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A high-fidelity model for coupling flow and mechanical deformation of the porous paper web - a key to improved understanding of dewatering and rewet at the press section in paper making

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Project Title: A high-fidelity model for coupling flow and mechanical deformation of the porous paper web – a key to improved understanding of dewatering and rewet at the press section in paper making

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Computational Resources used for Project:

System	Time (MCH)	Commercial Software	Custom Software
Linux	12.5	N/A	Chombo-Crunch
Linux	0.4	N/A	Geocentric and GEOS

EXECUTIVE SUMMARY

The U.S. pulp and paper industry is the third-largest manufacturing user of energy, with an energy demand of 2,540 trillion Btu in 2010. Within the papermaking process, drying consumes over 400 trillion Btu annually which makes it one of the largest energy saving opportunities. In the 2014 Forest Products Industry Technology Roadmap, it is concluded that increasing the paper web solid content entering the dryer section from the current 45-55 percent to approaching 65 percent, which would save 1.0 MMBtu per ton or 20 percent of the energy used in drying, is one of the most needed technology breakthroughs to achieve a more sustainable approach for manufacturing pulp and paper products. Achieving such significant energy savings highly depends on understanding the fundamental dynamics of the wet press process and then developing optimized solutions for design of more energy-efficient press processes and equipment.

The objective of this project is to develop reliable computational capabilities to accurately simulate the flow of water from/to the porous pulp medium (dewatering/rewetting) during the pressing process in paper making. This project is a close collaborative effort among Lawrence Livermore National Laboratory (LLNL), Lawrence Berkeley National Laboratory (LBNL), and Agenda 2020 Technology Alliance.

In this work, we have leveraged advanced simulation capabilities and high performance computing (HPC) resources, experimental measurements and paper machine data to develop an integrated, multi-scale and multi-physics modeling framework. Specifically, Agenda 2020 provides the domain expertise and data in the area, and guide LLNL/LBNL in model calibration, validation, and application to the paper manufacturing process. LLNL develops a continuum simulation framework to couple mechanical and two-phase flow models, which applies Richards' equation to describe two-phase flow in paper/felts and modified Cam-Clay model to describe paper plastic deformation. LBNL performs high-resolution direct simulation of microscale flow in complex pore structures in press felts, utilizing sophisticated pore-scale modeling capabilities. Detailed pore-scale simulations are used to inform better parametrization of porosity and permeability for continuum-scale computations. The resulting multi-physics model is tested for simulating paper dewatering/rewetting at various wet press configurations, and validated by comparison with both shoe- and roll-press data. Additionally, we perform sensitivity analysis to quantitatively address model parameter uncertainties, and identify the parameters or factors that significantly influence paper pressing processes.

The project not only leads to improved understanding of the mechanisms driving paper substrate dewatering at the press section, but also provides an integrated modeling framework that can serve as a theoretical validation and simulation toolbox for the design of more energy efficient pressing technology, and therefore help the pulp and paper manufacturing industry to ultimately reduce the energy required during the drying process of paper manufacture. We will work with our paper industry partners to continue to improve our developed modeling capabilities, and utilize them to help guide press section configuration and roll/felt design to maximize paper water removal.

INTRODUCTION

Paper manufacturers are vitally important to the local economies in many parts of the United States. With 359 pulp and paper mills located in 40 states, the U.S. pulp and paper industry provides almost 400,000 well-paying manufacturing jobs with many in rural areas. The U.S. pulp and paper industry is extremely energy-intensive. It is the third-largest manufacturing user of energy, with an energy demand of 2,540 trillion Btu in 2010. Seeking large energy savings in pulp and paper manufacturing aligns with national goals of sustainability, clean energy, energy independence, and doubling industrial energy productivity.

Within the papermaking process, drying consumes over 400 trillion Btu annually which makes it one of the largest energy saving opportunities. In the 2014 Forest Products Industry Technology Roadmap, it is concluded that increasing the solid content entering the dryer section from the current 45-55 percent to approaching 65 percent is one of the most needed technology breakthroughs to achieve a more sustainable approach for manufacturing pulp and paper products. Raising the web solids from 50 to 60 percent would lower drying energy by 0.7 MMBtu per ton. Raising solids as high as 65 percent would save 1.0 MMBtu per ton or 20 percent of the energy used in drying. Reducing energy by 20 percent would save an estimated 80 trillion Btu per year in the United States, worth approximately $250 million annually.

Achieving such significant energy savings highly depends on development of optimized solutions for design of more energy-efficient press processes and equipment. Over the past few decades, optimization of the pressing technology has drawn considerable attention, and been mostly guided by either expensive pilot tests or simplified empirical models. Despite the large number of experimental and modeling studies devoted to understanding the fundamental dynamics of the wet press process paper dewatering and rewet phenomena are still not well understood today due to lack of sufficient data and reliable computational models. For this reason, it is of great importance to develop a better understanding of coupled two-phase flow and mechanical deformation in paper sheet and fabric felts at the press section, and ability to accurately model and predict these processes under practical operating conditions.

The objective of this project is to develop reliable computational capabilities to accurately simulate the flow of water from/to the porous pulp medium (dewatering/rewetting) during the pressing process in paper making. As illustrated in Figure 1, at the press section, the paper sheet runs between two rotating rolls or a roll and a shoe, which exert certain amounts of pressure to the sheet surface to press the water out of the paper, and water is then transferred to another surface called the felt. The felt is a fabric acting like a sponge to help carry the water off the system. The rollers are about 1 m in diameter, and rotate at up to 2000 m/min. The line load at the nip region could be as high as more than 1000 kN/m. When the wet paper sheet and felts enter the nip region both are compressed and the paper sheet first becomes saturated from unsaturated

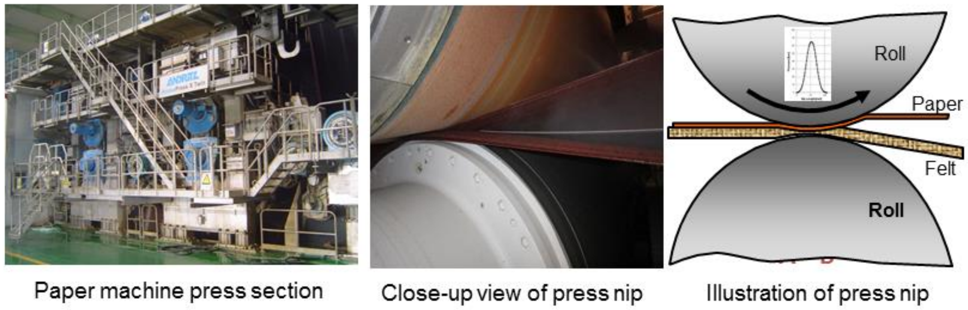


Figure 1. Illustration of the press section of a paper machine

conditions. Then as the paper and felts approach the nip center the nip load continues to increase until reaching the peak value, and meanwhile water is squeezed from paper sheet to felt, making felt become saturated. After passing the nip center the nip load decreases, and both paper sheet and felts expand and become partially saturated. Then water may re-enter the paper before press felts and paper sheet separate, consequently reducing drying efficacy. Understanding and modeling such multi-stage phenomena are the key component of this project, which would serve as the first but critical step towards reducing rewet and maximizing water removal.

