CSF4 BREAKTHROUGH TECHNOLOGY ROADMAP

Exploring breakthrough technologies for the papermaking industry

March 2018
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The Dutch paper and board sector consists of 18 companies that run a total of 22 mills. More than 70% of our production is used for packaging purposes, while 25% is graphical paper (paper for magazines, brochures, leaflets). The remaining part are hygiene papers. The main raw material used is recycled paper (80%). Alternative fibres like tomato stems, grass, miscanthus and beverage cartons are also increasingly popular. The sector employs 4,000 people.

The sector is cooperating closely in a number of innovation paths. In our innovation strategy CSF (creating sustainable fibre solutions) teams are working on different subjects, like alternative fibres, sustainable energy, multiple use & recyclability and breakthrough technologies. Professionals from our member companies participate in the teams.

For more information, please contact Annita Westenbroek (innovation manager of the Royal VNP): a.westenbroek@vnp.nl.

Deze studie is uitgevoerd in opdracht van RVO.nl in het kader van topsector energie en het TKI Energie en Industrie.
PREFACE

The Dutch paper and board industry has achieved major material and energy savings in recent years. Good progress has been made in the use of sustainable energy, increasing recycling rates and promoting circularity. However the core of the paper making process has hardly changed over the decades.

During that process, water is added and subsequently removed. This requires a lot of energy. Breakthroughs are needed to dramatically reduce our energy consumption. Therefore, the Dutch paper industry has started a voyage of discovery towards technologies that will enable paper to be produced in a completely different way.

without water

or

without having to evaporate water

This is the only route towards a carbon neutral sector in 2050 – a journey that starts today. But which technology will provide the much-needed breakthrough innovation? Such breakthroughs require inspiration and creativity.

We are challenging scientists, students, technology developers, or basically anyone with bright ideas to elaborate on solutions, especially young people who realize the necessity and are not yet stuck in fixed patterns and processes.

Findest was asked to make a start with this challenge, scouring cyberspace for potential technologies that might support future papermaking without water or without water evaporation.

The elaborated technologies in this report are just a selection of a vast list. This selection is meant as a start, it is not meant to be complete or exclusive, neither as a specific direction.

This report shows that we are serious. We mean business. We are willing to invest in a technology that can revolutionise the papermaking process.

This is a change that will not come from inside the sector. It should come from you!

Be challenged, be inspired, elaborate your ideas and contact us for any help or support required! The following people contributed to the content of this report:

- Bert Bodewes (Eska)
- Tjerk Boersma (Sappi)
- Bart Broens (Papierfabriek Doetinchem)
- René Kort (Schut Papier)
- Martin van de Pol (Crown Van Gelder)
- Arnoud Roelandse (Neenah Coldenhove)
- Claire Schreurs (Smurfit Kappa Roermond Papier)
- August Steinkellner (Mayr-Melnhof)
- Eric van Tulden (DS Smith Paper De Hoop)
- Jan Wattenberg (Parenco)
- Gerrit Jan Koopman (VNP)
- Rutger van Dijk (VNP)
- Corneel Lambregts (VNP)
- Annita Westenbroek (VNP)
- Laurens de Vries (KCPK)
- Arie Hooimeijer (KCPK)
- Peter Ros (Permanent Beta)
- Kim van den Berg (Permanent Beta)

The talents of ConnEQt:
- Tymon Knibbe
- Mirle Willems
- Samuel van Amerongen
- Ron van Klaveren (Findest)
- Vincent Franken (Findest)
- Jorick Houtkamp (Findest)
- Roel Boekel (Findest)
Dear paper innovator,

Findest and CSF4 have worked together on a breakthrough technologies roadmap containing technical concepts that will recreate the papermaking process. The goal is to decrease the CO$_2$-emissions and energy-usage required for papermaking substantially! After two engineering design challenges, two hackathons and analysing thousands scientific papers, the technology scouts and IGOR\textsuperscript{AI} found 50 potential technology fields that can impact the future of papermaking (see appendix I for the full list). Fourteen of them are described in depth in this document.

