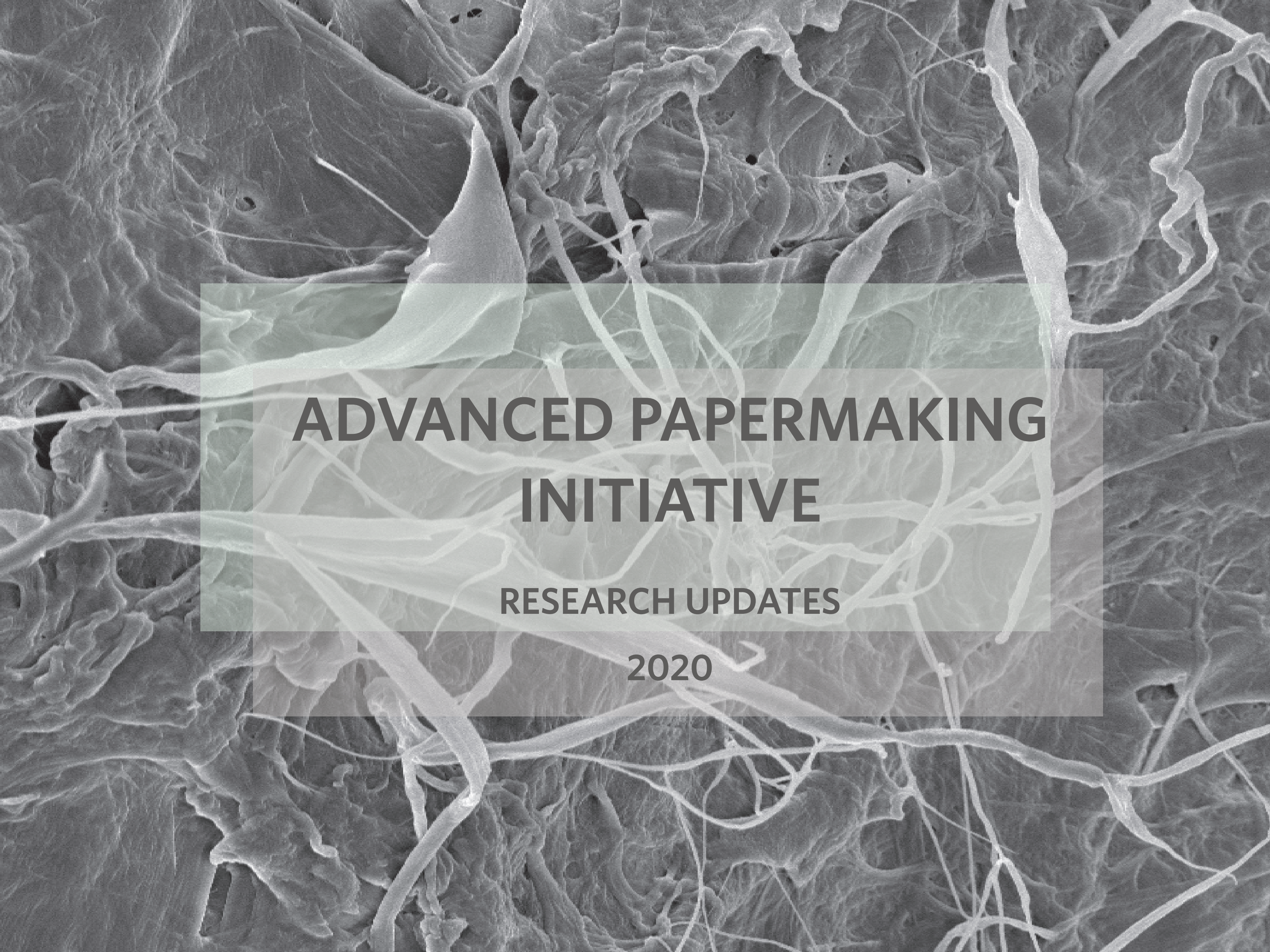

ADVANCED PAPERMAKING INITIATIVE

RESEARCH UPDATES

2020

THE UNIVERSITY OF BRITISH COLUMBIA

WELCOME MESSAGE

Dear readers,

This Advanced Papermaking Initiative (API) Annual report provides an overview of the research scholars supported by the API Retention Research project. In this report, we are pleased to introduce you to the research work of Dr. Dana Grecov, Dr. Ahmad Mohammadpanah, Dr. Minkyun Noh, Dr. Srikantha Phani, and Dr. Mauricio Ponga, all members of the Mechanical Engineering department at the University of British Columbia. All researchers introduced their current research interests in the most recent Steering Committee meeting hold online in November 2020, receiving valuable feedback from the industry. Please see the following pages for a more profound review of their profiles, current research goals, and progress.

Since our last annual report, multiple developments have occurred in the faculty. I am pleased to announce the start of the third phase of the Energy Reduction in Mechanical Pulping research program. This new phase includes an increased research scope, organized in three research programs and eight projects in total, reflecting the need to expand mechanical pulping markets.

In other news, it is a very exciting time for the BioProducts Institute (BPI) at the university, which has recently become the newest Global Research Excellence (GREx) Institute. This approval opens up new possibilities to support UBC as one of the leaders in bioproducts research and innovation, helping develop partnerships and attract investments to continue making essential contributions to Canada's global development in green products and sustainability.

My thanks to all faculty members, Steering committee members, staff, students, and researchers for your continued support in making our community more vibrant even during these challenging times.