APPROACH

In this work, we have leveraged advanced simulation capabilities, experimental measurements and paper machine data to develop an integrated, multi-physics modeling framework, as illustrated in Figure 2. The integrated continuum-scale flow and

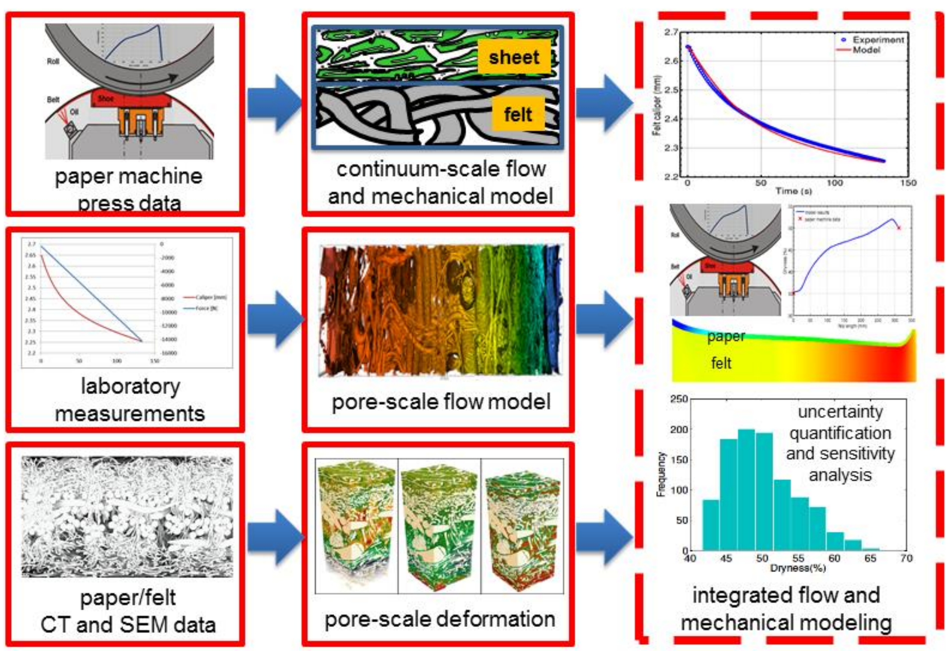


Figure 2. Integrated modeling framework for paper dewatering and rewet simulation. The continuum-scale coupled flow and mechanical modeling framework, which is calibrated and validated by paper machine data, experimental measurements and pore-scale simulations, is enclosed by the dashed box. Note that development of the pore-scale mechanical deformation model is not included in the current project statement of work (SOW).

mechanical model represents the critical component of this modeling framework that can be used to simulate dewatering /rewet at a press operational scale, and therefore help optimize wet press operations and guide design of energy-efficient equipment. However, this continuum model requires calibration and validation by laboratory and operational press data, and high-resolution pore-scale simulations. The pore-scale model can provide a fundamental understanding of pore-scale physical phenomena especially when laboratory measurements or machine data are not available.

This project is a close collaborative effort among Lawrence Livermore National Laboratory (LLNL), Lawrence Berkeley National Laboratory (LBNL), and Agenda 2020 Technology Alliance (Agenda 2020).

The Agenda 2020 Technology Alliance consists of member companies that work cooperatively with universities, research institutes and government agencies to transform the paper and forest products industry through innovation in its manufacturing process and products. They provide the domain expertise in this area and guide LLNL and LBNL in application of advance modeling and simulation to the dewatering/rewet processes in order to better understand and improve paper manufacturing process.

LBNL has strong expertise in development of advanced numerical algorithms for applied partial differential equations, adaptive multiscale methods as well as high performance computing. They leverage their pore scale modeling capability called Chombo-Crunch to perform high-resolution direct simulation of microscale flow in complex pore structures in paper pulp and press felts. Chombo-Crunch which has been applied to wide variety of flow and transport problems in resolved porous media including reactive transport related to carbon sequestration, mesoscale resolution of flows in hydraulic fracturing, electrochemical transport in battery electrodes and large scale turbulent flows. The largest pore scale simulations to date have been performed with Chombo-Crunch including the first simulation of resolved flow in fractured shale.

LLNL has extensive experience and expertise in coupling mathematical models of multiphase fluid flow, chemical transport, and mechanical deformation in porous media and terrestrial environmental systems. They utilize the modeling capabilities implemented in two LLNL simulation tools, the Geocentric and GEOS codes, to develop a continuum simulation framework to simulate mechanical deformation and two-phase flow in porous paper and felts. The Geocentric code is a massively-parallel finite-element / finite-volume code designed primarily for tightly-coupled poromechanical problems. It simulates either single-phase or multi-phase flow in a deformable porous medium. The GEOS code that is a multi-physics computational platform has recently been developed to simulate complex flow and mechanical behaviors for continuum and discontinuum domains.

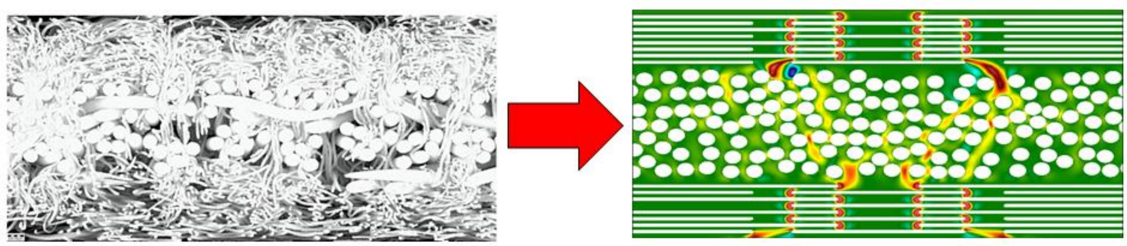
In the following subsections, we describe the pore- and continuum-scale modeling approaches, respectively.