Over the past months, the team has dived deep into the science behind each case. They found out if, and how, the technologies could be applied in the papermaking process. In this document, the fourteen cases will be presented on a roadmap. The roadmap consists of three dimensions:

1. **Technology readiness level (TRL)**. The TRL is narrowed done to five quickly interpretable levels:

   ![TRL Levels](image)

   - Commercially available
   - Large scale pilot
   - Small scale pilot
   - Experimental stage
   - Theoretical stage

2. **Emission reduction potential (ERP)**. The many differences between the technologies and their implications on the papermaking process, make it impossible to define a percentage of emission reduction. Therefore, a three-level scale is determined based on the potential emission reduction:

   ![ERP Levels](image)

   - Low emission reduction potential
   - Moderate emission reduction potential
   - High emission reduction potential

3. **Impact on current papermaking process**. The technology scouts have looked at papermaking designs from various viewpoints. Each viewpoint results in different configurations with varying impact on the current process. A three-level scale is designed to show the impact of a concept on the current papermaking process:

   ![Impact Levels](image)

   - Completely different process
   - Substantial changes to current process
   - Minor changes to current process
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CASE 1 DRY FORMATION

Introduction
The most challenging aim for energy reduction in papermaking is the complete mitigation of water in the process. This case encompasses the scouting for techniques that can form a paper-like-web in a dry environment. The use of dry formation techniques is already broadly applied in the field of nonwoven textile production. Techniques like carding and needle punching have the aim to align and physically entangle the textile fibres mechanically. Two categories have been identified: Mechanical web formation and air-based web formation.

Application to papermaking

Air-based web-formation is a technology that is already applied in papermaking industry on a large scale for the creation of soft paper products (air laying). The papermaking technique is not yet able to produce paper with similar strength and properties to wet-laid papers [1]. The biggest advantages are energy reduction up to 50%, elimination of wastewater treatment, 30-50% reduction in investment costs, low power and operation costs [2]. Disadvantages are its increase in electricity use, less uniform paper thickness, lower sheet strength and reduced smoothness [2]. In 2004 a research from Aalto University had shown that it is possible to use Air Dynamic Forming (ADF) as an alternative to conventional papermaking [3]. This technology might be able to overcome the limitation of traditional air-laying technique.

Mechanical web formation. In literature, there is no evidence for using mechanical nonwoven production techniques (carding, needle punching) to produce pulp-based nonwovens. The fibre length of a few mm’s can be the underlying reason which is ten-fold smaller than textile fibres (10-25 mm) while having similar diameters. Further experimental research is required to develop a mechanical technique to form a paper web.

Potential partners

- Dan-Web
- Anpap
- Rando
- Aalto University: founder of air dynamic forming

<table>
<thead>
<tr>
<th>Energy reduction potential</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="leaf.png" alt="Leaf Icon" /></td>
<td><img src="tech.png" alt="Tech Icon" /></td>
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</tbody>
</table>
## Requirements table

<table>
<thead>
<tr>
<th>Concept</th>
<th>Commercial viability</th>
<th>Energy reduction</th>
<th>Paper strength</th>
<th>Water usage</th>
<th>recyclability</th>
<th>Continuous</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-laid technology (including ADF)</td>
<td>Yes, Air laid technology is applied on commercial scale</td>
<td>up to 50%</td>
<td>Low</td>
<td>None when not accounting for a strength binder</td>
<td>Similar to normal paper</td>
<td>Yes</td>
<td>5-6</td>
</tr>
<tr>
<td>Mechanical nonwoven</td>
<td>Biggest challenge will be formation of the short fibre length (1-2mm)</td>
<td>High energy reduction potential</td>
<td>Assumed low</td>
<td>May be required for crosslinking</td>
<td>Expected similar to normal paper</td>
<td>N/A</td>
<td>1-2</td>
</tr>
</tbody>
</table>

 Sources [4]–[8]
CASE 2A SOLUTION SPINNING

Introduction

The main constituent of papermaking pulp is cellulose a natural polymer that, with the proper solvent, can be dissolved. Dissolved cellulose can be solidified to fibres by using an anti-solvent or by removing the solvent. Fibers can, therefore, be generated with a tailored length and diameter. It is valuable to explore the properties of such fibres and what techniques are available to spin such fibres.

