel Villalba, Taraneh Kordi and Bahar Soltanmohammadi have all submitted and successfully defended their theses, and we still have students completing their projects and working towards graduation. I invite you to read more about our project updates and publications in the following pages. I hope you will also join us for the next Steering Committee meeting on June 5, 2019 in Whistler, a prelude to the PACWest conference.

In addition to our own group's efforts, it is a very exciting time for UBC's BioProducts Institute (BPI) and its broader network. Dr. Emily Cranston has joined UBC's faculties of Forestry and Chemical and Biological Engineering as the President's Excellence Chair in Forest Bioproducts, bringing $3 million in funding, and will be a researcher in the ERMP program. Funding from the Canadian Foundation for Innovation ($11.6 million) and British Columbia Knowledge Development Fund ($6 million) that BPI was awarded last year are also being used to purchase new research tools and instrumentation. These exciting awards are breathing new life into the UBC's Pulp and Paper Centre, which will be undergoing renovations and changes to accommodate new researchers, students, and state-of-the-art lab equipment.

I am also pleased to announce that UBC will be hosting the 32nd International Mechanical Pulping Conference from June 7–10, 2020 (IMPC 2020) at our Vancouver campus. I hope you will all mark your calendars and join us for this event.

Sincerely,

James Olson

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CONTENTS

RESEARCH UPDATES

PROGRAM UPDATES

CONTACTS

ON THE COVER

ERMP researcher Miguel Villalba visited Catalyst Paper in Port Alberni, British Columbia. He is pictured in front of the refiners. Read about his visit on page 18.

MIGUEL VILLALBA

PROJECT 1.1 - COMPRESSION SCREW FEED OPTIMIZATION AND ENERGY SAVINGS IN HC REFINING

In the thermomechanical pulping (TMP) process, wood is reduced to its constituent fibres by mechanical means to make the pulp that is used in paper and other bioproducts. Refiners defibrate wood fibres into pulp but consume high amounts of electrical energy in the process. A combination of compression and chemical impregnation prior to refining leads to a reduction of energy requirements in the refining stages (Gorski et al. 2010; Nelsson et al. 2012). The use of enzymes as a chemical agent in impregnation positively influences energy reduction and improves pulp properties (Hart et al., 2009). This project focused on understanding the effects of screw feeder operating conditions (i.e. screw speed, power input and geometries) on wood chip morphology that relate to its chemical uptake ability. We directed our efforts to developing a simple screw press model that would characterize the operation of a modular screw press device for wood chips. We aimed to understand the effect compression has on the accessibility of enzymes on wood chips.

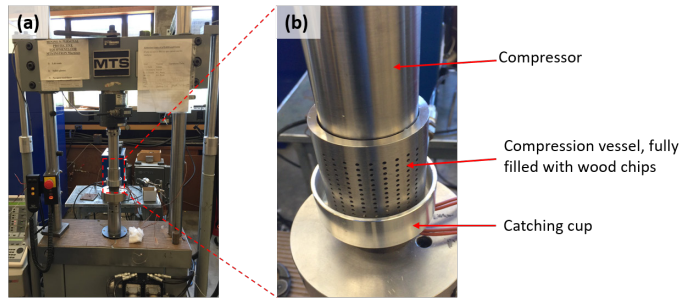


Figure 2(a): MTS 810 Load frame. 2(b): Close-up of the compressor, compression chamber and catching cup.

Test 1: Fixed Compression Time		Test 2: Variable Compression Time	
CR	Time (sec)	CR	Time (sec)
3:1	5	3:1	3, 5, 10
4:1	5	N/A	N/A
5:1	5	5:1	3, 5, 10
6:1	5	6:1	3, 5, 10

Table 1: MTS compression conditions

MTS Compression and Enzyme Treatment

The experimental part of our research involved compressing wood chips to different degrees and impregnating them with enzymes at ideal conditions (Figure 1). A cylindrical compressor and a compression chamber (Figure 2) were designed to simulate a pocket element in a screw feeder. The compression chamber has holes on the sides for the extrusion of water. A small aluminum cap catches the liquid at every compression. The bottom end of the chamber is heated up to about 90 °C. The compressor and compression chamber were mounted to a material testing system (MTS) 810 Load Frame. A highly accurate load cell measured the uni-axial force applied over time. Different compression ratios (CRs) and compression times were assessed in this experiment. The compression conditions are presented in Table 1. After each compression test, the amount of water extract was collected. The compressed chips samples were saved for microscopy and enzyme treatment in the laboratory.

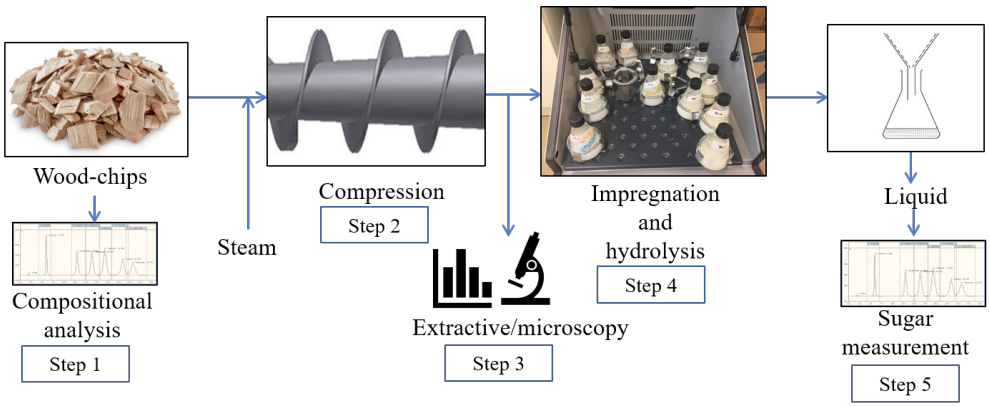


Figure 1: Experimental layout for this work. Step 1: Compositional analysis of wood. Step 2: Mechanical treatment of wood. Step 3: Measurement of extractives and microscopy. Step 4: Enzyme impregnation and hydrolysis of wood. Step 5: Filtrate liquid fraction and perform analysis of sugars released.

PROJECT 1.1

Wood-chip samples were mixed with buffer and enzyme solution in Erlenmeyer flasks bringing the mixture to a consistency of 2.5 % for all samples. A very high dosage of 1 g enzyme/g dried wood was used. The enzyme used contained a mixture of cellulase provided by ABEnzymes. The enzyme was designed to degrade biomass and used to track cellulose accessibility in this experiment. The hydrolysis experiment was run in an incubator shaker at 50 °C and 120 RPM for 2 hours. The buffer maintained the pH of the samples at an optimum of 4.8. Each sample was run in triplicate. As much as 10 ml of sample was removed for every sampling period (i.e. 15 min, 30 min, 45 min and 2 hours). We analyzed the liquor samples for soluble carbohydrates with a high-performance liquid chromatograph (HPLC). The normalized glucose released was calculated to assess cellulose accessibility.