Sincerely,

Mark Martinez

Mark Martinez, Ph.D., P. Eng.,
Professor of Chemical and Biological Engineering, UBC
Principal Investigator, ERMP Research Program
Director of Advanced Papermaking Initiative, API

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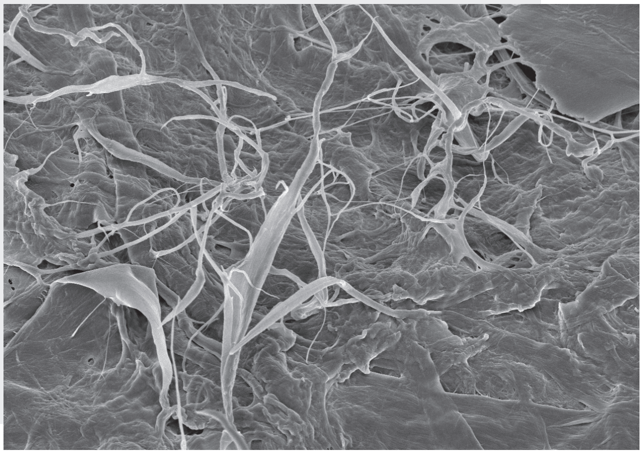


ON THE COVER

Scanning Electron Microcope image of the surface of a handsheet made with highly LC refined TMP. Image at 30° to the plane with a magnification of 2.50k using HitachiS4700 FE-SEM at the UBC BioImaging Facility.
Photo credit: Daniela Vargas Figueroa

API SCHOLARS

In the next pages, we invite you to learn more about our API Research Scholars. We are pleased to introduce you to the research work of Dr. Dana Grecov, Dr. Ahmad Mohammadpanah, Dr. Minkyun Noh, Dr. Srikantha Phani, and Dr. Mauricio Ponga, all members of the Mechanical Engineering department at the University of British Columbia, UBC.

Dana Grecov, PhD

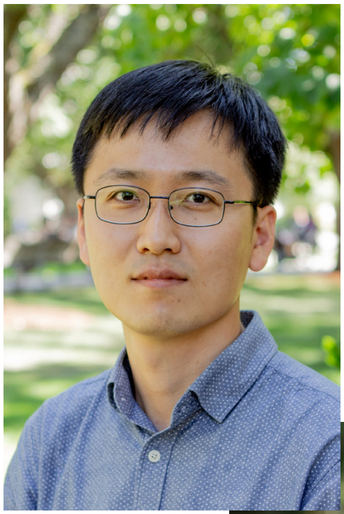
Dana Grecov is an Associate Professor at the Department of Mechanical Engineering, UBC. Dana received her BEng degree in Mechanical Engineering from University Politehnica in Bucharest and her PhD in Fluid Mechanics from Institut National Polytechnique de Grenoble. After a postdoctoral research fellow position at McGill University, she joined the University of British Columbia in 2005.

Her expertise is in biofluid mechanics, non-Newtonian fluid mechanics, rheology, tribology and mathematical modeling. She has 25 years of experience in complex fluids research, constitutive modeling development, and numerical simulations. She received the CFI (Canada Foundation for Innovation) Leaders Opportunity Award in 2007, a Peter Wall Early Career Scholar Award in 2007, the NSERC (Natural Sci. & Eng. Res. Council) Discovery Accelerator Award in 2016, the Wall Scholars Research Award in 2016. She is a fellow of Engineers Canada from 2019 .

A. Srikantha Phani, PhD

Srikanth is an Associate Professor at the Department of Mechanical Engineering, UBC. He received PhD from Cambridge University in Dynamics and Applied Mechanics group under the supervision of Prof. Woodhouse and there he pursued postdoctoral work with Prof. Fleck in Cambridge Center for Micromechanics. His principal research interests include, Dynamics and Vibrations, Nanomechanics of advanced materials, and their applications in engineering and cardiovascular medicine. At UBC, he held a Tier 2 Canada Research chair, and received Killam Teaching prize. An ongoing research activity of particular relevance to API is his work on mechanics of tissue paper making in collaboration with industrial partners in North America.

API SCHOLARS



Minkyun Noh, PhD

Minkyun Noh is an Assistant Professor at the Department of Mechanical Engineering, UBC, Vancouver, BC. He received the B.S. degree in mechanical and aerospace engineering from Seoul National University, Seoul, South Korea, in 2012, and the S.M. and the Ph.D. degrees in mechanical engineering from the Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, in 2014 and 2018, respectively. Prior to joining UBC, he was a Postdoctoral Associate with the Laser Interferometer Gravitational-Wave Observatory (LIGO) laboratory at MIT for a year. His research interest includes the design and control of precision mechatronic systems, with applications to electric machines and drives, biomedical devices, scientific instruments, and manufacturing systems.

Ahmad Mohammadpanah, PhD

Dr. Ahmad Mohammadpanah is currently a lecturer at the department of Mechanical Engineering at UBC. His expertise is in Solid Mechanics, Dynamics and Vibrations, Applications of AI in Manufacturing and Design for Additive Manufacturing. Prior to joining UBC, he worked as a scientist at FPInnovations, department of lumber manufacturing, where he invented and developed a unique temperature sensor for fast moving surface, designed the new generation of guided circular saws in wood industry, and developed charts and best practices in smart lumber manufacturing. His research currently involves developing an AI system for mechanical pulp refiners, using ultrahigh frequency acoustic emission sensors and machine learning.

Mauricio Ponga, PhD

Dr. Mauricio Ponga is an Assistant Professor in Mechanical Engineering at UBC and joined as a faculty member in 2016. Ponga is an expert in computational mechanics, modelling and simulation, with a specific focus on multiscale and multiphysics phenomena in materials at the nanoscale. Ponga's research group develops novel modelling techniques to analyze coupled problems in nanoscale systems. These techniques include large-scale abinitio methodologies, coarse-grained molecular dynamics, coupling phonons and electrons in molecular dynamics simulations, mechanics of polymer brushes, etc. These techniques extend the realm of atomistic simulations and represent the state-of-the-art modelling tools for materials at the nanoscale. Ponga has been awarded several allocations in HPC facilities, including the prestigious and competitive U.S. Department of Energy ALCC allocation with more than 20 million CPU hours to the use of large-scale ab-initio simulations, and about 3 million CPU hours from Compute Canada.

A. SRIKANTHA PHANI

PROJECT 1: MICRO-ARCHITECTED FIBROUS NETWORKS

Background: Paper towels, introduced in North America in the 1920s, are replacing textile derived products world-wide as low cost alternatives [1, 2]. They are environmentally sustainable, easily degradable and recyclable products. Low density (< 300 kg/m3) and basis weight or grammage (< 50 g/m2), low strength and stiffness, high tensile stretch, and high bulk compared to office grade printing paper are some of the features of these products. However, unlike textile products, low density paper products have limited wet strength. Despite the fact that paper products have been utilized for many decades and produced using proprietary technologies, the science of desirable paper to towel making is not definitive due to the complexity of the material and manufacturing processes involved.

