Mathematical modeling of mechanical dewatering in the press section

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INTRODUCTION:

Sustainability has recently been a focal point of attention in the industry. This development has been highly accelerated by the soaring prices for fossil energy following the current global market situation. Sustainability comprises decarbonization of energy sources as well as lower energy and resource consumption. An improved mechanical drainage significantly reduces thermal energy consumption in the subsequent dryer section and hence increases the energy efficiency of the papermaking process. Furthermore, mechanical draining significantly defines the properties and quality of the paper. However, the physical processes inside the press nip are still poorly understood and can be only measured with high efforts. Sophisticated mathematical modelling and high-performance simulations offer process insights, which are difficult to achieve by measurements, and can be used to improve and redesign the process and components involved.

The drying process of the paper web is the reason that the pulp and paper industry is one of the most energy intensive industrial sectors. Within an integrated pulp and paper mill the energy requirements of the dryer section is one of the largest energy consumers [1] and is responsible for about 20% of the total energy consumption in the papermaking process [2]. By increasing the dry content of the paper web before it enters the drying section, high energy savings can be achieved (see Figure 1).

To reach this goal, the mechanical dewatering in the press section plays an integral role and needs to be optimized. In the press section the dry content of the paper web is increased by the application of mechanical pressure leading to a removal of free water from its pores. The mechanical dewatering in the press section not only allows for a reduction of steam consumption crucially in the dryer section, but also increases the strength of the web crucial to avoid web breaks. However, despite the economic and environmental importance of press dewatering, the processes taking place inside the press nip are not yet fully understood. These include the interaction between the two-phase flow of water and air, as well as the mechanical compression and expansion of the porous materials of the press fabric and the paper web.

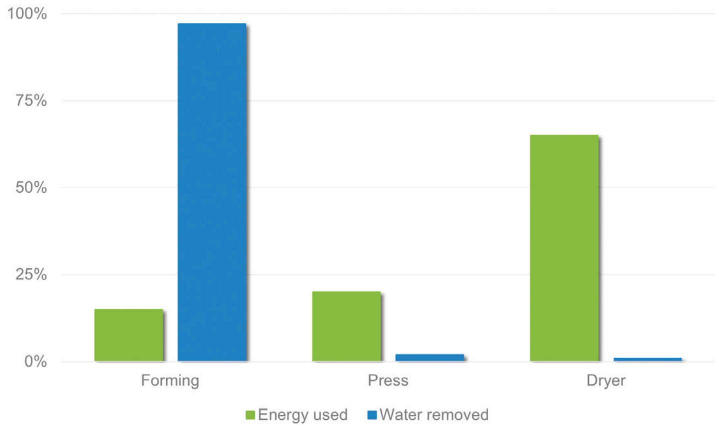


Figure 1: Comparison of the press section with the forming and drying sections concerning overall water removed and energy used [3].

Modeling and simulation of the process steps involved in the dewatering of the paper web offers insights into the mechanisms of water removal and sheet formation, which are not available solely from measurements and experiments. Additionally, virtual parameter studies allow for the identification of important influencing factors that are the basis for a suitable choice of test cases. In this work we will show that our simulations give new impulses that can directly be used to improve processes and redesign components. We will start by introducing our modeling approach and then present results of our simulations which are used to support and speed-up the development of new products in the press section. We will also point to challenges of the method especially in the identification of effective material parameters to describe the wet paper web and fabrics.

Figure 2: Voith's Tandem NipcoFlex press which combines two inline shoe presses is a press concept with a wide application window.