Application to papermaking

The technique aims to efficiently remove the solvent from the dissolved cellulose ensuring the aggregation and solidification of the cellulose. Based on the type of spinning technique a thread or a nonwoven mat can be produced. The process is applied to create nano-cellulose fibres (crystalline or micro-fibrillated) [9]. The main challenges are to seek a high-throughput spinneret and use a cheap, scalable, non-volatile and non-toxic solvent [10], [11] (See case 2B). Other challenges are scalability of the technique and paper-like material spinning [12]. The scouted techniques to create a cellulose web are electrospinning and solution spinning.

- **Electrospinning**: Is a technique that uses electricity to extract the solvent from the cellulose solute. The solution is pressed through a nozzle into a charged field (kV). In this charged field the solution evaporates allowing the cellulose to solidify in small fibres (nano- & microfibers).

- **Solution blowing**: is based on a liquid (solute) that is pressed through a nozzle. Solidification occurs using heat to evaporate the solvent and by using an anti-solvent (e.g. water). Therefore, a rinse and drying step is still required.

Potential partners

- Neenah Gessner
- Lenzing
- Ri.se
- Elmarco
- Areka

<table>
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<tr>
<th>Energy reduction potential</th>
<th>Technology Readiness Level</th>
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<td><img src="image1.png" alt="Leaves" /></td>
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<td></td>
<td><img src="image3.png" alt="Light bulb" /></td>
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<tr>
<td></td>
<td><img src="image4.png" alt="Tool" /></td>
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<tr>
<td></td>
<td><img src="image5.png" alt="Shopping cart" /></td>
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</table>
## Requirements table

<table>
<thead>
<tr>
<th>Concept</th>
<th>CO2 emission reduction</th>
<th>Paper-like material</th>
<th>Homogeneous application</th>
<th>Bond other fibres</th>
<th>Recyclable</th>
<th>Paper web formation</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrospinning</td>
<td>Substantial electricity use: Applied voltage 2-12 kV/cm, flow rate 5-20 µl/min</td>
<td>Yes, Similar to air-laid paper (nonwoven napkin)</td>
<td>Yes, with electrospinning it can be tailored</td>
<td>Yes, but fibre strength is not known</td>
<td>Solvent evaporates</td>
<td>Yes, for example, a nonwoven napkin is made (Young’s modulus between 5 - 30 Mpa)</td>
<td>5-6</td>
</tr>
<tr>
<td>Melt/solution blowing technique</td>
<td>Hot air pressure is used (140 degrees C), the solution is heated up to 140 degrees C. Coagulation occurs in water, also washed in water. CO2 drying could be applied</td>
<td>Nonwoven type of fabric, a thin or thick web can be created</td>
<td>Yes</td>
<td>Yes, web is formed</td>
<td>Assumed based on dissolvability, but complexity in recycling the solvent (see case 2B)</td>
<td>Extruded to form a web with fibres with a diameter of 0.1 mm.</td>
<td>5-6</td>
</tr>
<tr>
<td>Airgap spinning / Dry jet wet spinning: Cellulose fibres</td>
<td>Dissolution at 80 degrees C, completely dissolved after 90 min</td>
<td>Viscose-like material is created, tenacities above 50 cN/tex and initial modulus of 34 GPa</td>
<td>No, a thread is created</td>
<td>The spin head allows only to create single spun fibres; a new system should be designed in which the fibres coagulate in a web rather than a spun thread.</td>
<td>Fibre recycling similar to viscose/rayon recycling. Recycling of solvent by evaporation</td>
<td>No</td>
<td>5-6</td>
</tr>
</tbody>
</table>

Sources [13]–[30]
CASE 2B CELLULOSE SOLUTION

Introduction

Case 2A has shown that it is theoretically possible to produce a cellulose nonwoven from a cellulose solution. The solvent for cellulose dissolution plays an important role in the spin-ability and properties of cellulose. Four solvent-systems have been determined that can dissolve cellulose while being subject to requirements like environmental impact and toxicity: NaOH, urea and thiourea, Ionic liquids (ILs), N-Methylmorpholine-N-oxide (NMMO) and Deep Eutectic solvents.