Development of a pore-scale flow model (LBNL)

We perform high resolution pore scale simulations of water flow in complex pore structures of paper and press felts to calculate/calibrate the intrinsic permeability and porosity-permeability relationship for different grades of felt designs, which are required for the continuum model. It is assumed that the porous medium is stationary and the solid matrix is nondeformable. The modeling approach involves several steps as follows:

Step 1: Assessment of pore structures in press felts
We examine the representative pore structure patterns observed in both two-dimensional segmented scanning electron microscopy (SEM) and three-dimensional computed tomography (CT) images, and identify both pores (void space) and solid phases (e.g. fibers) based on appropriately-selected gray-scale ranges from the CT characterization data.

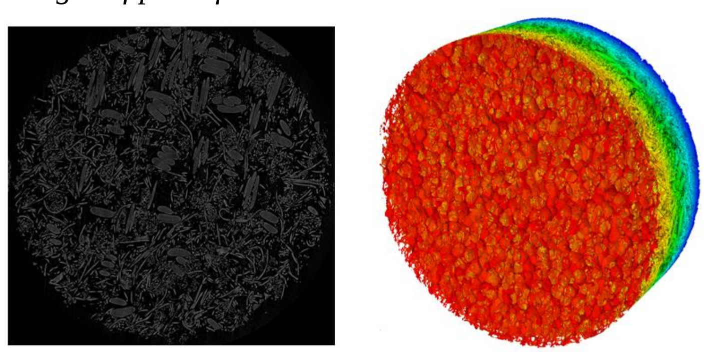
Step 2: Development of two-dimensional (2D) pore-scale models based on synthetic representations of felts
Based on CT image data we construct synthetic pore-scale geometries to represent heterogeneous pore structures in the press felt, and then demonstrate two-dimensional flow simulation of flow in such an idealized geometric pore scale representation to test and verify the pore-scale modeling approach (Figure 3).



(a) (b)

Figure 3. (a) Tomography image of felt pore structures; (b) Two-dimensional simulation of microscale flow in synthetic pore-scale representation of image data (flow velocity distribution).

Step 3: Development of three-dimensional (3D) pore-scale models based on pore geometries obtained from CT scanned images of press felts
First, a 3D felt CT image is reconstructed by a stack of 2D image slices (Figure 4). In the next step, we extract a slice of the 3D region to visualize and quantify the resolved pore space and solid materials, and then use it to construct a 3D pore-scale model for direct simulation of water movement in complex pore structures in felts.



(a) (b)

Figure 4. (a) 2D felt CT image (Note that the circular and slender shapes represent fibers of different orientation.); (b) 3D reconstruction of the felt sample from CT images.

Step 4: Analysis and upscaling of pore-scale simulations
The pore-scale model is used to analyze the important influences of pore-scale heterogeneity on water flow through complex pore structures in felts, and further calibrate macroscopic parameters used in the continuum model such as bulk porosity and permeability, and porosity-permeability correlations.

Step 5: Development of a pore-scale two-phase flow model (capability demonstration)
As described in the project SOW, one of the tasks is to develop and demonstrate a prototype capability of modeling two-phase flow in porous paper sheets and press felts. Our initial approach to two-phase flow modeling is to explicitly represent two fluids moving through pore space. In this approach water is advected into air-filled regions with a diffusive interface. Although a sharp interface approach is not employed and as such capillary pressure jump conditions are not represented at the interface this initial approach is meant to provide a proof of concept that represents two-fluid movement (water into air) through complex geometry, and a useful basis for continued two-phase flow model improvement (e.g. extending the model to track sharp interfaces between multiple fluids and triple point contact angles).

Development of a continuum simulation framework to couple mechanical deformation and two-phase flow models (LLNL)

Broadly speaking, there are two numerical approaches that are used to simulate the coupled hydromechanical processes, say, pore- and continuum-scale models. Pore-scale models can provide a direct simulation of dewatering and rewet in deformed (compressed/expanded) porous paper and felt layers, therefore allowing for a more accurate representation of the coupled physical behaviors at various scales. However, developing such a fully coupled pore-scale model is challenging and not included in this work, because it requires explicit descriptions of interactions between water and solid phases (paper/felt fibers) at a pore-scale, and frictional contact between the fiber structures. The continuum-scale model offers an alternative way to simulate dewatering and deformation in paper web/felts. Because continuum poromechanics theory can most appropriately characterize the hydromechanical process occurring at the press section we develop a fully coupled continuum modeling framework to simulate two-phase flow and elastic-plastic deformation in both paper web and felts. Hydrodynamic and mechanical properties of the paper web and press felt used in the continuum models (including material porosity and permeability, porosity-permeability relationships, capillary pressure and material elastic and plastic parameters) can be calibrated by either experimental measurements or high-fidelity pore-scale modeling. In view of strong interdependence between effective stress, flow pressure and water fluxes during wet pressing it is necessary to integrate flow and mechanical models in an implicitly coupled way in order to make reliable predictions. Key components of this work follow.

Modeling elastic and elastoplastic deformation of paper and felts
Paper and felts are considered as deformable porous media, and assumed to be perfectly bonded at the interface. We also assume that mechanical responses of the felt and paper are elastic and elastoplastic, respectively. Specifically, we choose a most widely used

critical state model, modified Cam-Clay(MCC) plastic model, to account for the permanent deformation (thickness decrease) of paper after pressing. The MCC model, which incorporates pressure sensitivity and hardening/softening responses, is capable of modeling medium volume changes more realistically. For elasto-plastic deformation the total strain of the solid skeleton can be decomposed into the sum of recoverable elastic and permanent plastic components. The yield surface that defines the boundary between elastic and plastic deformation for the MCC model is largely dependent on material plastic parameters (e.g. virgin compression index, slope of critical state line, preconsolidation pressure), as illustrated in Figure 5.