From the perspective of mechanics, formidable challenges to scientific modelling and understanding arise from the lowdensity of the complex poroelastic network structure. A fibrous network, particularly at very low densities, can undergo significant deformation with little resistance before force transmission paths are fully established to give stiffness. This situation is not too dissimilar to the behaviour of a fibrous biological tissue [3], such as a human ear; it takes finite extension to go past the initial soft response so that collagen fibers are recruited in resisting the load. A network, with an engineered three dimensional architecture, can exhibit topology governed stiffness and toughness– a property widely exploited in the so called “meta"materials [4–6].

Fibers and their bonding properties become significant with increasing deformation and may eventually dominate the strength of the network. The structure can be tailored through several processes, as shown in Fig.1. The entire tensile response of a typical low density paper and the change in structure are shown in Fig.2. Non-affine deformation effects are evident. Thus both furnish and the network architecture are important, and for any given furnish beneficial properties can be engineered through architecting the fiber network, specifically through the layering hierarchy emanating from forming and pressing as well as the overall network topology.

Objectives: Several theories for paper strength [7–11] rely on Cox’s shear lag analysis [7]. The advantage of such theories lies in the constitutive modeling of paper. In a continuum mechanics setting [12], such a constitutive description has enormous explanatory power and offers predictive capabilities for design. However, in the presence of percolation [13–15] effects coupled with non-affine deformations, it is unclear [16] if shear lag framework holds at all for low density networks. This forms the first objective for the proposed PhD student’s work. The second objective is concerned with the influence of micro-architecture of the fibrous network, created through various processes including forming, pressing, creping, embossing. There is a growing body of knowledge concerned with the so called “metamaterials" wherein architecting (fibers in our case) of the topology is the governing design principle to access material property space not reachable by naturally occurring materials. Some examples of this class of hybrid materials [17] are lattice materials and cellular solids [18].

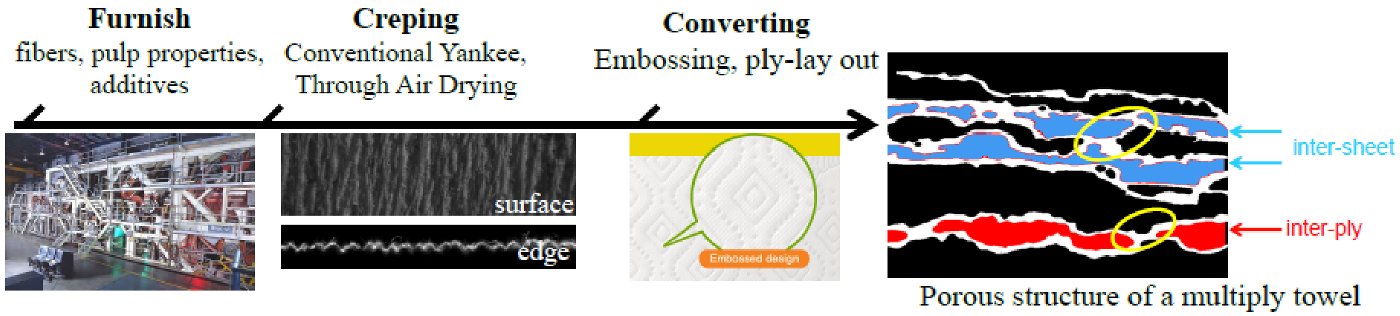


Figure 1: Towel making processes and the resulting poroelastic structure. Conventional- Wet-Pressing (CWP) and more modern Through-Air-Drying (TAD) processes are used before performing creping on a Yankee to produce the individual plies of a towel, followed by converting operations such as embossing and adhesive joining to form multiple plies. The resulting inter and intra-ply pore sizes and bending stiffness of each ply dictate the elastocapillary length scale, absorbency and strength properties. Acknowledgement: FPI.

They are classified as bending or stretching dominated based on the network topology. A stretching dominated topology is stiff whereas a bending dominated topology is compliant, for a given density. Some topologies switch between these two regimes due to imperfections or network re-arrangement [19]. Ideas from this field can be extended to paper making as well. The following objectives are identified for a potential PhD project over four years:

1. Does Cox's shear lag theory, on which many theories for paper strength at higher grammages are based, hold for low grammage networks with an out-of-plane structure? What is the minimum density required for the validity of shear lag based homogenization?

2. What is the role of network topology and the properties of the network fibers (furnish) on macroscopic strength and stiffness?