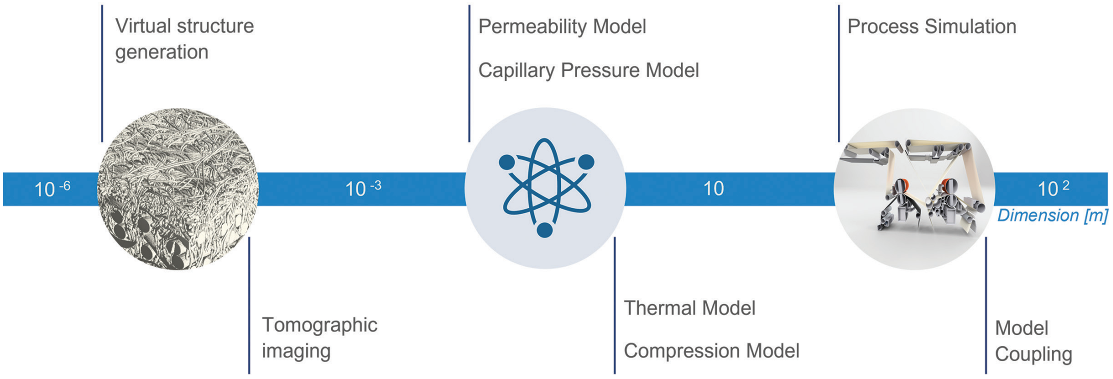


Figure 3: Multi scale approach to the simulation of the papermaking process.

Simulation approach

Our modeling covers the full paper machine from the initial dewatering of the paper suspension, over the mechanical dewatering of the preformed paper web up to the thermal treatment of the paper web in the dryer section. To achieve this, we use a multiscale approach, as shown schematically in reference (see Figure 3) with models covering the whole range of length scales from the micrometer scale of fibers and fillers to the several hundred meters of a full-scale paper machine. To obtain the needed geometry and parameters for our models, lab measurements especially tomographic imaging as well as virtually generated structures are used. On the micrometer scale, the effect of fines and fillers is included by modifying, parameters such as dewatering behavior or the pore volume distribution.

Different kinds of mathematical modeling and simulation tools for different length scales enable us to determine the necessary parameters and derive the required material models as described in the following sections. On the paper machine scale we use an in-house process simulation library that allows us to simulate complete sections of the paper machine. Here, we follow a modular concept starting from individual flow and material transport modules that are then combined to larger units, e.g., suction boxes or a press nip. It ensures fast and efficient calculations by reducing the level of detail and defining effective parameters describing the important aspects of the materials. Finally, we combine the different section models to describe the full length of the paper machine.

Image-based structural analysis and flow analysis

Realistic material parameters for both press fabrics and the paper web are required as input parameters for the process simulation model of the press section. The availability of high-accuracy tomographic imaging together with fast and efficient numerical methods to study the mechanical and fluid dynamic properties of the fiber web and paper machine fabrics enable a detailed view of the structures and properties of the materials. In CFD simulations, mass, momentum and energy balance equations are solved with numerical methods based on a calculation grid which describes the porous structures of the press fabric or the paper web. As a result, flow velocities v, concentrations c and pressure p distributions inside the pore volume of the press fabrics can be visualized in detail (see Figure 4). Studies of the fabric in different compression stages allow the determination of the compressed pore structure and its physical properties. The absolute and relative permeabilities κ and κ_r, which are related to pore size distribution and water saturation respectively, are derived from Darcy's law [3]

$$v = -\frac{\kappa\,\kappa_r}{\mu}\frac{\partial p}{\partial x}$$

with μ being the dynamic viscosity of the fluid and ∂p/∂x being the local pressure gradient. Darcy's law describes the two-phase flow of water and air, where water is described as incompressible medium, while air is compressible following the ideal gas law. These parameters are then used to describe the dewatering capability of the porous material during the process of mechanical dewatering within the process simulation.

Image-based analyses provide additional information on the pore size distribution, porosity and capillary pressure curves as a function of the water saturation. Porosity and permeability are related, e.g. by power-laws, depending on the results of the image analysis. For the process simulation of the press section this relationship is of great importance.