Application to papermaking

Solvents systems based on Sodium hydroxide (NaOH), urea and thiourea can be used in different compositions to dissolve cellulose. The dissolving occurs in minutes at low temperatures (-10°C to 10°C). Fibre characteristics, when spun from this system, are with a crystallinity similar to cellulose II (regenerated cellulose) and good mechanical properties [31].

Ionic Liquids are complex salt structures that are environmental-friendly compared to conventional harmful cellulose solvents used for viscose production. Cellulose dissolves in room temperature ILs and can be combined with electrospinning technique [32], [33].

NMMO is the solvent currently used in the Lyocell-process that is less harmful than the volatile viscose process solvents. Viscose type fibres can be created at temperatures in the range of 80°C to 100°C and solidify in an aqueous bath [34], [35].

Deep Eutectic solvents are a class of ionic liquids from natural resources with the ability to dissolve cellulose. This new class of liquids are biodegradable, non-flammable, non-volatile, non-toxic and biocompatible [36]. DESs have been used in the electrospinning of PVA and Chitin [37], [38].

Potential partners

- Iolitec (ILs)
- Solvionic (ILs)
- Proionic (ILs)
- Lenzing (NMMO)
- Shrieve chemical products (DES patent holder)

<table>
<thead>
<tr>
<th>Energy reduction potential</th>
<th>Technology Readiness Level</th>
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<tbody>
<tr>
<td><img src="image1" alt="Leaf" /> <img src="image2" alt="Leaf" /> <img src="image3" alt="Leaf" /></td>
<td><img src="image4" alt="Icon1" /> <img src="image5" alt="Icon2" /> <img src="image6" alt="Icon3" /> <img src="image7" alt="Icon4" /> <img src="image8" alt="Icon5" /></td>
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</tbody>
</table>
## Requirements table

<table>
<thead>
<tr>
<th>Concept</th>
<th>Scalability</th>
<th>Environmental effects</th>
<th>Material availability</th>
<th>Toxicity</th>
<th>Speed of solubility</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaOH, urea and thiourea in aqueous solution</td>
<td>Scalability complexity is the low-temperature dissolution</td>
<td>When the solvents are diluted NaOH and urea are unpleasant. Thiourea affects plant growth</td>
<td>All products readily available</td>
<td>NaOH LD50 is 40 mg/kg; Thiourea LD50 is 125 mg/kg furthermore it inhibits the thyroid function, Urea LD50 is 8500 mg/kg</td>
<td>5 min, -10 to 8 °C</td>
<td>5</td>
</tr>
<tr>
<td>Ionic liquid: 1-ethyl-3-methylimidazolium chloride (CMIMCl), 1-butyl-3-methylimidazolium chloride (BMIMCl), Tetrabutylphosphonium hydroxide, 1-ethyl-3-methylimidazolium acetate and 1-decyl-3-methylimidazolium chloride, 1-ethyl-3-methyl imidazolium diethyl phosphate, Lithium chloride/N, N-dimethylacetamide (LiCl/DMAc), 1-allyl-3-methylimidazolium chloride</td>
<td>High-temperature processability</td>
<td>ILs claimed to be a &quot;green alternative&quot; for harmful current cellulose solvents</td>
<td>Available but not in industrial quantities</td>
<td>EMI was negative in the LLNA, the irritancy assay, and the MEST</td>
<td>A few minutes up to hours at elevated temperatures</td>
<td>2-3, not applied yet in the papermaking process</td>
</tr>
<tr>
<td>N-Methylmorpholine-N-oxide (NMMO)</td>
<td>Scalability is determined by compatibility with nonwoven spinning techniques</td>
<td>Considered to be the most environmental-friendly process, &gt;98% re</td>
<td>Commercially available</td>
<td>Toxic product and explosive by-products are created at elevated temperatures</td>
<td>N/A</td>
<td>8 (applied in industrial scale)</td>
</tr>
<tr>
<td>Deep eutectic solvents (DESs): formic acid: choline chloride, lactic acid: choline chloride, acetic acid: choline chloride, lactic acid: betaine, and lactic acid: proline</td>
<td>Not presented at large scale however small ecological footprint, lower price, no waste in process and no purification make it easier to scale up the technology</td>
<td>Biocompatible and biodegradable</td>
<td>Available on large scale</td>
<td>Nontoxic</td>
<td>N/A</td>
<td>3-4</td>
</tr>
</tbody>
</table>