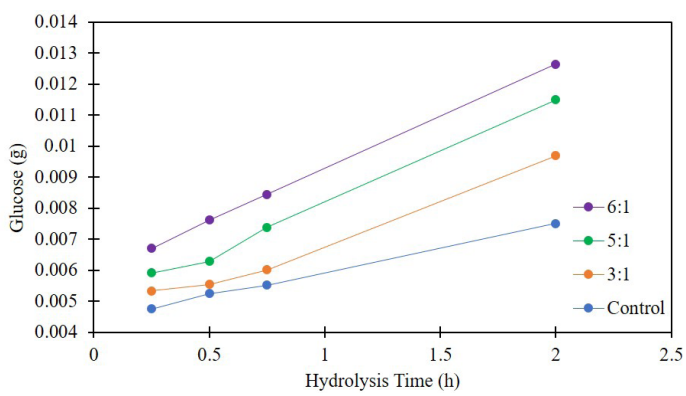
Effect of Compression on Hydrolysis Rate

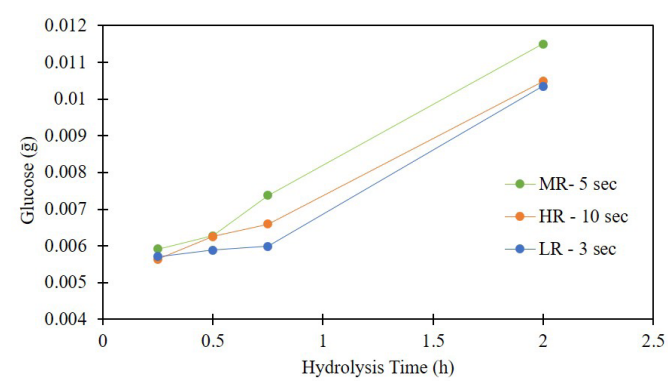
Figure 3(a) displays the normalized glucose released into the liquor over time at varying compression ratios for a compression time of 5 seconds. Figure 3(b), on the other hand, displays the normalized glucose released over time at varying compression times for a constant CR of 5:1. It is evident that the amount of glucose released is affected by the compression ratio. We can see increasing enzyme activity at increasing compression ratios. However, these experiments show that the enzyme activity was not dependent on the compression time/ rate. The highest amount of glucose released in that case was shown for the sample compressed at 5 seconds.

The hydrolysis rate of test 1 (i.e. fixed compression time) is displayed in Figure 3(c). The hydrolysis rate increases first rapidly with compression ratio, and then slows at very high loads. This indicates that further compression leads to no significant increases in hydrolysis rate as the wood could not be compressed any further.

Effect of Compression on Water Extract

We weighed the extractive water in the capture cup for every compression run. Figure 4(a) displays the amount of water extract collected at each compression ratio. The amount of water expelled varies almost linearly with increasing compression ratio. Figure 4(a) also displays the relationship of the expelled water with the compression time. For the 3:1 and 6:1 compression case, the amount of water expelled





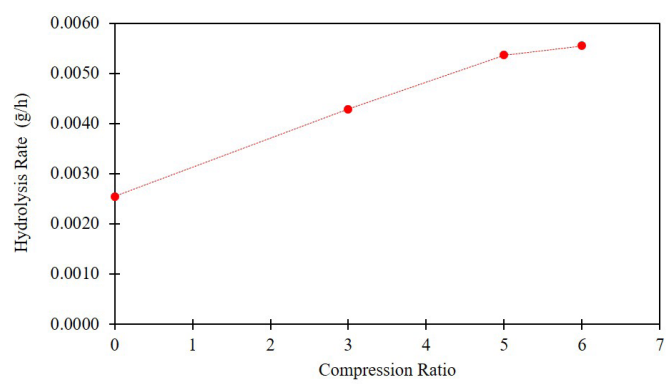
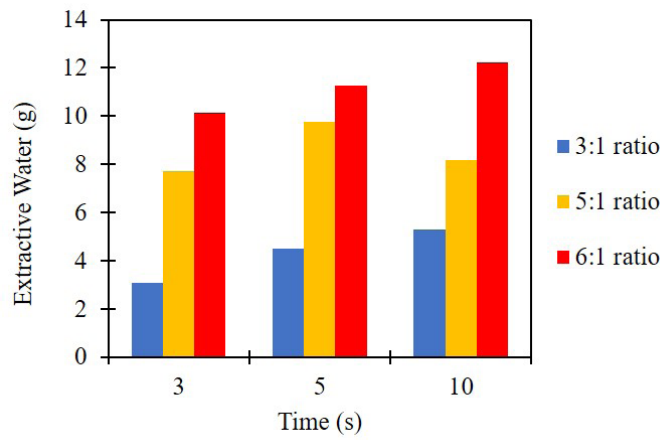


Figure 3: Normalized glucose released over time for a high dosage (1 g of enzyme/ g of odw). (a) Wood chips compressed at different compression ratios are considered. (b) Wood chips compressed at different compression times are considered. Here, LC is 3:1 compression, MC is 5:1 compression ratio and HC is 6:1 compression ratio. LR is 3 sec of compression, MR is 5 sec of compression and HR is 10 sec of compression time.(c) Enzyme rate as function of compression ratio applied to the wood chips.

PROJECT 1.1

increases with compression time. That is not the case for the 5:1 compression. This implies that the amount of water expelled is mainly affected by the compression ratio, and to a lesser extent by the compression time or rate. Our findings agree with Thornton and Nunn (1978) who noted that the amount of ether soluble extractives did not vary significantly with screw feeder feed rate.

In either case, the amount of extractive expelled is an indication of how much compression was achieved. This removal could explain the increase in enzymatic hydrolysis with compression because extractives act as inhibitors of cellulase enzyme by restricting its access (Belt et al. 2018; Holtzapple and Humphrey 1984). The carbohydrates and lignin composition of the water extract is shown in Figure 4(b). There is an overall increase of lignin and carbohydrate concentration with increasing compression ratio. The extractives contain mainly dissolved hemicellulose and lignin (apart from the terpenoids and fatty acids and other compounds), which are well known to inhibit cellulase hydrolysis (Chandra et al. 2016; Kumar et al. 2012). Therefore, we infer that compressed wood showed improved enzyme uptake in part due to the removal of extractives.



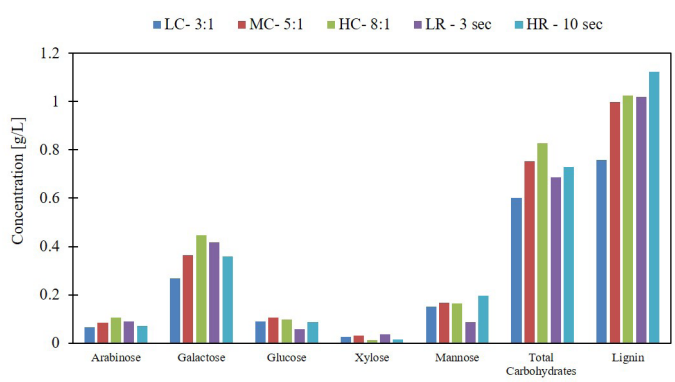


Figure 4: (a) Extractive water squeezed out of the compression chamber at increasing compression time and compression ratios. 4(b) Extractive water composition for all compression tests. The composition includes the total amount of oligomeric carbohydrates as well as the soluble lignin content. Here, LC is 3:1 compression, MC is 5:1 compression ratio and HC is 6:1 compression ratio for 5 sec of compression time. LR is 3 sec of compression and HR is 10 sec of compression time at 5:1 compression.