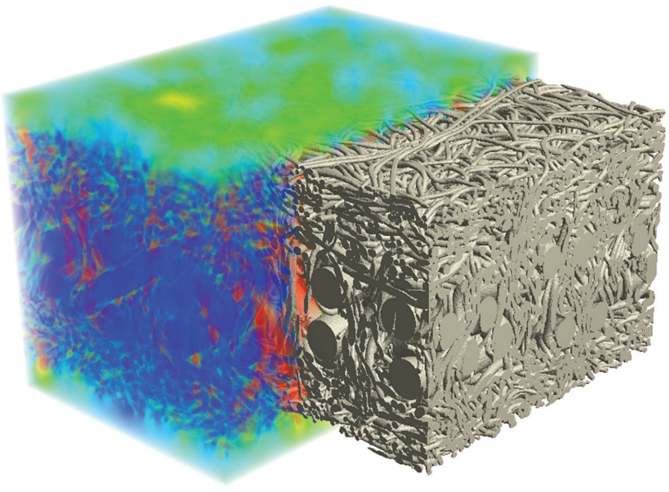
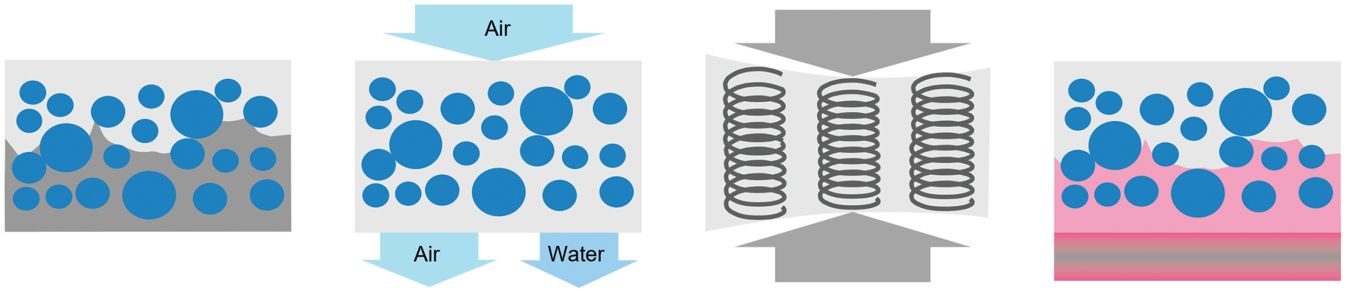


Figure 4: Flow Field of press fabric subject to a laminar flow.

Effective material models

With the small-scale simulations described in the above section, we obtain the effective parameters for the process simulation, describing the important aspects of the materials involved in the dewatering process. This is necessary because the complete process of paper dewatering cannot be modeled on this high level of detail. One of these models is described by Terzaghi's principle [5], where the total pressure is divided into hydrostatic pressure and structural stress and thus coupling flow and structural properties of the porous materials.

Other examples of our material models, as shown in Figure 5, are capillary pressure relations and relative permeability curves. These flow properties are archived by fitting, for example, a Brooks-Corey model [6] on the results obtained by CFD simulations described in the section above.



Capillary pressure model · Permeability model · Compression model · Thermal model

Figure 5: Examples of effective material models describing different aspects of the fluid-fluid, fluid-structure and structure-structure interaction which are used in the simulation.

To account for the compression of the paper web and the press fabrics either a viscoelastic-plastic model of the fiber mat [7] or an empirical model following compression curves from lab measurement are introduced as effective material models. For the study of thermal effects such as e.g., the evaporation and condensation of water inside the pores or temperature dependent changes of the viscosity of water we also included a thermal model based on the heat transport in a partially saturated porous media.

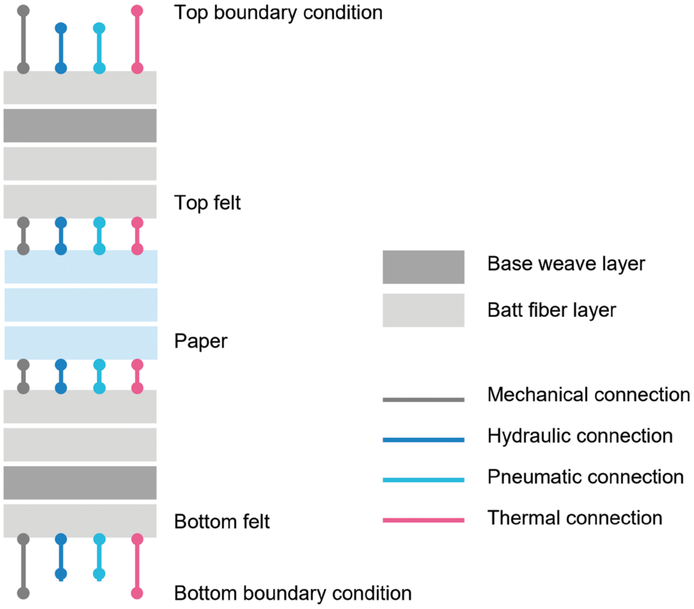


Figure 6: Schematic view of the process simulation model of a double-felted press nip showing the modular approach for the porous media layers as well as the press boundary conditions.