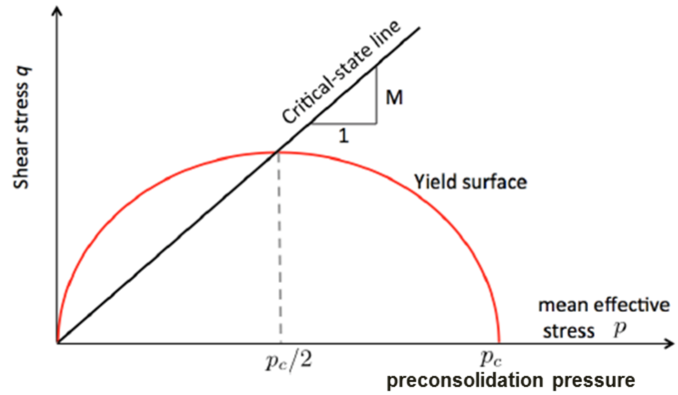


Figure 5. Modified Cam-Clay (MCC) model

Modeling two phase flow in porous paper and felts

Based on Darcy's law that approximates momentum balance for fluid flow through a porous medium, and the principle of mass conservation, we employ the Richards' equation to describe the movement of water in variably saturated porous paper web and press felts. The commonly used van-Genuchten correlation is used to relate the degree of water saturation to medium relative permeability and capillary suction.
The porosity-permeability relationship is another important parameter for modeling flow processes at a continuum scale, because mechanical deformation changes transport properties of the paper and felts. The medium permeability evolution resulting from porosity change is evaluated from such a pre-defined porosity-permeability relationship. In this work, we adopt the traditional Kozeny-Carman correlation or a simplified power-law equation (that is calibrated by pore-scale simulation) to describe the dependence of permeability on porosity change due to mechanical deformation,

$$K_t = K_0\left(\frac{\phi_t}{\phi_0}\right)^n \qquad (1)$$

where φ and K are porosity and permeability; *0* and *t* indicate initial and evolving time values; and the exponent *n* is an empirical power index derived here from pore-scale simulation.

Model calibration and validation

Model calibration and validation is an important task, which spans multiple spatial and time scales. It involves calibrating and validating the model with the data at laboratory and operational scales. For example, we employ the felt static compression measurement data to calibrate the felt elastic parameters used in the continuum model. Figure 6 compares the felt caliper evolution under compressive pressure between model results and experimental measurements. The integrated flow and mechanical model is further calibrated and validated by matching paper machine data for both shoe and roll press configurations, which is discussed in a later section.

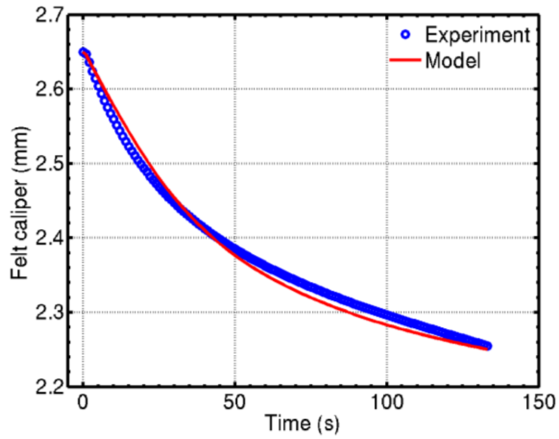


Figure 6. Experiment-model comparison of static felt compression

RESULTS

Direct simulation of pore-scale flow in press felts

Single-phase flow in felts
In order to inform better parametrizations of porosity and permeability for continuum scale computations of paper pressing we have performed high-resolution direct numerical simulation of microscale flows in both synthetic representations as well as geometries obtained from 3D tomography data of press felts. Figure 7 demonstrates direct 3D simulation of flow in felt from CT image data on 6912 CPU cores. The predicted felt bulk permeability is $7.732 \times 10^{-11} m^2$, which is consistent with the experimentally determined permeability values and is also used in the continuum model. It is observed that pressure drop inside the felt is nonlinear, indicating the permeability is not constant along the felt because of pore-scale heterogeneity. We further refine the model with high performance computing (up to 50,000 CPU cores) to fully resolve the heterogeneous micropore structures.

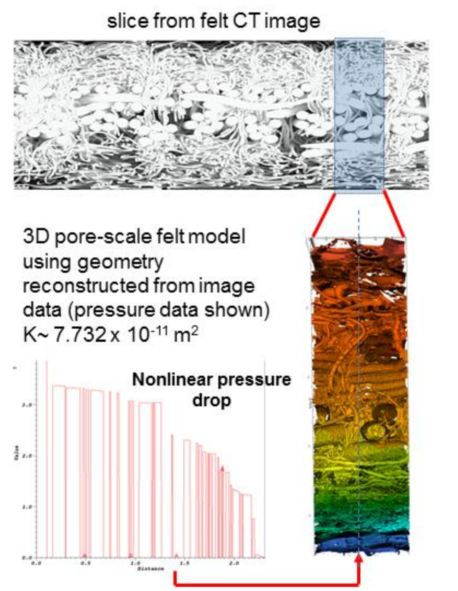


Figure 7. 3D pore-scale felt flow model results — Pressure distribution in the felt and pressure drop in the press direction

Effects of deformation on permeability change
Darcy-scale continuum models rely on porosity-permeability correlations to quantify the effects of deformation on permeability change. We use an empirical power law (Equation 1) in the continuum model to relate local permeability change to porosity, and the exponent *n* is required to be calibrated by high-fidelity pore-scale modeling data. For this purpose, we perform high-resolution simulations of microscale flow in uncompressed and

compressed pore geometries that are constructed from separate 3D felt CT image data sets (Figures 8 and 9). The bulk permeability and porosity values predicted by the pore-scale model provide a useful constraint for the form of porosity-permeability function used in the continuum model, and they are fitted to the power law function (Equation 1) with exponent *n* as 5.0 for this felt design. The developed pore-scale modeling approach can be extended to calibrate the *n* value for other felt designs. Note that different grades of felt may exhibit different mechanical and transport behaviors, thus resulting in different *n* values to control porosity-permeability evolution.

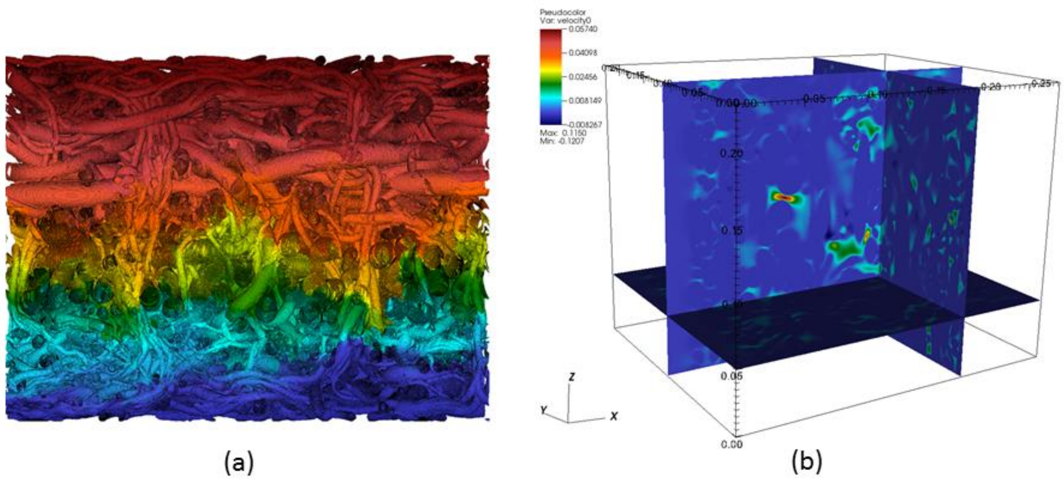


Figure 8. 3D pore-scale felt flow model results — (a) pressure and (b) flow velocity distributions in the felt