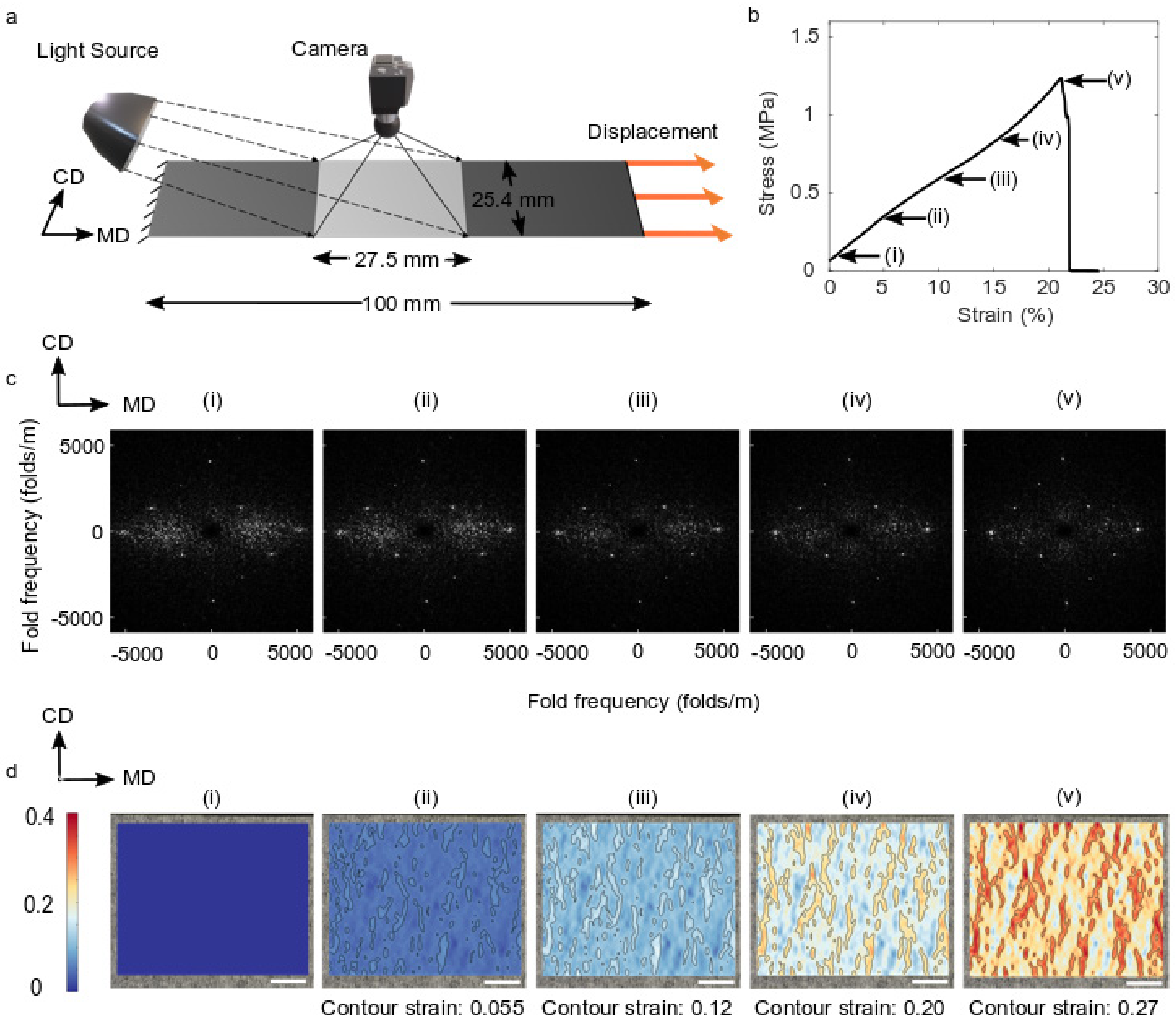


Figure 2: Structural evolution of creped tissue with uniaxial tensile load along Machine Direction. (a) Schematic of the tensile test with an imaging setup. (b) Typical stress-strain response of a tissue paper along Machine Direction with strains indicated at which images were taken. (c) Evolution of the tissue surface topography in frequency domain. (d) Evolution of the 2D Green Lagrangian principal strain field of tissue surface. Scale bars, 5 mm. Note the residual structure even at failure, presumably originating from the forming process.

A. SRIKANTHA PHANI

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DANA GRECOV

PROJECT 2. CELLULOSE NANOCRYSTALS - BASED NOVEL LUBRICANTS

Summary: The development of a new generation of lubricants is of paramount technological and economic relevance since it is estimated that one-third of the world's energy resources in present use are needed to overcome friction in one form or another. Cellulose Nanocrystal (CNC) suspensions and gels are appropriate candidates to be used as lubricants to lower the friction coefficients, wear rates, and contact temperature of sliding surfaces due to ordered layers near solid boundaries and high load-carrying capacity . The main objective of this research work is the development of a new generation of green CNC-based nano-lubricants, with ultra-low friction and reduced wear. The high performance lubricants could be used for a large number of industrial and biomedical applications.

Background: Friction and wear are the major causes of material wastage and loss of mechanical performance. The development of a new generation of lubricants is of paramount technological and economic relevance since it is estimated that one-third of the world's energy resources in present use are needed to overcome friction in one form or another. Hence, any reduction in friction and wear can result in considerable energy savings.

A good lubricant must have a low viscosity for a low friction coefficient and must produce a large lift-force to prevent contact of the surfaces and wear. In a normal liquid, these two criteria are difficult to achieve since the large lift force requires a large viscosity.

To reduce the friction, mineral or synthetic oils are used to lubricate most of the mechanical devices. The base oils usually contain toxic substances such as polycyclic aromatic hydrocarbons or additives like cadmium, zinc, phosphorus, lead, and chlorine. In some applications, water is used as a lubricant. It is environmentally friendly, inexpensive, readily available, and non-flammable and has high thermal conductivity. However, due to its low viscosity, corrosive properties, low boiling point and high freezing point, it is unacceptable for most tribological applications. To enhance the properties of lubricants a chemical component or blend could be added to improve the fluid performance. With the development of nano-lubricating technology and the deepening understanding of the particularity of functional nano-materials, nanoparticles used as additives show unique physical and chemical properties and have a broad application prospect in lubrication.

One of the nanoparticles, which is soluble in water and with additional treatments (surface modification) it can be soluble in oil, environmental friendly, is cellulose nanocrystal (CNC). CNCs are obtained from naturally occurring cellulose fibers and are renewable in nature [1]. CNC possesses many advantages, such as nanoscale dimension, high modulus of elasticity, high surface area, unique optical properties, renewable, biodegradable, non-toxic [2]. Another salient feature of CNC is the formation of liquid crystalline networks. Due to the rod-like shape, size and surface charge of particles, CNC aqueous suspension exhibits liquid crystalline state in its phase diagram [3].

Liquid crystals (LCs) are anisotropic materials with properties of both conventional liquid and solid crystals. The ability of LCs to form ordered boundary layers with good load-carrying capacity, and to lower the friction coefficients, wear rates and contact temperatures of sliding surfaces has been demonstrated [4]. Liquid crystalline materials are known to construct an ordered molecular layer close to any solid boundaries, which has been known to improve tribological performance. Moreover, the self-aligning pattern of liquid crystalline molecules was detected close to the solid surfaces using imaging techniques [5].

So far, the mechanism of the ultralow friction coefficients is not fully understood, but several studies indicate that external pressure and shear stress can induce a molecular ordering of the LC molecules [6]. A theoretical explanation of the dependence of the friction force on the molecular orientation has also been proposed [6], indicating that an increase in the shear velocity results in an alignment of the LC molecules with the flow, and consequently in a reduction of the friction force.