Process simulation library

The effective material models described above are then used as building blocks of the process simulation model describing the process behavior in the entire press section. They enable predictions of state variables like dry solid content, hydraulic pressure or water saturation, while not resolving the microscopic aspects of flow and compression. We use the Modelica modeling language and follow a modular concept, starting from the individual flow and material transport equations that are then combined to larger units. These units describe, for example, a press fabric layer or a layer of the paper web and can be combined to any requested paper – fabric – roll cover sandwich. The different units interact via connectors exchanging physical information about mechanical, hydraulic, pneumatic or thermal states and flows as shown in Figure 6. We include process variables as e.g., machine speed, line load and pressure shape (roll or shoe press) and are thus able to analyze the dewatering performance of different press sections or compare press fabrics for a defined press nip setup.

Application

To study the validity of our process model we developed a simulation setup analogous to a test setup in our experimental and pilot facilities. The setup defines a roll press nip with a single felt with defined initial saturation of the felt, constant speed and constant line load. Two different press fabrics were measured on the experimental setup and simulated in the process simulation by changing the press fabric parameters, e.g., permeability, porosity and compressibility. These parameters were obtained from lab data and small-scale simulations as described in the sections above. As a measure of the dewatering performance of the press fabric, the cumulated water mass flow from the bottom of the press fabric after the press nip is shown (Figure 7). The results show that felt A had a significant better dewatering performance compared to felt B. These results were also confirmed by the experimental setup where the same trends could be seen.

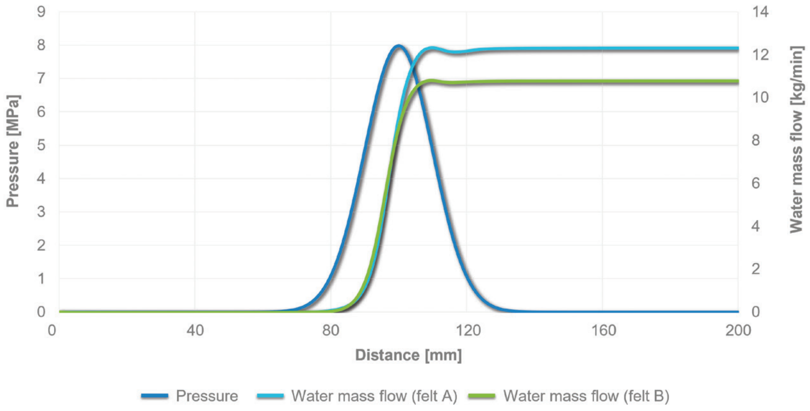


Figure 7: Results from the process simulation: Pressure profile and dewatering behavior of two different press fabrics in a roll press nip.

In addition, the influence of machine parameters, e.g., line load, as well as the influence of initial parameters, e.g., initial saturation of the press fabric, have been analyzed and confirm that we gain a deeper understanding of the interaction of the different elements in the press nip by making use of the mathematical modeling and simulation. Therefore, the process simulation helps us to reevaluate existing press fabrics and press nip concepts and is also used to develop new customized fabrics and concepts for specific customer needs. With each application of the current model library, we constantly reevaluate and refine the existing models and extend their validity and range of application.

CONCLUSIONS AND OUTLOOK

With its capabilities to optimize current processes with respect to resource efficiency and product quality process, simulation is at the intersection of two megatrends: digital transformation and sustainability. In comparison to virtual sensors or pure data models which gain their high reliability in the prediction of process parameters from a period of training, multiscale simulations keep their strong physical backbone in each step and allow insights into processes and materials. In the context of decarbonization and increased process automation, where new and disruptive technologies are discussed and no long-term experience is available, scientifically sound prediction of process stability, process efficiency, and production costs are essential to effectively decide which path to follow. Also, with new green materials finding their way into the product development of paper machine fabrics and roll covers, process simulation can help to predict their performance in their final application at the customer site. With an ever-growing field of applications and a constant advancement in the extent and the quality of our process simulation library our efforts also help in addition to secure know-how and extend technical expertise with modern and state-of-the-art tools and methods.

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