Effect of Compression on Morphology

Microscopy images illustrate how compression affected the morphology of wood-chips at the microscopic level. Figure 5 shows micrographs of wood chip cross-sections that were compressed at different compression ratios. The control wood-chips are also shown for comparison. The figure also shows pictures of wood-chips from each run. First, Figure 5(a) displays the cross-section of a wood-chip that has not been compressed, described as 'control'. Normal arrangement and shape of cell walls is present. Upon compressing the wood-chips at a 3:1 ratio, buckling of the cell walls is noticeable in some areas, and the formation of small cracks is observed in Figure 5(b). The buckling or distortion of the cell wall is a sign that irrecoverable damage was done to the cell structure.

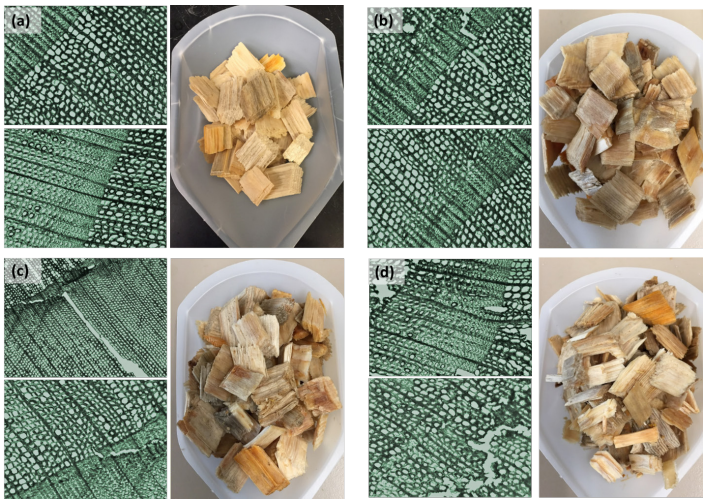


Figure 5: Microscopy samples from (a) Control chips. (b) Wood chips compressed at 3:1 compression ratio. (c) Wood chips compressed at 5:1 compression ratio, and (d) Wood chips compressed at highest compression ratio of 6:1.

PROJECT 1.1

Further compression leads to the formation of cracks in the buckled wall. At a higher compression ratio of 5:1, the smaller cracks start to propagate forming even larger and wider cracks across the cell walls as seen in Figure 5(c). At this point, the cracks are so large that they are visible on the wood chip surface. Finally, further compression of the wood chip to the highest possible compression ratio results in further crack formation as well as distortion of both early and late wood cell walls as seen in Figure 5(d). This leads to fragmentations of the cell walls and separation in the middle lamella. Moreover, wood-chips at the large scale are broken into smaller chips because of the high load.

Overall Effect of Compression on Cellulose Accessibility

Initial hydrolysis rate of the enzyme was used to assess the cellulose accessibility of the compressed wood chips. The trial results showed that the cellulose accessibility increased with compression ratio. Compression time had no apparent effect on the cellulose accessibility. The improved accessibility is mainly caused by changes in wood morphology as well as the removal of enzyme-inhibitory extractives. The relative importance of morphology and extractives on accessibility was not determined. Microscopy imagining showed buckling and fractures of the cell walls. Fractures lead to improved enzyme penetration and the reduction of chips size resulted in higher available surface area.

Future Work

Data of compression load was collected in the MTS compression trial. This data was used for a simple screw feeder analysis. In this analysis, the performance of a screw feeder could be estimated for different compression ratios. Future work in this area could be to develop a mechanistic model of screw feeder. Further work is necessary to refine an accurate model.

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PROF. RODGER BEATSON

1.3 - OPTIMIZATION OF CHEMICAL CHARGE DISTRIBUTION THROUGHOUT THE PROCESS

Growing demand for paper products can be met through producing high yield pulps by the thermomechanical pulping process. The biggest disadvantage with thermomechanical pulp (TMP), however, is that its production consumes a large amount of electrical energy. A promising strategy to overcome this drawback could be conducting chemical treatment on the high-consistency (HC) refined TMP prior to low-consistency (LC) refining. In prior work, we have shown that the treatment of TMP with oxidizing agents such as highly alkaline hydrogen peroxide, oxygen and ozone, can improve the tensile strength of TMP and protect the fibre from cutting during subsequent LC refining (Chang et al. 2010, 2011, 2016; Yu et al. 2016). The improved tensile strength is a result of the formation of acid groups in the fibres and fines. The combination of oxidation and LC refining can result in total energy savings, to a given tensile, of around 1000 kWh/t. We are currently investigating chlorine dioxide, as a potential oxidizing agent for this treatment. In the previous newsletter (April 2018) we reported the results from chlorine dioxide treatment of Hemlock TMP with a freeness of 380 mL, collected after the second stage of HC refining. This treatment led to modest tensile strength gains however, much more significant tensile strength gains were found when chlorine dioxide treated TMP was soaked in sodium hydroxide. In order to assess potential energy savings when combining chlorine dioxide treatment with low consistency refining it was necessary to do the treatments on a higher freeness pulp. This was achieved by treating a 680 mL freeness primary-stage TMP, produced from a mixture of spruce and pine chips, with chlorine dioxide. The chlorine dioxide treatment was followed by an alkaline soak prior to refining in a Waring blendor.

Effects of chlorine dioxide treatment and caustic soaking on the properties of high-freeness spruce-pine TMP

The pulp used for this investigation was high freeness primary-stage TMP, made from a mixture of spruce and pine wood chips. In a similar manner to the hemlock pulp, the spruce-pine TMP was treated with chlorine dioxide at two charges (1 and 5%), for several times (10-60 minutes) and at two temperatures (45 and 55 °C). The chlorine dioxide treatments were followed by an alkali soak over a range of sodium hydroxide charges (0.4–3% w/w). A treated pulp with high strength was chosen for further refining at low consistency on a laboratory scale. Pulp strength and optical properties were assessed.

As shown in Figure 1a, under the investigated conditions, the tensile strength of the treated pulp increased only slightly when increasing the chlorine dioxide charge from 1% to 5% w/w. When the chlorine dioxide-treated pulps were soaked with sodium hydroxide for 60 minutes, increases in pulp tensile became evident (Figure 1b). The increase in tensile on soaking with 1 % sodium hydroxide for 60 minutes was 28% to around 25.5 N·m/g. The increase was similar for both 1% and 5% chlorine dioxide treatments. With increasing the charge of sodium hydroxide used for soaking, a further increase in tensile strength for the TMP treated at the higher chlorine dioxide charge (5% w/w) was observed. For example, at a sodium hydroxide charge of 3% w/w, a tensile strength of 32 N·m/g was achieved. However, no further increase in tensile strength