Sources: NaOH-Urea-Thiourea [31], [39]–[41], ILs [32], [33], [42]–[47], NMMO [48]–[50], DESs [36]–[38]


CASE 3 CROSS-LINKING

Introduction

In paper production, water plays the general role as carrier and facilitator to the resultant paper properties. Especially the facilitation of web formation and hydrogen bonds between the fibres enable the creation of paper as we know it. In a scenario that reduces or eliminates water use, cellulosic fibres still need to form a strong web. It is important to be aware of the cross-linking additives that are available to improve (nearly) dry formed paper sheets. In this scout, multiple cross-linking additives have been searched. They can be categorised into three groups: Solution-based cross-linkers for use in nearly-dry sheet formation, dry based cross-linkers for dry sheet formation and dry-based cross-linking methods.

Application to papermaking

Category 1 – Nearly-dry-sheet formation: In this approach, materials assist crosslinking when in (aqueous) solvent. This technique does not mitigate the need for water, and therefore a drying step is still required. However, it is possible that these cross-linkers can be applied in a low amount of water to support the crosslinking of water for generating cross-linked bonds besides the hydrogen bonds.

Category 2 – Dry-sheet formation: For this web formation approach cross-linking additives are added when paper is dry-formed. Dry-sheet formation can be created using resins to bind paper fibres [51]. The dry formation can be enabled using bio-based resins and binders.

Category 3 – Dry-based cross-linking methods: The third category encompasses techniques that facilitate solvent free cross-linking. Two techniques have been observed: Mechanochemical crosslinking and dry-state surface treatment.

Potential partners

- Epson PaperLab (Cat 2)
- Senbis (Cat 2)
- UTwente - Dr. ir. Jos Paulusse, mechanochemistry (Cat 3)
- The Brown research group (Cat 3)

<table>
<thead>
<tr>
<th>Energy reduction potential</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
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<td>![Icon]</td>
</tr>
</tbody>
</table>