CNC suspensions in their liquid crystalline stage, are appropriate candidates to be used as lubricants to lower the friction coefficients, wear rates, and contact temperature of sliding surfaces due to ordered layers near solid boundaries and high load-carrying capacity [7]. They perform as a sustainable and environmentally friendly material which makes them worthwhile candidates as green lubricants. To enhance the performance of CNC suspensions as lubricants, one must possess a good knowledge of their flowing properties.

DANA GRECOV

Objectives: The main objective of this research is the development of a new generation of green CNC-based nano-lubricants, with ultra-low friction and reduced wear. To improve lubrication efficiency and therefore reduce energy consumption we aim to conduct experiments and develop a model for the lubrication mechanism in CNC suspensions. The development of a fundamental understanding of the lubrication mechanism can lead to a new generation of sustainable, high performance lubricants for different industrial and biomedical applications.

The specific objectives of this research work are:

1) Rheo-structural characterization of different CNC suspensions/gels (water, polyalphaolefin synthetic oil, canola oil based lubricant) .

2) Assessment of the performance of different CNC suspensions/gels (water, polyalphaolefin synthetic oil, canola oil) as lubricants.

3) Establish of a correlation between rheology and tribology of CNC suspensions/gels and development of a model for the lubrication mechanism when using CNC suspensions/gels.

Results and Discussion:

The project started in June 2020. The team worked on the first and second objectives performing the rheological and tribological characterization of water-based CNC suspensions using never dried CNC as novel lubricants.

CNC samples at different concentrations were prepared by diluting never dried 6 wt% batches with deionized water. A pin on disk tribometer was used to determine the coefficient of friction at different concentrations. Using a rotational rheometer, steady state viscometry and oscillatory frequency sweep rheological measurements were performed on CNC suspensions at different concentrations.

Tribological Measurements

Figure 1 depicts the steady state coefficient of friction for deionized water and different CNC concentrations. As it can be observed, the coefficient of friction not only changes with the sample concentration but also with the applied normal loads. The highest coefficient of friction was found for water. Dispersing CNC particles into deionized water, the coefficient of friction has dropped significantly.

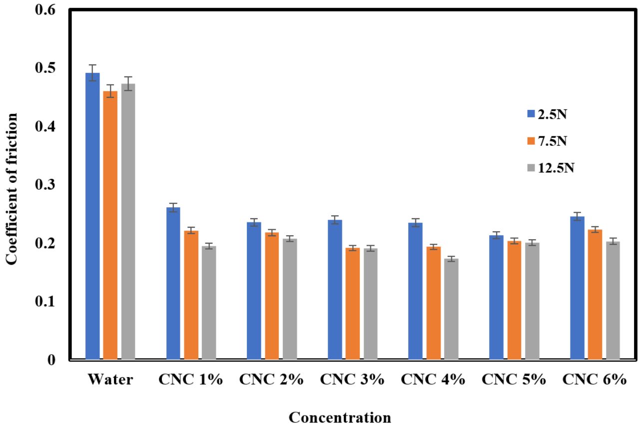

Figure 1 Steady state coefficient of friction values under different loads and concentrations.

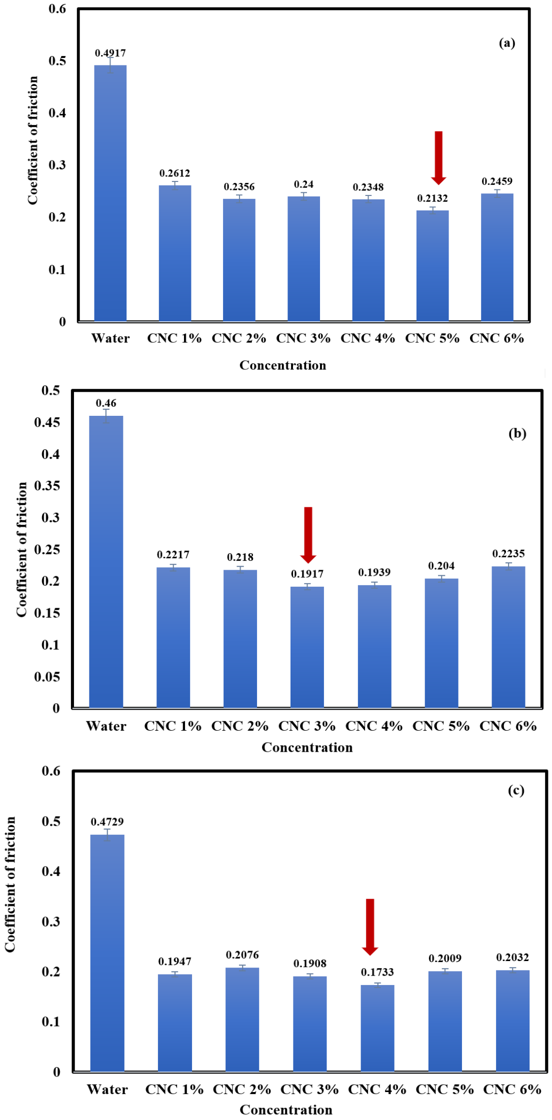

Figure 2 a-c Steady state coefficient of friction under different loads of (a) 2.5 N, (b)7.5 N and (c) 12.5 N. The red arrows indicate the concentration where the minimum coefficient of friction occurs.

Figures 2 a-c show the steady state coefficient of friction under different loads. As can be observed, the lowest coefficient of friction (ie. determines the optimum tribological measurements condition) is concentration and force dependent. For the case of 2.5, 7.5 and 12.5 N, the minimum of coefficient of friction occurs at 5, 3 and 4 wt% respectively.

Steady State Viscometry

Figure 3 illustrates the results of steady state viscometry on CNC samples at different concentrations. The concentration of suspension plays an important role in determining its rheology. At very low concentrations (1 and 2 wt%), CNC suspensions exhibit a constant viscosity at low shear rates, followed by a shear-thinning behavior at intermediate shear rates and another plateau at very high shear rates. This rheological behavior is typical of isotropic materials. In this dilute regime, CNC spindles are randomly oriented within the suspension.