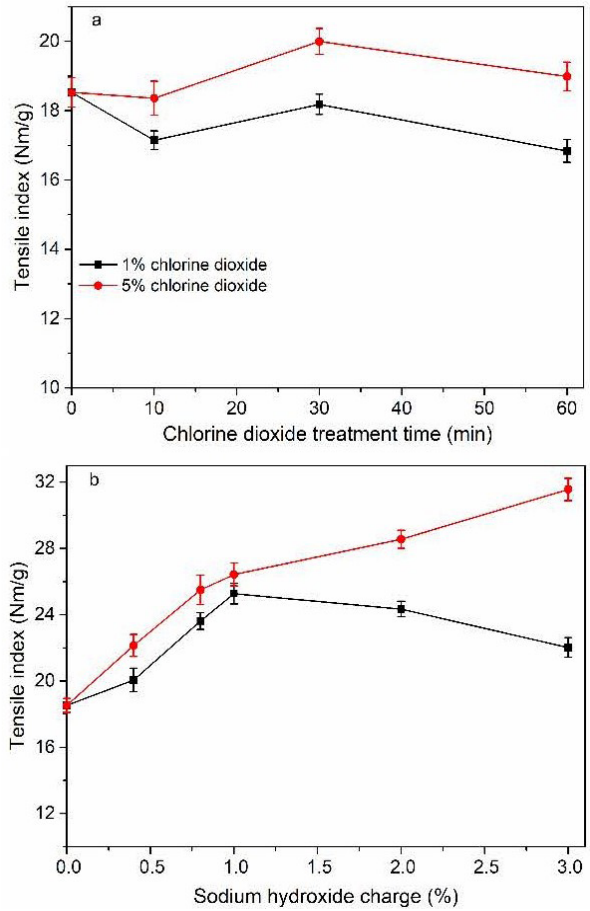

Figure 1: Effect of chlorine dioxide treatment and alkali soak on the tensile strength of the spruce-pine pulp. Chlorine dioxide treatment was carried out with 1% and 5% chlorine dioxide at 55 °C and 10% consistency. (a) Effect of chlorine dioxide treatment time. (b) Effect of sodium hydroxide charge.

PROJECT 1.3

was obtained by soaking the 1% w/w chlorine dioxide treated samples with increasing sodium hydroxide charge (Figure 1b). This is likely because lower amounts of acid groups are generated at the lower charge of chlorine dioxide and 1% w/w sodium hydroxide is sufficient to neutralize all of them under the conditions used for the soak. In addition, it should be noted that no tensile gain was observed on soaking the untreated pulp with 1% w/w sodium hydroxide charge. These observations are similar to those found with the lower freeness hemlock TMP, in which the benefits of the chlorine dioxide treatments are not realized until a subsequent alkali soak. As postulated previously, the strengthening effect is probably created by the formation of sodium salts of the carboxylic acids which were generated from the oxidation of lignin by chlorine dioxide. These sodium salts then lead to softening and swelling of the fibres and fines and resultant increased bonding and sheet consolidation, which is consistent with the negative the correlation between tensile strength and bulk of the paper (Figure 2a). The decreased pulp freeness is also consistent with the proposed mechanism (Figure 2b).

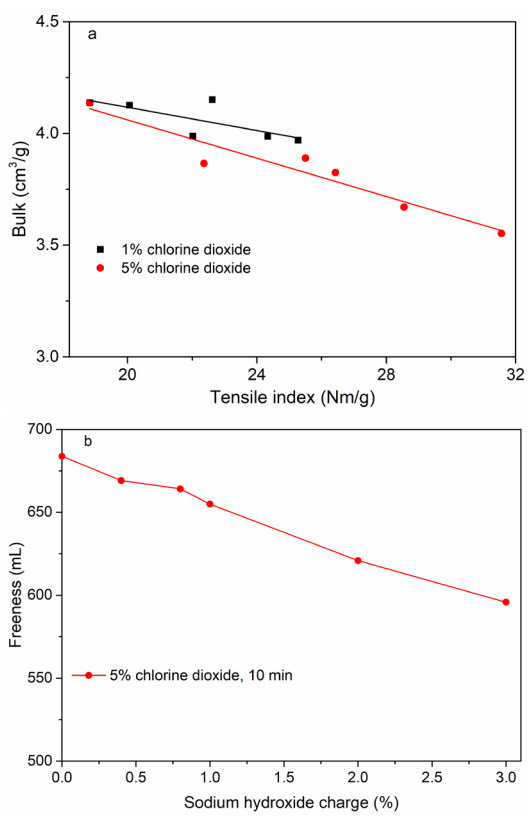

Figure 2: Effect of chlorine dioxide treatment on the spruce-pine TMP properties. Chlorine dioxide treatments were carried out at 55 °C and 10% treatment consistency (a) Correlation between bulk and tensile strength at different treatment times with chlorine dioxide, (b) Pulp freeness at different sodium hydroxide charges.

Development of Strength Properties on Low Consistency Refining

The spruce-pine TMP before and after treatment with chlorine dioxide (1% chlorine dioxide, 55 °C, 10 minutes, 10% consistency) plus alkali soak (1% NaOH, 60 minutes, 23 °C, 4% consistency) were refined in a Waring blendor at 2.4% consistency for 10, 20 and 30 minutes. This procedure has been previously shown to mimic pilot-scale LC refining with each 10 minutes of blending corresponding to the application of a specific energy of about 110 kWh/t (Chang et al. 2010).

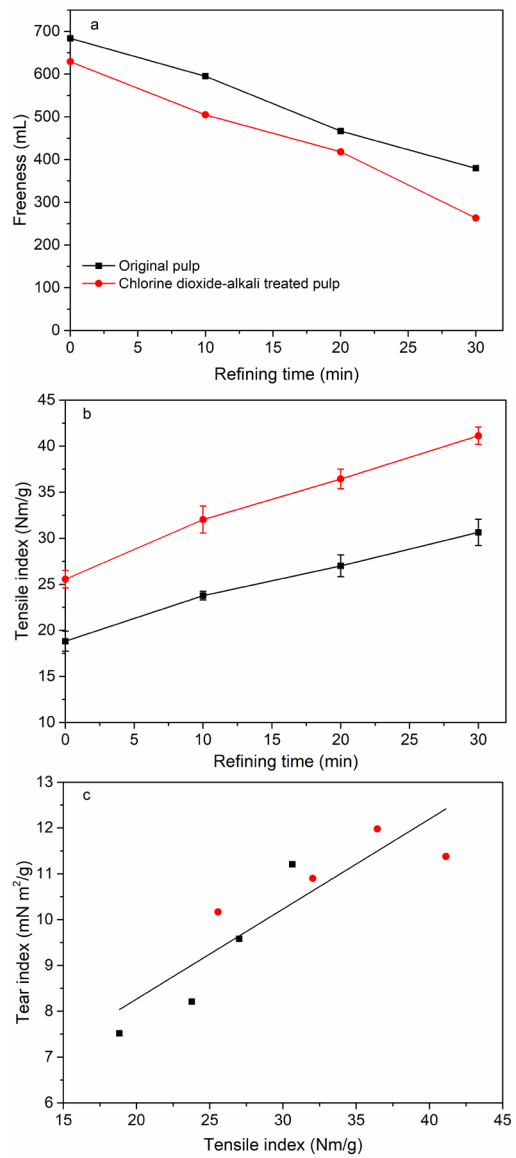

Figure 3: Effect of low consistency refining on the properties of chlorine dioxide treated spruce-pine TMP. Chlorine dioxide treatment was carried out at 1% chlorine dioxide charge for 10 min at 45 °C and 10% treatment consistency. The following alkali soak was carried out at 1% sodium hydroxide charge for 60 minutes at 23 °C and 4% treatment consistency. (a) Pulp freeness. (b) Tensile index. (c) Correlation between tear index and tensile index.