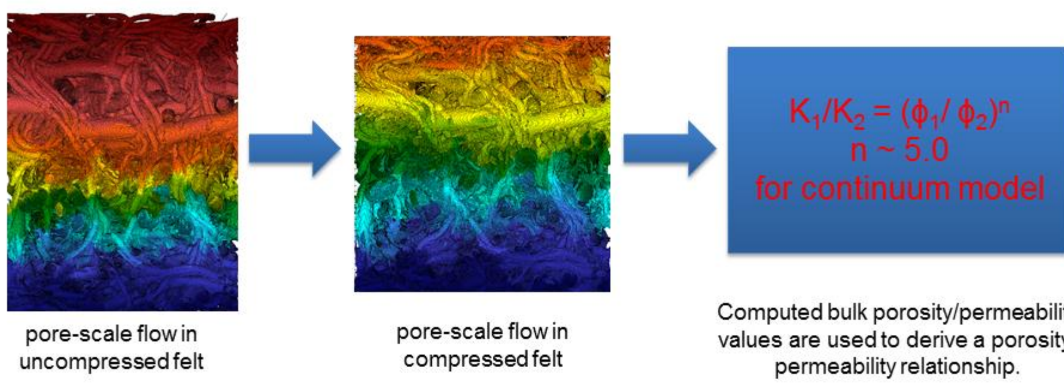


Figure 9. 3D pore-scale simulation of microscale flow behaviors (pressure distributions) in uncompressed and compressed (with compressing pressure as 5 MPa) felts, and a porosity-permeability relationship calibrated by pore-scale modeling results.

Two-phase flow model demonstration

A so-called diffusive front tracking approach is developed to tack interface between water and air phases. Figure 10 shows diffusive and advective water movement in a synthetic felt. The developed two-phase modeling capability can be extended to track sharp interfaces between multiple fluids and triple point contact angles, and eventually be used to help calibrate the important two-phase flow related parameters such as relative permeability and capillary pressure curves for the continuum model.

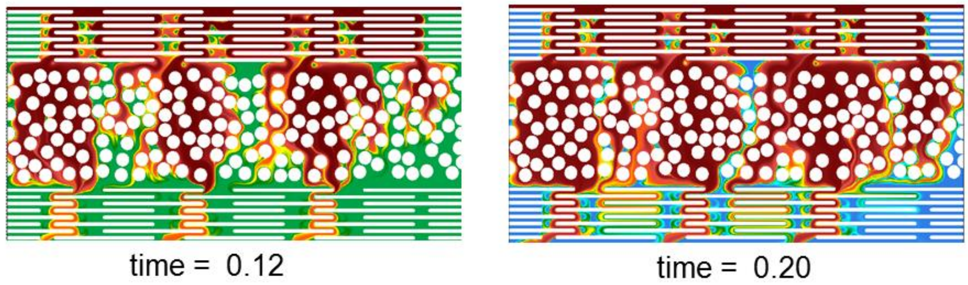


Figure 10. Two-phase flow simulation of diffusive and advective water movement through an uncompressed synthetic felt.

Continuum modeling of coupled two-phase flow and mechanical deformation
Based on paper machine data, experimental measurements and pore-scale simulations we have developed an integrated continuum modeling framework to simulate coupled two phase flow and mechanical deformation processes in paper sheet and press felts at the press section.

Modeling of mechanical dewatering at the shoe press section
We use a shoe press configuration, which includes one roll and an oil-lubricated pressure shoe, as the baseline case to develop and calibrate the model. In this case, the nip line load is 1250 kN/m, the nip length (zero to zero pressure) in the machine direction is 312 mm, and the roll rotates at a speed of 1500 m/min (Figure 11). The initial thicknesses of paper sheet and felt are 400 µm and 3.5 mm, respectively. The dryness of the paper web entering the nip region is measured at 35%. The developed model can fit the measured machine data, and predict that pressing increases the web solid content from 35% to 50%. Figure 12 shows the paper dryness evolution along the machine direction, and distributions of dryness, water saturation and porosity in deformed paper/felt.
It is noted that as unsaturated paper and felt enter the nip region both are compressed, and paper becomes saturated first, and then water is squeezed from paper sheet to felt, making felt become saturated as well. At the same time paper dryness increases with compressive pressure until reaching the highest dryness value. Once the nip load starts to decrease both paper sheet and felt expand, and then paper “rewet” occurs, leading to a slight decrease in paper dryness. These observations are consistent with our conceptual understanding of paper/felt dewatering/rewet processes.

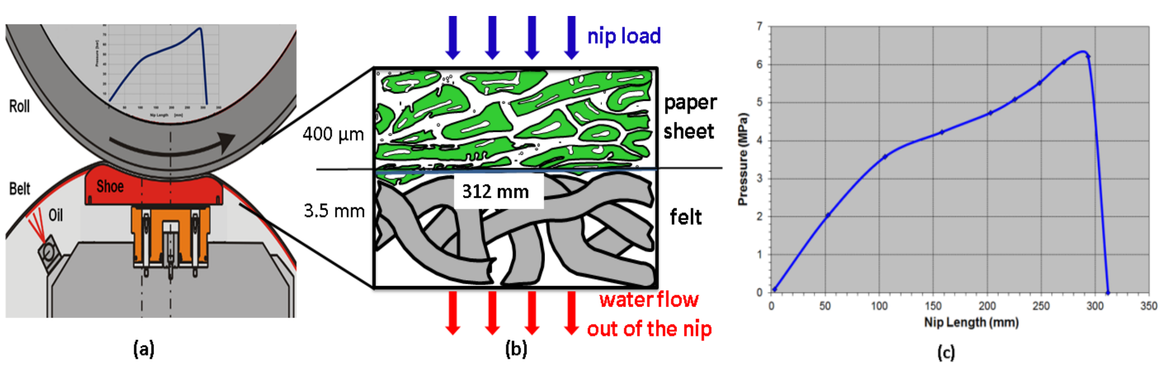


Figure 11. (a) Shoe press nip; (b) Conceptual press nip for a shoe press section where the nip length is 312 mm, and the initial thicknesses of paper and felt are 400 µm and 3.5 mm, respectively; (c) Shoe press nip pressure profile with a nip load of 1250 kN/m.