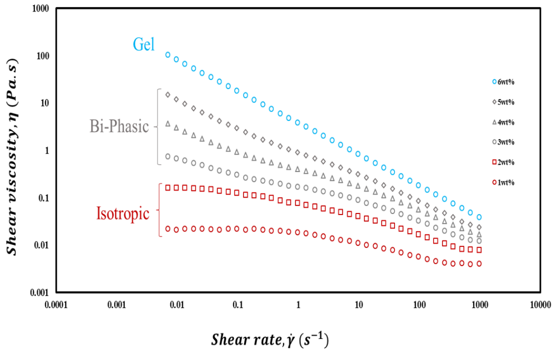

Figure 3 Steady state flow curves of CNC suspensions at different concentrations. The red, grey and blue colors represent isotropic, bi-phasic and gel behavior.

At higher concentrations, the spindles form the initial ordered domains known as tactoids. By increasing the CNC concentration, tactoids join together and form an anisotropic phase, leading to a nematic liquid crystalline alignment. The suspensions then possess two phases: the isotropic and the liquid crystalline. Increasing the concertation may lead to the increase of liquid crystalline phase over the isotropic one. Results of Figure 3 illustrate that under intermediate concentrations (3, 4 and 5wt%), the CNC suspensions present three-region curves typical of bi-phasic or liquid crystalline samples. At very low shear rates, the viscosity drops by increasing shear rate, where chiral nematic domains start to flow. As the applied shear rate increases further, these domains start to breakup, resulting in a plateau Newtonian viscosity. At very high shear rates, there is another shear-thinning behavior, due to the alignment of individual nanorods in flow direction. At even higher concentrations, the sample becomes gel (6 wt%). The formation of chiral nematic domains has been inhibited and the viscosity plot illustrates a pure shear-thinning behavior. The CNC samples possess yielding behavior under these high concentrations.

Frequency Sweep

Figure 4 depicts results of frequency sweep measurements within LVER on CNC samples at different concentrations. For the case of 1-4 wt % samples, G″ (loss modulus) is higher than G′ (elastic modulus) and both viscoelastic moduli increase linearly with the applied frequency. This behavior is typical of viscoelastic liquids. At 5 wt%, G′ and G″ overlap for a wide range of frequencies illustrating the behavior of a liquid crystalline gel. For the case of 6 wt% the viscoelastic moduli are almost frequency independent, illustrating a viscoelastic solid behavior. As observed in Figure 4, by increasing the concentration form 1 to 6 wt%, the difference between G″ and G′ becomes less, an overlap occurs at 5 wt% and under higher concentrations G′ becomes more dominant. Through this transition by increasing concentration, the slope of viscoelastic moduli declines.

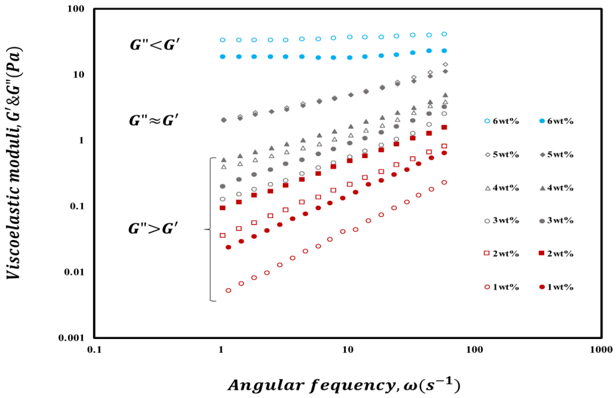

Figure 4 Frequency sweep flow curves of CNC suspensions at different concentrations. The red, grey and blue colors represent isotropic, bi-phasic and viscoelastic solid behavior illustrated in Figure 3. The open and filled symbols represent G′ and G″ viscoelastic moduli respectively.

Based on the results from Figures 2 a-c and Figure 3, one may conclude that the minimum coefficient of friction occurred when the CNC suspensions showed bi-phasic or liquid crystalline behavior (3-5 wt%).

DANA GRECOV

Future Research

The project will continue with the following short term (3 -6 months) work plan:

- Study the effect of sonication and temperature on the rheological and tribological behavior of CNC suspensions
- Construct the Stribeck curves (the variation of the coefficient of friction in different lubrication regimes: boundary, elasto-hydrodynamic and hydrodynamic) for CNC suspensions with 3% wt, 4% wt and 5%wt
- Study of the relationship between tribological and rheological properties.

The long term plan is to perform the rheo-structural characterization and to assess the performance as lubricants of CNC suspensions/gels in polyalphaolefin synthetic oil and canola oil. The final objective of this project is to establish a correlation between rheology and tribology of CNC suspensions/gels and to develop a model for the lubrication mechanism when using CNC suspensions/gels.

Acknowledgements

The CNC samples have been provided by CelluForce which is highly appreciated.

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MINKYUN NOH
AHMAD MOHAMMADPANAH

PROJECT 3. NON-DESTRUCTIVE MONITORING SYSTEM FOR MECHANICAL PULP REFINERS BASED ON ACOUSTIC SIGNAL PROCESSING AND MACHINE LEARNING

Background: There are two main approaches to separating wood fibres: chemical refining and mechanical refining, and the application of each method depends on lignin. Lignin is an amorphous phenolic polymer responsible for holding wood fibres together. Lignin is dissolved during chemical refining. In a chemical refining a chemical process is used to dissolve lignin and separate fibers, but it also dissolves the fibrous material. Mechanical refining involves mechanically breaking the wood fibres apart from one another. In mechanical refining, therefore, the lignin remains. As a result, mechanical pulps have a considerably higher yield of 90-98% compared with 40-50% yield of chemical pulps [1, 2]. There are several types of mechanical refiners including single disc, double disc, twin, and conical refiners.

Currently there is not any monitoring system that informs when to change the blade (plates) in a refiner. The downtime for changing the blades inside a pulp refiner marks one of the most critical machines in a pulp mill as a production bottleneck. Changing the blade with fresh ones is inevitable, but when it comes to the question of the optimum time for changing the blades, the answer is vague. Besides, the clearance between the blades is a critical parameter which affect the quality of fiber. The fibers can be analyzed using FQA (Fiber Quality Analyzer), but it is only practical to conduct this on some occasional samples; and currently there is not any available online monitoring system for a refiner. Most of current refiners do not have a feedback system and the research on using sensors and collecting data from a refiner is limited. B. Prairie, et. al. [3] have conducted research where they used a piezo-ceramic sensor to measure normal and tangential shear forces applied to a bar at one location in the refining zone of a conical refiner. They concluded both the normal and shear force signals demonstrated significant periodicity, synchronous with the speed of rotor rotation. Force magnitudes vary by as much as a factor of 3 over one revolution. But they have not made any clear conclusion how these data could be used as a feedback system for a refiner. Plus, implementing such a force sensor inside a refiner is technically challenging and involves the interruption of production in a pulp mill.