PROJECT 1.3

The expected drop in freeness on refining was observed for both pulps (Figure 3a). The treated pulp started with lower freeness than the control non-treated pulp reflecting more consolidation of the pad during the freeness measurement, but the rate of freeness drop on refining was similar for both pulps. Figure 3b shows the effect of refining on the improvement of the tensile strength for the two pulps. As shown, the initial tensile strength of the treated pulp was higher than the control, consistent with reported above, and increased by 15.6 N·m/g after refining for 30 minutes, to final tensile of 41 N·m/g. The tensile gain for the control pulp on refining was less, at 11.8 N·m/g, to reach a final tensile of 30.6 N·m/g. It seems that not only did the chlorine dioxide treatment followed by the alkali soak increase the initial tensile strength, but the treatment also produced a pulp that was easier to refine. To achieve a tensile of 30 N·m/g took 23 minutes less refining for the treated pulp which is equivalent to a reduction in refining energy of around 253 kWh/t. Judging by the trend lines, the energy savings would be even greater at higher tensile values. For both pulps, the tear strength increased with tensile as seen in Figure 3c. The optical properties of these pulps are discussed in the following section.

Optical Properties

As was seen with the hemlock TMP, chlorine dioxide treatment lowered the brightness of the spruce–pine pulp (Figure 4). This brightness drop was more severe for the higher chlorine dioxide charge. In contrast with the hemlock TMP, the TMP from the pine–spruce furnish did not exhibit a further brightness drop on alkali soaking. This may be related to the nature of the extractives in the different species.

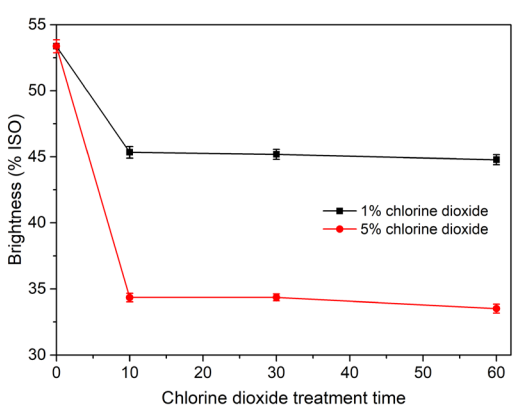

Figure 4: Effect of chlorine dioxide treatment time on the spruce–pine brightness.

Effect of Low Consistency Refining on Optical Properties

After the initial drop in brightness on chlorine dioxide treatment followed by an alkali soak (for conditions, see section on effects of soaking), refining increased pulp brightness through the generation of fines and increased scattering coefficient (Figure 5). The decrease in scattering coefficient on chemical treatment is consistent with increased bonding between the fibres and fines, and improved tensile strength.

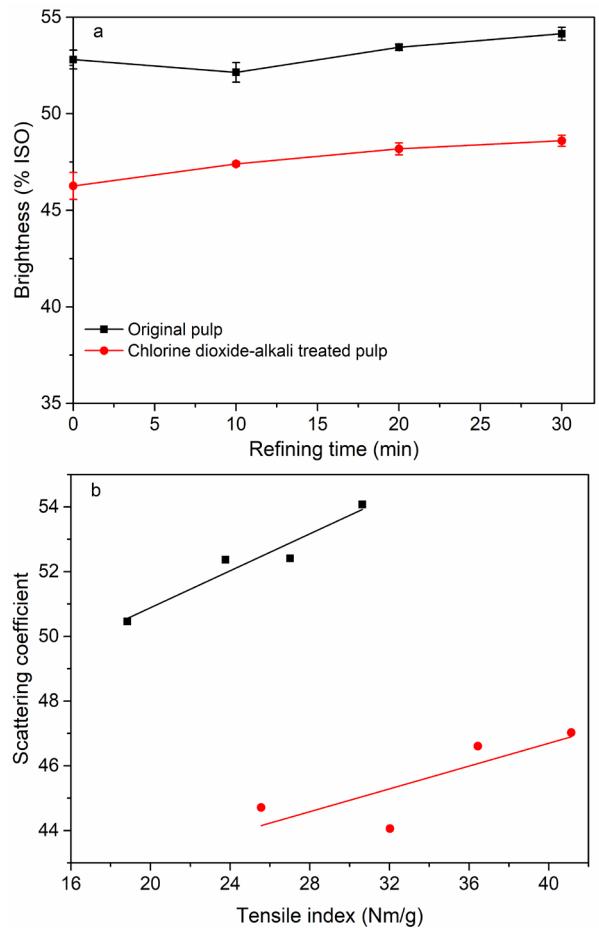

Figure 5: Effect of low consistency refining on the optical properties of spruce–pine TMP. Chlorine dioxide treatment was carried out at 1% chlorine dioxide charge for 10 min at 45 °C and 10% treatment consistency. The following alkali soak was carried out at 1% sodium hydroxide charge for 60 min at 23 °C and 4% treatment consistency. (a) Brightness. (b) Correlation between scattering coefficient and tensile index.

PROJECT 1.3

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HUI TIAN

2.1 - OPTIMIZATION AND CONTROL OF INTEGRATED HC AND LC REFINING

The focus of Project 2.1 is to develop advanced control and optimization approaches to reduce energy consumption and pulp quality variabilities. Through our work on this project over the last four years, we have made significant theoretical breakthroughs in developing the advanced control and estimation techniques including the economic MPC (econ MPC), multi-objective economic MPC (m-econ MPC), stochastic multi-objective economic MPC (SMEMPC), and moving horizon estimator (MHE) for a two-stage high consistency (HC) mechanical pulping process. In the MPC design, the accuracy of the process model plays a vital role in achieving good control performance. Therefore, we developed a nonlinear two-stage HC refining process model based on the data we collected from Alberta Newsprint Company. The simulations we carried out have shown that the proposed m-econ MPC can reduce specific energy consumption by 10 to 27 per cent compared with traditional tracking while maintaining satisfactory control and stabilizing performance. Moreover, the m-econ MPC and MHE, which comprise the control-estimation framework we proposed, made it possible for pulp mills to install advanced controllers when limited fast and reliable online sensors are available.

In addition, we also investigated the SMEMPC that tackles the control problem from a stochastic optimization point of view. Users can adjust the trade-offs between pulp property viabilities and tracking speed as needed by changing the scenario number in our proposed SMEMPC. All the aforementioned research work has been summarized in our publications (Tian et al. 2016a; 2016b; 2019a and 2019b). The next step of this project would be to validate the proposed control and estimation strategies through industrial experiments and trials. Since our primary researcher, Hui Tian, is currently focusing on completing her thesis and planning to graduate before summer 2019, the more detailed validation work will be continued by another research student in the future.

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MATTHIAS AIGNER

2.2 - LOW CONSISTENCY REFINER BAR FORCE SENSOR BASED CONTROL STRATEGIES

Refiner control strategies are primarily based on global process variables such as rotational speed, flow rate, inlet pulp consistency and outlet fibre length (Luukkonen et al. 2010). In previous work on this project, most recently by Reza Harirforoush, a force sensor was developed to measure forces applied directly by the pulp to the refiner bars to monitor and validate the mechanical interactions in the refiner chamber. This type of sensor is used in a variety of high consistency (HC) (Olender 2007) and low consistency (LC) (Prairie et al. 2008, Harirforoush 2016) refiners. This sensor was embedded into plates of the AIKAWA 16" single disk pilot LC refiner at the Pulp and Paper Centre at the University of British Columbia and used in all trials of this project.