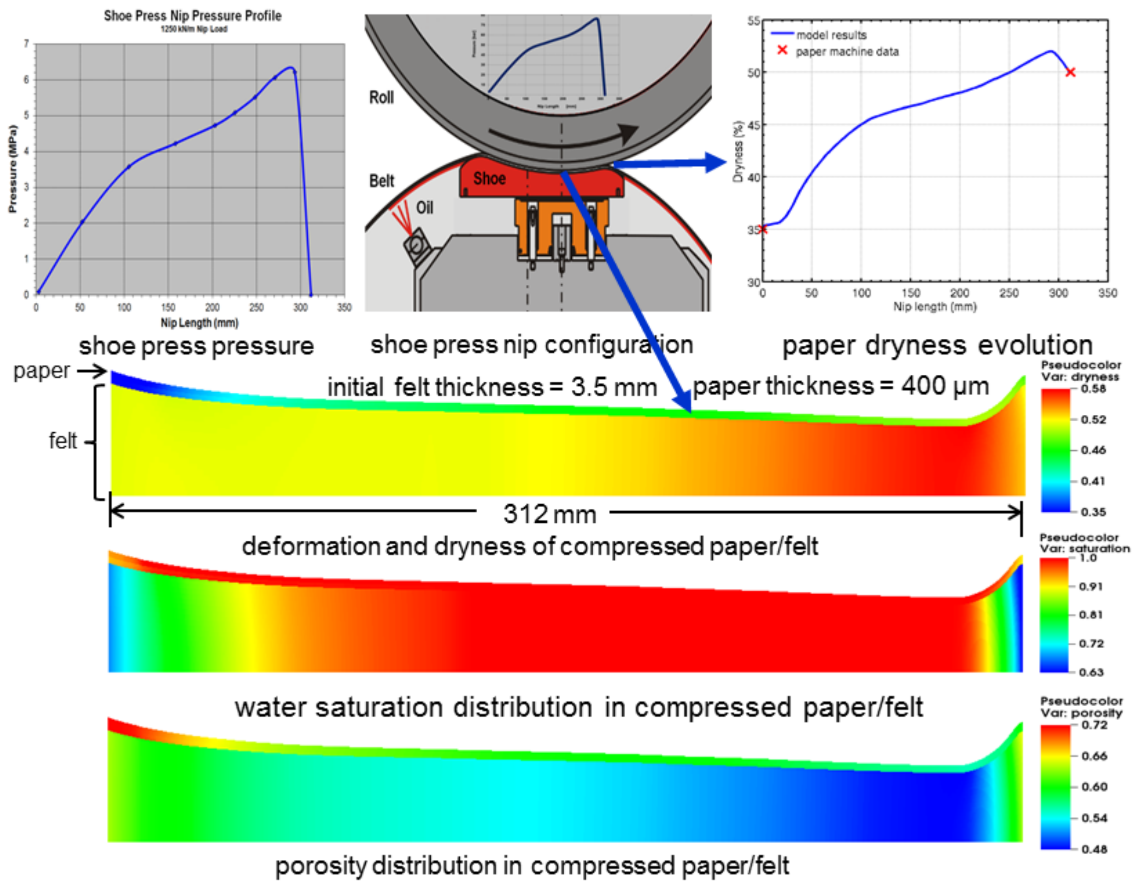


Figure 12. Two-dimensional simulation results of coupled flow and elastoplastic deformation in paper and felt at the shoe press nip region — Dryness, water saturation and porosity distribution in deformed paper and felt, and comparison between the simulated and measured evolution of paper dryness during wet press.

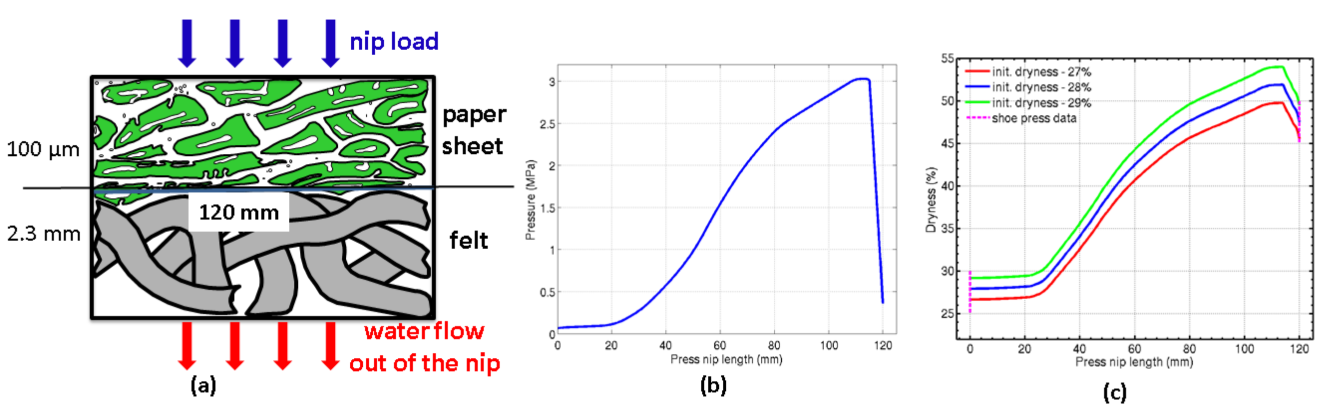


Figure 13. (a) Conceptual press nip for a shoe press section where the nip length is 120 mm, and the initial thicknesses of paper and felt are 100 μm and 2.3 mm, respectively; (b) Shoe press nip pressure profile; (c) Comparison between the simulated and measured evolution of paper dryness during wet press.

In order to more effectively validate the developed model, we apply the calibrated model to a different shoe press system. All the model parameters or functions are kept the same except for the operational/configuration parameters such as roll rotation speed (which is updated to 1800 m/min), initial paper and felt thicknesses (which are updated to 100 µm and 2.3 mm, respectively, Figure 13a), and nip pressure profile (Figure 13b), We run the model with different initial paper dryness between 25-30%, and the simulated final dryness falls in the range between 45 – 50%, which is consistent with the measured data (Figure 13c). The good agreement with the data helps build the confidence in our model.