Results: We are conducting research toward a pulp refiner monitoring system that infers the level of blade wear and pulp quality from acoustic signals. The main approach is as follows – we will measure acoustic signals using two types of sensors: microphones to measure waves through air and acoustic emission (AE) sensors to measure waves through the machine body. Based on our previous experience and discussion with the industry, we convinced ourselves that acoustic signals contain rich information to identify issues in a refiner. For example, a refiner sounds different when there are issues, e.g., dull blades and too large/small gaps between blades, which can be detected and recognized by skilled workers. Another benefit of acoustic sensing is on its non-destructive nature; unlike the force transducer used in [3], the acoustic sensors can be instrumented outside the refiner body and therefore minimally interrupt a regular operation of a refiner. We will use wide-bandwidth (4-20,000 Hz) and high-sensitivity (up to 120 dB (sound pressure level)) microphones, and a wide-bandwidth high-sensitivity differential AE sensor (e.g., D9203B from Physical Acoustics). In order to extract meaningful results from an AE sensor, the sampling rate should be sufficiently fast [4], for which we will develop a high-speed data acquisition system based on a field-programmable gate array (FPGA). Such a system will also enable implementation of real-time digital signal conditioning algorithms, such as envelop detection. We will also perform off-line signal processing, such as spectrogram, to capture time-varying spectra of the acoustic signals.

The acoustic data will be labelled based on their corresponding output pulp quality, e.g., good or bad, to form a “training set” to implement supervised learning techniques. We plan to collect the pulp quality data using Fiber Quality Analyzer (FQA) on-site for approximately a week. The result from supervised learning, i.e., classifier, will be used to implement a smart monitoring system that suggests the optimal time for blade changes and predicts the expected fiber quality.

Future Research: Being at the initial phase of the research, we had meetings and e-mail correspondence with engineers at FP Innovations, Prof. Peter Wild and his PhD student at the University of Victoria, and Prof. Mark Martinez at UBC to collect background information, and outlined our short-term goals. For a preliminary test, we will build a bench-level test setup to find a correlation between acoustic emission signal and fiber properties. Then, we will proceed with sensor instrumentation data collection on the pilot pulp-mill at the UBC- PPC.

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PROJECT 4. DYNAMICS OF CAPILLARY RISE IN SINUSOIDAL CORRUGATED CHANNELS

Summary: We have developed an analytical model for the dynamics of capillary rise in sinusoidal corrugated channels with variable separation of the plies as a geometrical extension to Lucas-Washburn's equation of capillary action, and have consequently investigated the effect of corrugation amplitude on the height and the rate of meniscus rise. Validation is made with the known Washburn solutions for a flat channel. The model is suitable for simultaneous structural coupling of the walls to model the deformation of the plies observed during the absorption in paper towel products, where a complicated interplay of ply expansion and elastocapillary coalescence is observed in the experiments.

Background: The need for low cost, high-performance consumer products such as towel and hygiene products, based on sustainable materials, is strong and growing due to an increased sensitivity to the environment, the industrialization of densely populated countries, and the growing global population [1]. New uses of, and markets for paper towel products, including adult incontinence in the aged, are emerging in Canada and worldwide [2]. Paper towel products are a strategic and rapidly growing market worldwide for Canadian industry [2], with $1.7B revenue in 2016 and projected to grow at 1.5% in 2017 with increasing long-term demand. Innovating the next generation of absorbent products requires a fundamental scientific understanding on how novel material compositions (furnishes and additives) and modern processes influence the properties such as enhanced bulk, absorption, and wet-strength properties. Paper towel use after frying cooking highly reduces the amount of fat and results in healthier nutrition [3].

Paper towels are replacing textile-derived products world-wide as low-cost alternatives, and saving water in some developing countries [1]. They are environmentally sustainable, easily degradable, and recyclable products. Low density (< 300 kg/m3) and grammage (< 50 g/m2), low strength and stiffness, high tensile stretch, and high bulk compared to office-grade printing paper are some of the features of these products. The absorption rate (how fast a spill is absorbed) and the absorbency (retained sucked volume of liquid) set the market price [2,4]. Hence, understanding how microscopic features in paper towels affect these properties could provide valuable information in the design of new ultra-absorbent paper towel-related products. In this work, we seek to understand the effect of the corrugation of the paper plies in the capillary rise in paper towels [5–8]. To do so, we develop an analytical model where the fluid flow is controlled by the capillary pressure that appear between plies and at the liquid-air interface. The goal is to compare the height and rate of fluid rise between the flat, tapered, and corrugated channels.

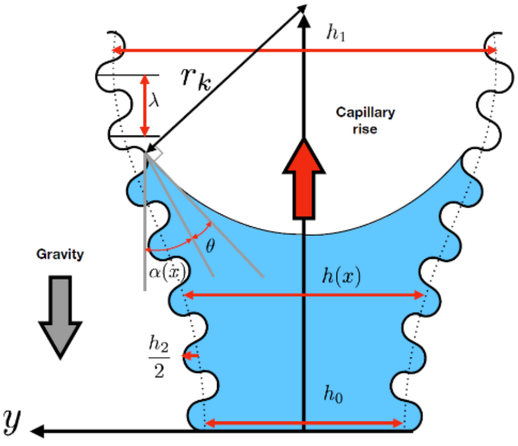

Figure 1. The schematic of the problem considered.