Figure 5 Cellulose crosslinking with citric acid © Cuadro et al. [226]
<table>
<thead>
<tr>
<th>Concept</th>
<th>Environmental impact</th>
<th>Safety</th>
<th>CO2 emission reduction</th>
<th>Energy reduction</th>
<th>Cost-effective</th>
<th>Material availability</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat 1 – (Dialdehyde) carboxymethyl cellulose (CMC), EDC, adipic dihydrazide, polyelectrolyte complexes [52]–[57]</td>
<td>Low</td>
<td>High</td>
<td>N/A</td>
<td>In combination with EDC up to 500% and 100% in wet web strength can be achieved, furthermore substantial energy reduction in the pre-treatment process for NFC production</td>
<td>N/A</td>
<td>High</td>
<td>3-4 (Lab scale)</td>
</tr>
<tr>
<td>Cat 2 – Gelatine (thermoformability) [58]</td>
<td>Directly none, indirectly from cattle industry</td>
<td>High</td>
<td>N/A</td>
<td>No high-temperature curing is required to make strength paper.</td>
<td>N/A</td>
<td>Inexpensive and facile method to improve plasticity of fibre networks</td>
<td>Medium</td>
</tr>
<tr>
<td>Cat 1 – glutaraldehyde-chitosan, glutaraldehyde-PVA [59], [60]</td>
<td>Aquatic toxicity but can be biologically degraded</td>
<td>Is toxic, so may cause skin irritation, nausea, headache and breath shortness</td>
<td>Assumed, as partial replacement in water-based production</td>
<td>No high-temperature curing is required to make strength paper.</td>
<td>Less expensive alternative for formaldehyde</td>
<td>High</td>
<td>3-4</td>
</tr>
<tr>
<td>Cat 1 – Ester crosslinking: Citric acid (CA), Polyamino carboxylic acid, 1,2,3,4-butane tetracarboxylic acid [61]–[64]</td>
<td>Low, bio-based</td>
<td>Exposure to pure citric acid causes adverse effects</td>
<td>Depends, The crosslinker is an additional step in papermaking (using pad-dry-cure process). Experimental studies must show if this material can be used to increase paper strength of dry-formed papers</td>
<td>Similar to the previous requirement</td>
<td>It can be applied in an open, paper-like production plant</td>
<td>Available</td>
<td>N/A</td>
</tr>
<tr>
<td>Cat 1 - Protein: Cellulose crosslinking protein (CCP &amp; CBD) [65]</td>
<td>Environmental-friendly</td>
<td>High</td>
<td>N/A</td>
<td>Assumed, as dry fibres can be used for MDF production. The “glue” should be examined for dry laid paper production and press</td>
<td>Costly production</td>
<td>Low</td>
<td>2-3</td>
</tr>
<tr>
<td>Cat 2 - Enzymatic binder: Laccase [66]</td>
<td>Low</td>
<td>Low</td>
<td>Assumed, as the laccases can be used to create a glue-type cross-link as presented in the production of MDF board</td>
<td>Assumed, as dry fibres can be used for MDF production. The “glue” should be examined for dry laid paper production and press</td>
<td>Yes, if mediator (4-hydroxybenzoic acid) is used</td>
<td>Medium</td>
<td>5-6 (Pilot)</td>
</tr>
<tr>
<td>Cat 3 – Dry surface treatment (DST) [67]</td>
<td>Depends on applied coating, For example when PLA is used the environmental impact is low</td>
<td>High</td>
<td>High if the coating material can exclude the use of water as binder</td>
<td>High if the coating material can exclude the use of water as binder</td>
<td>Cost-effectiveness claimed, can also be used in coating and sizing process</td>
<td>Depends on binder/polymer/coating used</td>
<td>3-4</td>
</tr>
<tr>
<td>Cat 3 – Mechanochemical crosslinking with succinic anhydride [68]</td>
<td>Environmentally benign technique, however slow biodegradability of PVA</td>
<td>High</td>
<td>Low, biggest benefit is the mitigation of toxic solvents</td>
<td>Mechanochemistry is energy intensive</td>
<td>N/A</td>
<td>High</td>
<td>3-4</td>
</tr>
<tr>
<td>Cat 1 – Waterborne polyurethane (WPU) microemulsions [69]</td>
<td>Medium, uses nondegradable polyurethanes</td>
<td>Inert when PU is fully reacted when combusted CO and HCN are generated</td>
<td>When only used as linker in dry-formed sheets</td>
<td>Similar to CO2 reduction</td>
<td>Only if high paper quality is achieved</td>
<td>High</td>
<td>5-6</td>
</tr>
<tr>
<td>Cat 2 – Green binders for air-laid paper: Proteins, carbohydrates, lignin, phenolic compounds [70]</td>
<td>Low</td>
<td>High</td>
<td>Only if similar strength to wet-laid can be reached.</td>
<td>Only if similar strength to wet-laid can be reached.</td>
<td>Reasonably priced</td>
<td>Available in large quantities</td>
<td>5-6</td>
</tr>
</tbody>
</table>
CASE 4 ALCOHOL AS A CARRIER

Introduction

Water plays an important role in the production of paper. It acts as a swelling agent for the cellulose fibres which enhance the mutual contact area. It serves as a solvent for chemical additives, as suspending medium for solids and enables good dispersing to create a uniform sheet [71]. Water is a strongly polar molecule. The dipole moment (Figure 6) makes the oxygen partially negative and each hydrogen partially positive. The dipole moment contributes to hydrogen bonding and explains many of the properties of water (e.g. capillary action). One of this properties is the very high specific heat capacity (4.181 J/(g·K) at 25 °C), as well as a high heat of vaporisation (2257 kJ/kg at the normal boiling point). The high heat of vaporisation results in high energy demand for paper drying.