Our research project used this sensor to measure normal and shear forces applied to the refiner bars by the pulp under various process configurations. We added a rotary encoder to this LC refiner to collect data on the angular position of the rotor during the refining process. This measurement is used to determine the position of the bars of the rotor plate, relative to the bars on the stator plate.

The angular position of the refiner plates is measured through a high-resolution rotary encoder with a maximum of 65,536 pulses per revolution. This encoder, mounted as shown in Figure 1, records the rotation of the drive shaft through a measuring wheel. To detect any slip of the rubber wheel and to reference the rotation of the encoder with the rotation of the rotor, a photoelectric sensor directed at the drive shaft provides a synchronous pulse with each revolution.

We conducted a set of two trials in 2018 using the refiner plates with bar edge length (BEL) of 2.74. Both trials where conducted at 1200 rpm and a consistency of 3.4%, and the plate gap was varied from 3.5 to 0.2 mm. The first trial used BCTMP at low freeness and the second trial used Miller Western hardwood pulp.

The position of the rotor bars relative to the stator bars was analyzed in conjunction with the bar force data. Bar force data typically consists of a repeating sequence of three peaks, each of which corresponds to the passage of a bar on the rotor plate over the force sensor located in the stator plate. The rotary encoder data was used to record these force peaks in combination with the position of the rotor bars as they pass over the sensor. Figure 2 shows a characteristic normal (blue) and shear (orange) force profile plotted over the relative distance of the associated rotor bar to the bar force sensor centre. Further, the positions where the leading edge first engages with the sensor and where the trailing edge of the rotor bar leaves the sensor is marked with "start" and "end" respectively. This data will be used to study the mechanics of the refining process at the point of interaction between the bars and the pulp.

Preliminary results show that the occurrence of the normal force peaks, relative to the centre of the bar passing event, varies with the plate gap and with pulp furnish as illustrated in Figure 3 and Figure 4 respectively.

Figure 1: Encoder set up at the AIKIWA 16" test refiner at the UBC Pulp and Paper Centre.

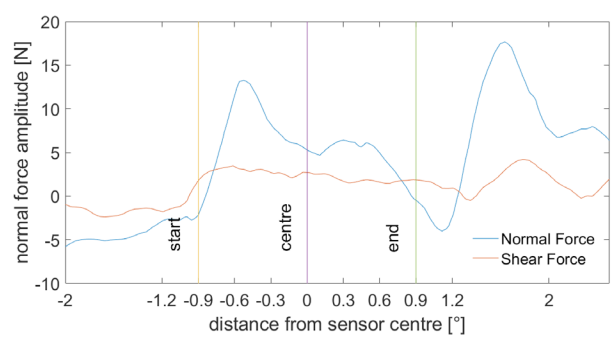

Figure 2: Normal and shear force signal for bar passing event plotted over the angular position of the rotor bar relative to the sensor centre.

PROJECT 2.2

Further investigation of the normal force peaks for the 0.2 mm plate gap show that all peaks produced by the passage of a given rotor bar (named B#1 to B#47 for the 1st to the 47th bar) over the sensor are offset from the stator bar centreline, and the sensor centreline, by similar distances, as shown in Figure 5. This variation in the offsets of peak forces among the rotor bars is the subject of ongoing investigation.

A new set of trials is planned for April 2019 to establish reproducibility of the trials.

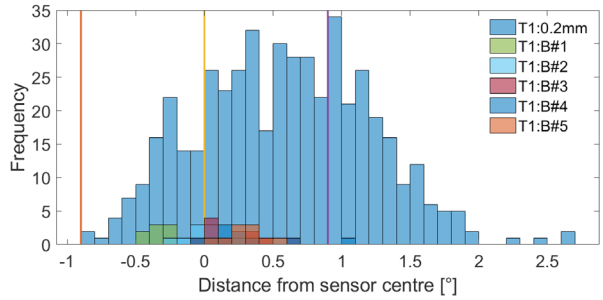

Figure 5: Comparison between different rotor bars. Frequency plot for the occurrence of the normal force peak relative to the rotor bar position. This figure looks at the first 5 bars of the refiner rotor namely B#1- B#5.

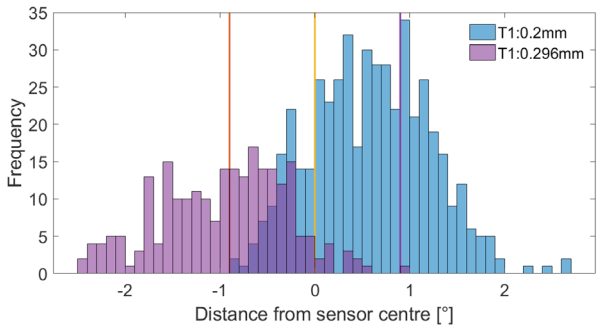

Figure 3: Comparison between different plate gaps. Frequency plot for the occurrence of the normal force peak relative to the rotor bar position. T1 was conducted with BCTMP low freeness pulp. blue: plate gap at 0.2mm, purple: plate gap at 0.296 mm.

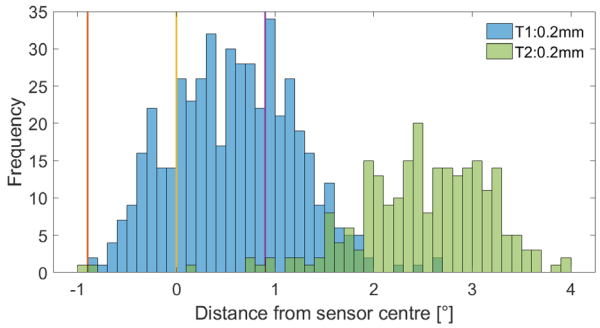

Figure 4: Comparison between different pulp furnishes. Frequency plot for the occurrence of the normal force peak relative to the rotor bar position. T1 was conducted with BCTMP low freeness. T2 was conducted with Hardwood Millar Western pulp.

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Harirforoush, R., P. Wild, and J.A. Olson. 2016. "The relation between net power, gap, and forces on bars in low consistency refining." *Nordic Pulp and Paper Research Journal*. 31, (1):71–78.

BRYAN BOHN

2.3 - ADVANCED PUMP PERFORMANCE MONITORING SYSTEM

Centrifugal pumps are employed in fluid-moving operations across nearly all industries. This project aims to develop an improved method for quantifying the performance of centrifugal pumps — specifically, a method that addresses practical barriers of industrial application, including implementation costs, required technical manpower, and scale of pumping processes. The goal is to develop a sensor system and analysis tool that capture a centrifugal pump's efficiency, state of impeller wear, and adverse flow conditions. This project initially investigated an online magnetic sensor to capture mechanical wear (Khoie et al. 2015). Since the last newsletter update, we have developed a new prototype system that uses pressure, temperature, and vibration sensors to extract pump performance data.

Technical Approach

A common low-cost approach to monitoring centrifugal pumps is to observe their vibrational characteristics using accelerometers (Al Tobi et al., 2017). Vibration measurement is particularly suited for detecting mechanical faults within the pump and driving motor (Abdulaziz and Kotb, 2017). In a typical application, the accelerometer signal is observed in the frequency spectrum, which allows for the extraction of performance features by correlating the resulting spectra to known pump behaviours. Vibration monitoring alone is not sufficient for determining operating efficiency. This suggests that additional sensing is needed to measure efficiency performance reliably.