Methodology:

Let us now consider a channel bounded by some impermeable and sinusoidal solid walls as shown in Fig. 1. The sinusoidal profile can be used to model the embossing pattern that is performed on paper towels. We distinguish several quantities of interest in the schematic picture. Particularly, we observe that the separation of the channels is a function of the vertical coordinate which we arbitrarily have selected to coincide with the x-axis. The varying separation between the walls due to the wicking in the paper towel, can be simplified as a prescribed linear tapering of a sinusoidal profile, expressed as:

$$h(x) = h_0 + (h_1 - h_0)\frac{x}{\ell} + h_2 \sin(\frac{\pi x}{\lambda}) \qquad (1)$$

Where h_o and h_1 are the wall separation at the origin and at the free end, respectively. This linear function can later easily be extended to higher-order polynomials when the analysis comes to deformability of the plies. ℓ is the total length of the channel capable of liquid absorption, h_2 is the amplitude of the sinusoidal corrugations used to represent the roughness of the channel, and λ is the periodic length of this sinusoidal profile. Fig. 1 shows a schematic of the problem.

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Using geometrical features of the problem, the Young-Laplace equation ($P_{sc} = \sigma_l(\kappa_1 + \kappa_2)$, with κ_i being the principal curvatures of the surface) leads to an expression for the capillary pressure:

$$P_{sc} = \frac{\sigma_l}{r_k} = \frac{2\sigma_l\left[\cos(\theta) - \sin(\theta)(d_1 + d_2\pi\cos(\frac{\pi x}{\lambda}))\right]}{\left[h_0\left(1 + d_3\xi + d_4\sin(\frac{\pi x}{\lambda})\right)\right]\sqrt{1 + [d_1 + \pi d_2\cos(\frac{\pi x}{\lambda})]^2}}, \quad (2)$$

where. $d_1 = \Delta h/\ell, d_2 = h_2/\lambda, d_3 = \Delta h/h_0, d_4 = h_2/h_0,$ and $\xi = x/\ell$ are dimensionless geometrical features and σ_l is the liquid-air surface tension at the interface. Using the laws of laminar fluid mechanics, an expression is found for the rate of meniscus rise (L):

$$\frac{dL}{dt} = \frac{\Delta P}{12\eta h(L)\int_0^{L(t)}\frac{dx}{h^3(x)}}. \quad (3)$$

Having found the rate in Eq. 3, the interest in evaluation of the meniscus height as a function of time eventually leads to a non-linear integro-differential equation, which is notoriously difficult to solve for $L(t)$. However, it can be shown that $L(t)$ is a one-to-one and thereby invertible function [9]. In case of no gravity, the driving pressure difference $\Delta P(x, L) = P_{sc} - \rho g L$ equates with the capillary pressure (P_{sc}). With recourse to this necessary simplification, the the problem could be reformulated in an inverse way to find the elapsed time as a function of the meniscus height:

$$t(L) = \int_0^L \frac{12\eta}{P_{sc}(x)} h(x) I(x) dx, \quad (4)$$

Where $I(x) = \int_0^x dX/h(X)^3$ is a nested integral function withing the main intregal and X represents its dummy variable. Eq. 4 is evaluated through numerical integration in this work.

Results: Fig. 2 shows the achieved goal of the study, the height of the meniscus as a function of time. The plot says that the corrugations always hinder the fast rise of the liquid in the capillary. In other words, the overall diffusivity of the channel decreases as the amplitude of the corrugations increases. The local maxima and minima of the rate of the rise also occur at the inflection points of the channel profile, where the curvature of the meniscus is extremal (Fig. 3). The results are then compared with CFD simulations for both flat and corrugated channels (Fig 4). The discrepancy between the analytical and CFD approach is owing to negligence of inertia in the analytical approach. The effect of inertia is much more significant at the beginning stages of the rise. However, it can be shown that the effect of inertia becomes less important after some time and the rate of the rise can be predicted accurately [9].

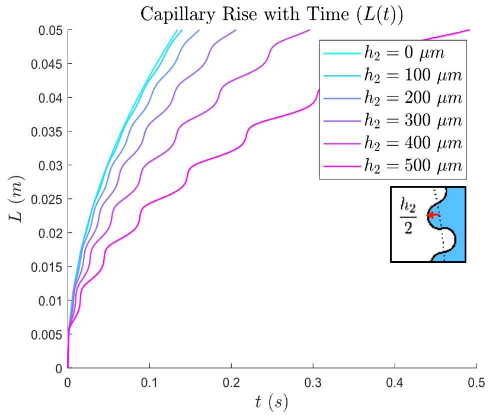

Figure 2. The height of the meniscus as a function of time. The corrugation amplitude (h_2) is the varying parameter in the curves.

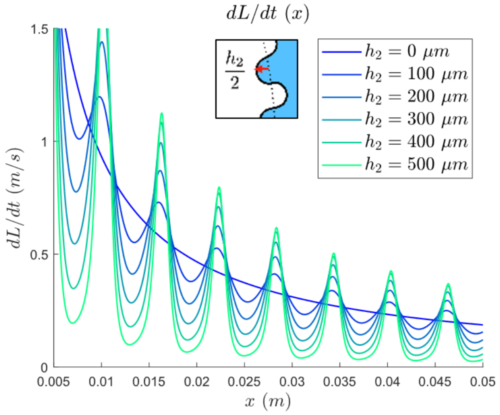

Figure 3. The rate of the meniscus rise as a function of time. The corrugation amplitude (h_2) is the varying parameter in the curves.

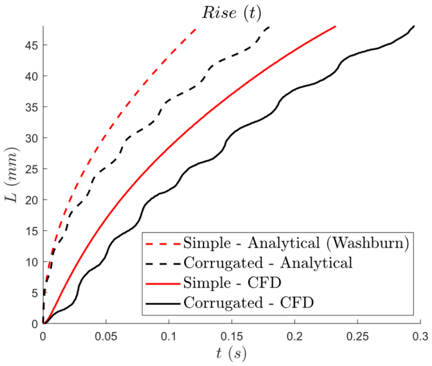

Figure 4. Comparison of the analytical solution with CFD simulation for both flat and corrugated channels.

Perspective of Future Research: Future work may include the consideration of both permeability and deformability of the plies so that a more realistic representation of the paper towel medium is achieved by the analytical model. The interplay of *elastocapillary coalescence* and ply swelling in the absorption capacity of paper towels is a very interesting avenue to explore, as they act against and in favor of absorption respectively.

The permeability of the plies also enables the possibility of investigating the *partially-saturated* region of the paper towel, where the liquid is present within the plies but not between them.

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