Modeling of mechanical dewatering at the roll press section

In addition to shoe nip press we apply the developed model to simulate paper dewatering and deformation at a roll press section. For the test case two rolls rotate at a speed of 540 m/min, and a symmetric pressure distribution is applied to the paper sheet that is sandwiched by two felts (Figure 14a). The development of paper dryness along the machine direction is illustrated in Figure 14b. Both model prediction and press data indicate that paper solid content increases from 22% to 33% under these roll-pressing conditions. It also noticed that the shoe press design allows for more efficient water removal than the conventional roll nip press. Furthermore, in order to better test and validate the model we simulate paper dewatering for different nip loads, and compare the model-predicted paper dryness with additional pilot press data (Figure 15). The reasonably good agreements between model and data suggest that the model can be used to predict paper dryness under practical wet press operating conditions, and therefore help explore and understand the relative impact of different operating and design parameters on paper dewatering.

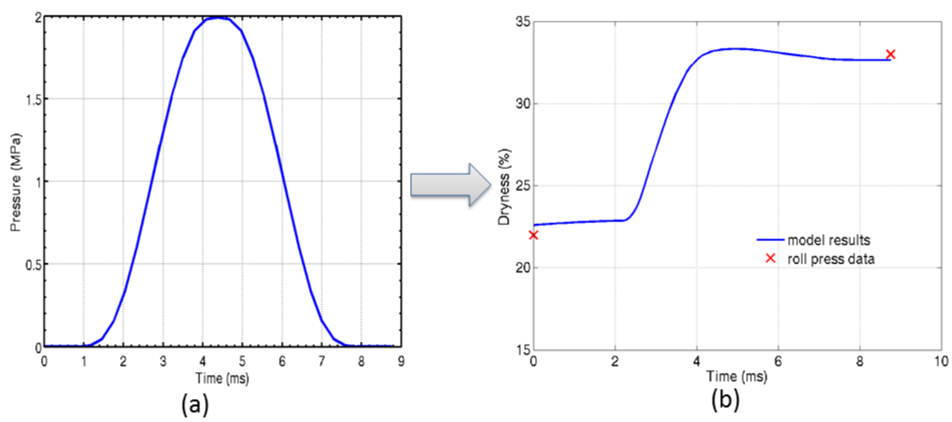


Figure 14. (a) roll press pressure distribution; (b) comparison of paper dryness between roll press data and model prediction.

Model sensitivity and uncertainty analysis

As we know we often don’t have sufficient data to calibrate model parameters, which may therefore prevent the model from reliably predicting practical wet press operations. To address such model uncertainties, we perform preliminary sensitivity analysis for the shoe press case to evaluate the impact of model parameters on paper dryness prediction. The sensitivity analysis can not only help reduce model uncertainty, but also provide useful information in terms of which parameters are critical, and therefore need more rigorous evaluation/calibration either by laboratory measurement or pore-scale simulation. In this work, we select 10 important model parameters for analysis, which are associated with paper and felt mechanical and transport properties (e.g. porosity, permeability, capillary pressure curve, elastic modulus, plastic parameters), and generate a thousand realizations of these parameters using a Latin hypercube sampling method. Sensitivity index is computed to measure the sensitivity of final paper dryness to each parameter. The purpose of sensitivity analysis is to identify the parameters that influence the paper dewatering process significantly. Figure 16 shows the distribution of dryness curves of the one thousand simulations along with the average and 90% confidence intervals (between 5% and 95% quantile). With the initial condition (35% solid content of paper sheet incoming to nip) most of the final paper dryness falls in the range between 45% and 55%, which agrees with the measured press data.

Figure 17 lists normalized Sobol's sensitivity index of each parameter, measuring its relative importance across parameter space. Among 10 selected model parameters the MCC plastic model parameters, say, virgin compression index, slope of critical state line, and preconsolidation pressure, have stronger influences on paper final dryness. The scatter plots of these parameters indicate that the final paper dryness is directly proportional to virgin compression index, but inversely proportional to slope of critical state line, and preconsolidation pressure (Figure 18). This observation further highlights the need to use measurement data of paper's mechanical properties to fully calibrate and validate the paper plastic model (MCC model) used in this study before applying it for predicting practical wet pressing operations.

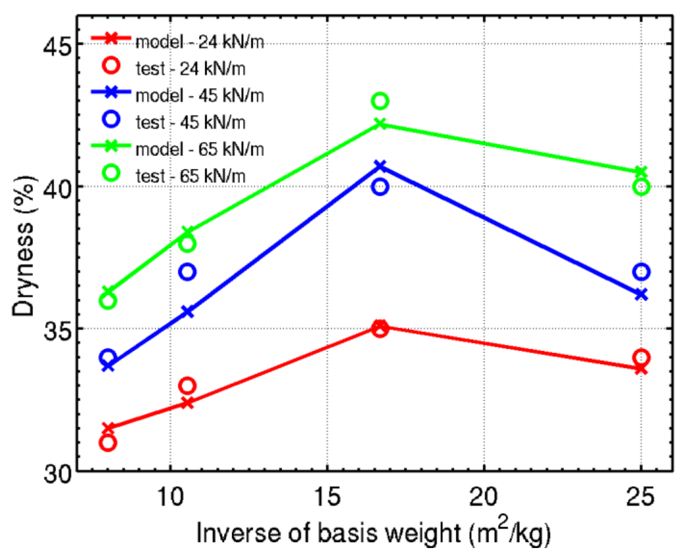


Figure 15. Comparison of predicted paper dryness to pilot roll press data for different nip loads.

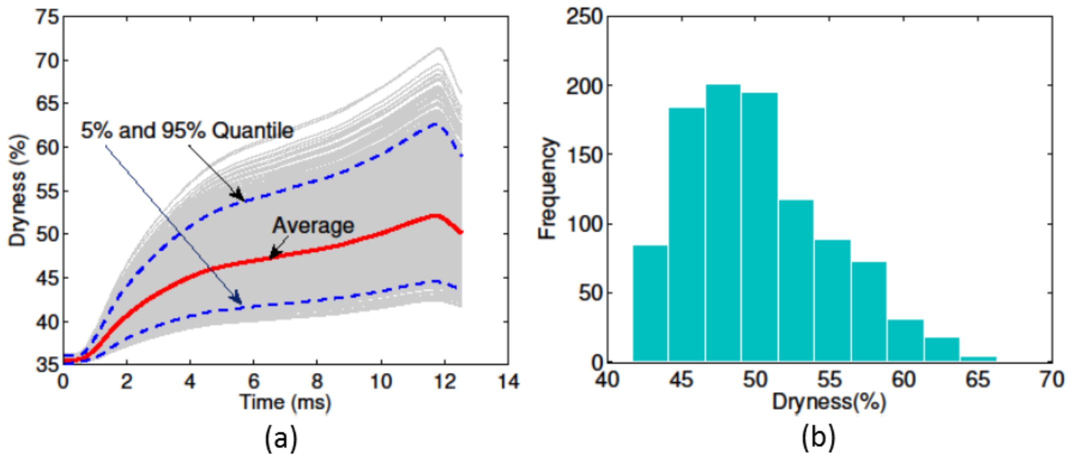


Figure 16. (a) Distribution of paper dryness curves of one thousand realizations with the average and 90% confidence intervals (between 5% and 95%quantile); (b) Distribution of one thousand realizations in terms of final paper dryness.