Conventional thermal efficiency measurement necessitates the use of two pressure sensors and a flow sensor to determine the output fluid power from a centrifugal pump, and a wattmeter to determine the electrical power into the driving motor (BS EN ISO 5198, 1999). While suitable for laboratory experiments and fixed pump installations, this measurement method is impractical for wide-scale monitoring of industrial pumps. This is predominantly because attaining reliable flow-rate measurements on multiple pumps—that are likely moving different media under different operating conditions—is often only achievable using several flow sensors. Such an approach raises costs and may ultimately require permanently installed flow sensors on most pumps. The implementation costs of such a monitoring approach would be impractical for pump users with extensive applications.

Whillier (1968) addressed the issue when he conceived a thermodynamic method of efficiency determination. His approach eliminates the need for a flow sensor, and instead determines the efficiency by measuring the energy lost into the working fluid as heat (Cattaert 2007).

$$\eta_{thermo} = \frac{1}{1+\rho C_p(\Delta T-\Delta T_i)/(\Delta \mathrm{P})}$$

Note: p is the fluid density, Cp is the specific heat of the working fluid ΔT, and ΔTi are the temperature changes across the actual pump and an idealized isentropic pump respectively, and ΔP is the pressure change between the suction and discharge ports.

Using this method, an efficiency determination can be made using simpler, more affordable instrumentation; two pressure sensors and two temperature sensors.

This proposed monitoring system combines vibration measurement with Whillier's Thermodynamic Efficiency Method (TEM) into a single low-cost sensor system. Whillier's unique approach captures a variety of pump performance characteristics, yet is sufficiently affordable and versatile for wide-scale implementation in industrial pumping processes.

Prototype System

The prototype system comprises five sensors: pressure sensors at the pump's intake and discharge, temperature sensors at the intake and discharge, and an accelerometer located on the volute (Figure 1).

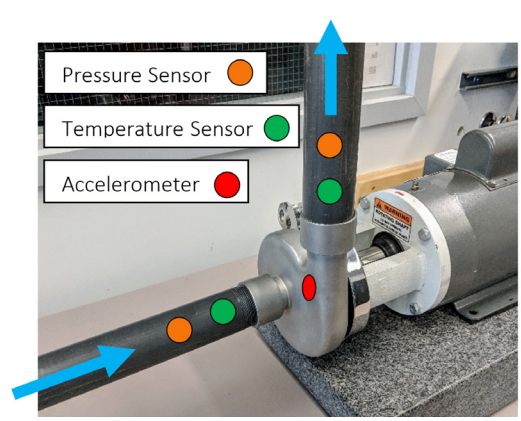


Figure 1: A bench-top centrifugal pump showing the relative sensor orientation.

PROJECT 2.3

By combining the TEM and vibration measurement, it is anticipated that the monitoring system will be able to identify thermal efficiency, the state of wear on the centrifugal pump impeller, cavitation, vortexing, and flow recirculation. It should be noted that these conditions are interdependent and manifest in multiple ways, some of which may be identifiable only through correlation between the efficiency and vibration measurements.

Preliminary Results

To validate the feasibility of the instrumentation approach, preliminary testing was performed on the pilot plant pump loop at UBC's Paper and Pulp Centre. The objective was to demonstrate vibration, pressure, and temperature measurement, and then use the resulting data to extract fundamental performance information.

A single-axis piezoelectric accelerometer is used for the vibration measurement (Measurement Specialties model ACH-01-03/10). Data are collected at 48 kHz for a duration of one second. A Fast Fourier Transform (FFT) translates the time-domain signal to frequency domain. The resulting vibration spectra are shown in Figure 2.

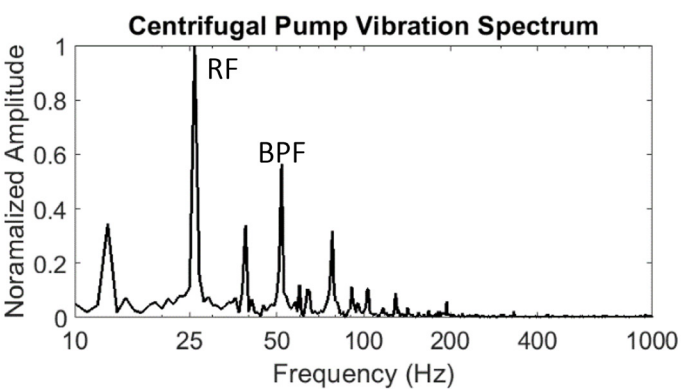
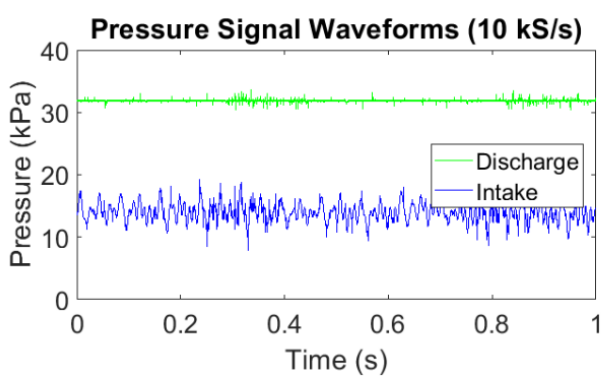


Figure 2: Vibration measurement of a centrifugal pump showing the rotational frequency (RF), blade-passing frequency (BPF), and other vibration features.



The measurement yields the pump's rotational frequency (RF), blade-passing frequency (BPF), and the presence of lower-magnitude peaks in multiples of the RF—a warning sign of potential mechanical issues.

The pressure measurements are performed using two Omegadyne PX-459 capacitive pressure transducers. Data are collected at 10 kHz for a duration of one second. The resulting signal is shown in Figure 3. It is noted that the pressure difference across the intake and discharge is only 18 kPa (2.6 psi). In this experiment, the operating fluid cycles within a closed loop. Thus, the pump was working against a minimal static head.

It is readily observed that the intake pressure signal has a dynamic character. This signal is analyzed in the frequency domain using FFT. The result is then overlaid with the accelerometer data from Figure 2 and compared in Figure 4.

Interestingly, the intake pressure sensor behaves as a hydrophone, detecting both the RF and BPF. In addition, the comparison also shows that the accelerometer and intake pressure sensor detect different components of the pump vibration, as is seen in the 13 Hz peak (accelerometer) and 104 Hz peak (pressure sensor) in Figure 4. This implies that there may be a benefit to using pressure sensors for dual purposes—measuring pressure and sensing fluid vibrations. This is a novel approach to performance monitoring of centrifugal pumps and warrants further investigation.

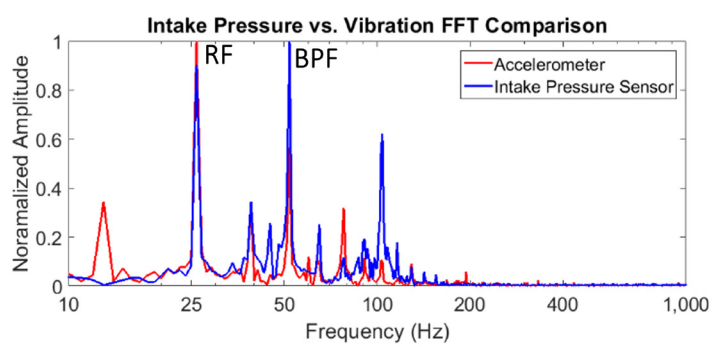


Figure 4: Comparison of the frequency content of the accelerometer signal (red) and the intake pressure sensor signal (blue).

Figure 3 (left): Pressure measurements of a centrifugal pump at the intake (blue) and discharge (green).

PROJECT 2.3

Under the low-pressure, low-power operating conditions of the preliminary testing, a reliable measurement of the fluid temperature change from pump intake to discharge could not be achieved. After additional literature review, it was determined that the TEM requires sufficient pressure head to generate a measurable temperature difference. It was also revealed that the practical operating bounds of the TEM are not well described in literature, and require further characterization.

Future Research

The preliminary testing demonstrated promising results and illuminated two new research paths; the feasibility of using pressure sensors for both pressure and fluid vibration monitoring, and the need to characterize the limitations of the TEM. In addition to exploring these topics and refining the prototype system, the next stages of the research will comprise a study of signal processing and data analysis methods for extracting more complex pump performance features from the sensor data.

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Whillier, A. 1968 "Pump Efficiency Determination in Chemical Plant from Temperature Measurements." *I&EC Process Design and Development*. 7(2):194–96.

ERMP PERSONNEL UPDATES

Sona Kazemi joined our ERMP program in the role of Program Manager early November 2018, and worked with Dr. Mark Martinez to complete and submit a proposal to NSERC for Phase 3 of the program. Sona accepted a new role in April with UBC's Vice President Research and Innovation Office as Innovation Development Officer. Meaghan Miller returned as Program Manager in March 2019.

Jennifer Mak has been working at BCIT as a coop student with Professor Rodger Beatson since January 2019, and will continue in that role until August 2019.

Since the last newsletter in April 2018, several students have graduated from the ERMP program. We congratulate Jorge Rubiano (PhD, UBC), Miguel Villalba (MASc, UBC), Taraneh Kordi (MASc, UofT) and Bahar Soltanmohammadi (MASc, UofT). Please see page 19 for their thesis details. PhD student Hui Tian is working on her thesis and plans to graduate summer 2019.

LAB AND TRIAL UPDATES

Research technician Reanna Seifert has been managing and running several trials with the LC refiner at UBC–PPC, including work with Meadow Lake Pulp, Canfor Pulp Innovation, and with visiting student Hui Cai who worked on old corrugated cardboard and ring crush testing.

As previously reported, we successfully obtained NSERC Research Tools and Instrumentation (RTI) funding to purchase a Dynamic Sheet Former (DSF), dryer and press. All of the equipment arrived at PPC and was installed in the papermaking lab this April. The DSF's key feature is the four separate stock chambers that enable several different pulp types to be used to create a single multilayered sheet of paper. Reanna has been trained by the manufacturer in its basic operation will be working on fine tuning its many settings, functions and sample preparation capabilities. We look forward to putting this new equipment to good use in future projects.

Controls firm Automation–X has upgraded the LC refiner control system. The new system enables faster and more accurate refining trials by introducing greater computer control with less reliance on manual input. The implementation of the Automation–X system has also eliminated a persistent equipment issue with that caused delays in past trials. Automation-X will also provide training on the new control system.

Efforts are underway in UBC-PPC to relocate and upgrade existing lab equipment as well as to prepare for upcoming renovations to the building and lab spaces as part of the BioProducts Institute initiatives. As part of some initial changes, the MR8 pressure screen was transferred to the high-head lab where the LC refiner is housed, and these systems will be integrated into one setup in the future. Along with the DSF, the LC refiner and MR8 setup will also be used for research in the next phase of the ERMP program.

Partner Meetings and Visits

We held a successful Steering Committee meeting at UBC on October 2, 2018 which included progress updates on remaining ERMP projects, as well as a round table discussion on the future of the research consortium. Chitra Arcot, Communications Coordinator provided a meeting report to partners in December 2018. Our next Steering Committee meeting will be held at the PACWest conference in Whistler, BC on June 5, 2019.

Miguel Villalba visited Catalyst Paper in Port Alberni, BC on October 18, 2018. His visit was a great opportunity to appreciate the industrial scale of the TMP process that he had studied in his research work. His visit included a tour of the TMP line and paper machine plant, and a close look at the Impressafiners. Miguel learned about the typical operating conditions of screw feeders and refiners; screw feeders are capable of compressing and feeding large amounts of wood-chips into the refiners. Miguel also shared experimental results of his work on Project 1.1 with the mill manager.

Dynamic sheet former purchased with NSERC RTI grant.

PUBLICATIONS

Journal Articles

Harirforoush R., J.A. Olson, and P. Wild. 2018. "Bar force measurement in low consistency refining: the effect of plate pattern". *Nordic Pulp and Paper Research Journal*. 33(2):210–19.

Rubiano Berna J.E., M. Martinez, and J.A. Olson (2019): "Power–gap relationships in low consistency refining." *Nordic Pulp and Paper Research Journal.* 34(1):36–45.

Rubiano Berna J.E., C. Sandberg, M. Martinez, and J.A. Olson. 2019. "Theoretical analysis of LC-refining – pressure screening systems in TMP". *Nordic Pulp and Paper Research Journal*. 34(1):46–58.

Tian H., Q. Lu, R.B. Gopaluni, V.M. Zavala, and J.A. Olson. 2019. "An economic model predictive control framework for mechanical pulping processes." *Journal of Control Engineering Practice.* 85:100–09.

Conference Papers and Presentations

Aigner M. and P. Wild, "Normal and shear force characteristics in low consistency refining with respect to rotor position," Paper Week Canada Conference, Montreal, QC, February 4-7, 2019.

Rubiano Berna J. E., C. Sandberg, M. Martinez, J.A. Olson, "Theoretical study of systems composed of low consistency refining and pressure screening," 31st International Mechanical Pulping Conference, Trondheim, Norway, May 27-30, 2018.

Yuan Z., J. Dimayacyac, and R. Beatson, "Effect of chlorine dioxide treatment on the properties of thermomechanical pulp," 31st International Mechanical Pulping Conference, Trondheim, Norway, May 27-30, 2018.

Yuan Z., J. Dimayacyac, and R. Beatson, "Reducing energy consumption in thermomechanical pulp production using chlorine dioxide," AIChE Annual Meeting, Pittsburgh, Pennsylvania, USA, October 25 -November 2, 2018.*
*This paper was also presented at the AIChE Pacific North West Student Regional Conference in Bozeman, Montana, April 13-14, 2018, and awarded the second prize.

Internal Report

Miller M. et al. 2018. "Effect of LC Refining Conditions on Reject Aspen Pulp." Internal Report on Andritz 2017 Trials.

Theses

Jorge Enrique Rubiano Berna. "On Low Consistency Refining of Mechanical Pulps", PhD Thesis, University of British Columbia, 2018.

Miguel Esteban Villalba Chehab. "Characterization of Screw Feeder Compression and its Effect on Wood Chip Cellulose Accessibility", MASc Thesis, University of British Columbia, 2018.

Taraneh Kordi. "Effect of Low Consistency Refining and Fractionation on Folding Boxboards and Discrete Element Modelling of Plybond Strength", MASc Thesis, University of Toronto, 2018.

Bahar Soltanmohammadi. "Fluorine-Free Omniphobic Flexible Packaging Papers Containing Low Consistency Refined Mechanical and Chemical Pulp Blends", MASc Thesis, University of Toronto, 2018.

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