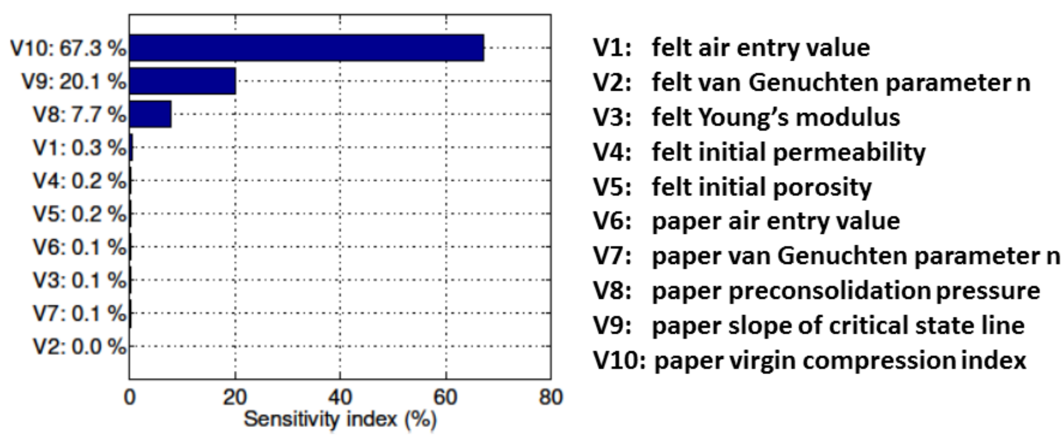


Figure 17. Normalized Sobol's sensitivity indices for final paper dryness with respect to uncertain model parameters.

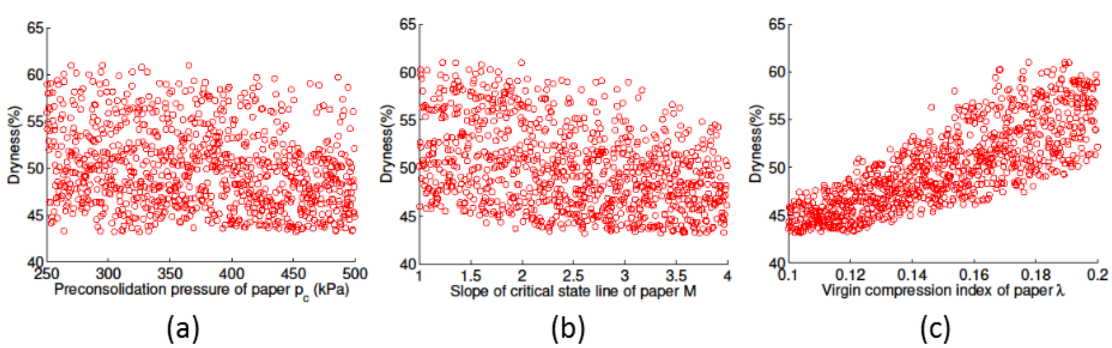


Figure 18. Scatter plots of final dryness as a function of paper plastic parameters: (a) preconsolidation pressure; (b) slope of critical state line; and (c) virgin compression index.

SUMMARY

In this work, we have developed an integrated multi-physics modeling framework for simulating two-phase (water and air) flow in deformable porous pulp media at the press section in paper making. The model is extensively calibrated and validated with high-resolution pore-scale simulations, laboratory measurements and paper machine data collected from various wet press configurations and operations. The good agreements between model and paper machine data suggest that the calibrated continuum-scale model can be used to predict practical wet press operations. Although some important physical phenomena are not well addressed due to lack of sufficient data our continuum modeling framework can capture the general dewatering patterns or trend observed at the press section. Furthermore, the numerical work presented in this study provides a calibrated benchmark model, which can not only help improve understanding of the physical behaviors associated with wet press, but also serve as a workable platform for continued model improvement and practical application. Finally, we will continue to work with our paper industry partners to apply the developed model to help guide press section configuration and roll/felt design to minimize rewet and maximize water removal.

FUTURE WORK

We have developed a fully functional simulation platform, which can be used to predict practical wet pressing operations. To continue to improve the modeling work, and make it more useful in developing a complete understanding of such complex physical phenomena, and guiding design of energy-efficient press processes and equipment, we suggest focussing on the following areas for the future work,

- *Acquire more complete data to support model improvement*
  Data collection is not only important for gaining fundamental understanding of physical phenomena, but also is an integral part of the modeling process. Lack of sufficient data makes accurate modeling and analysis very challenging and difficult. The key data necessary to support model improvement includes,
    - **Experimentally measured paper material properties**
      As indicated in the sensitivity analysis, paper mechanical and transport properties have a strong influence in paper dewatering processes. Therefore, it is important to use experimentally measured data to calibrate and validate the macroscopic paper-property parameters used in the continuum model, reducing model uncertainty and improving numerical prediction.
    - **High-resolution micro-CT images of paper**
      High-resolution micro-CT imaging is the first necessary step to develop a high-fidelity pore-scale model to simulate microscale flow and mechanical behaviors in complex porous structures in paper pulp.

- **Experimental data from laboratory-controlled felt (and paper) dewatering tests to better calibrate continuum models and validate pore-scale models**
- **Any paper press operation or laboratory measurement data that could provide insights into transient or dynamic behaviors of paper under mechanical pressing conditions**

- *Develop more sophisticated pore-scale models (that are not included in this SOW) to account for*
  - Relative permeability, equilibrium and dynamic capillary forces, and how they affect water-air migration between paper and felt under operational conditions
  - Coupled flow and mechanical deformation processes at a pore scale

- *Continue to bridge the gap between pore- and continuum-scale models, consequently improving our ability to confidently model and predict hydraulic and mechanical responses of paper pulp and felt under practical wet press operations*

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