Application to papermaking

A possible solution space to reduce the energy consumption during paper production is the substitution of water with a less polar molecule like alcohols. Compared with water the heat of vaporisation of different alcohols (methanol, ethanol, n-propanol and n-butanol) is much lower which indicate the possibility to reduce the energy needed for paper drying. Research shows a major downside for the use of alcohols in paper production as the paper strength properties will greatly decrease. Besides, the use of highly flammable and explosive alcohols at such a large scale is a point of attention. At last the recyclability must be investigated to make the use of alcohols economically interesting.

Potential partners

- National Centre for Research and Development, Poland
## Requirements table

<table>
<thead>
<tr>
<th>Medium</th>
<th>Heat of Vaporization (kJ/kg)</th>
<th>Braking Length (m)</th>
<th>Tear Resistance (mN)</th>
<th>Breaking Energy (J)</th>
<th>Process Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>2257</td>
<td>8020</td>
<td>581</td>
<td>0.169</td>
<td>None</td>
</tr>
<tr>
<td>Methanol</td>
<td>1104</td>
<td>3940</td>
<td>400</td>
<td>0.104</td>
<td>Highly flammable, Explosive</td>
</tr>
<tr>
<td>Ethanol</td>
<td>841</td>
<td>3690</td>
<td>379</td>
<td>0.102</td>
<td>Highly flammable, Explosive</td>
</tr>
<tr>
<td>n-Propanol</td>
<td>760</td>
<td>3020</td>
<td>304</td>
<td>0.096</td>
<td>Highly flammable, Explosive</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>590</td>
<td>1800</td>
<td>177</td>
<td>0.055</td>
<td>Highly flammable, Explosive</td>
</tr>
</tbody>
</table>

Sources [72], [73]
CASE 5 SUPERCritical SOLUTION

Introduction

In a supercritical solution, the temperature and pressure are brought above the critical point. In the supercritical state, the distinction between gas and liquid becomes closer to each other because the density of the liquid and gas phase become more equal. Supercriticality can be advantageous because products tend to dissolve better in a supercritical solution. The thermos-physical properties can be varied by adjusting operating pressure and temperature. Processes involving supercritical fluids require less energy and can be more environmentally friendly than solvent-based processes, due to their physical and chemical properties [74]. Therefore, it is interesting to explore if supercriticality can be applied to the papermaking process as dispersing solution.

Supercriticality can be used to dissolve cellulose in water. Under normal conditions, cellulose is insoluble in water but when brought to supercritical point cellulose can dissolve [75]. Cellulose dissolves due to a reduction of hydrogen bonds between water molecules and nearly ceases to exist above 573 K. The self-organisation of the water molecules decrease, and therefore the crystalline cellulose can be more easily dissolved [75].

Application to papermaking

The dissolved cellulose can be recrystallised when forced through a nozzle into a low-pressure chamber. This process is known as Rapid Expansion of Supercritical Solutions (RESS). The advantage of this process is good control of particle size, particle distribution and morphology. Although nothing is explicitly stated about a paper-web like structure, Jung and Parrut (2001) suggest that RESS can be used for the formation of fibres (cellulose II. [76], [77]). Also, the advantage of good distribution with RESS indicates that a web-like structure can be created. Water would in the low-pressure chamber be well above liquid phase and turns into steam.

Potential partners

- Steritech
- ThyssenKrupp
- Aalto University – Lasse Tolonen (lasse.tolonen@aalto.fi)

![Energy reduction potential and Technology Readiness Level](chart.png)
### Requirements table

<table>
<thead>
<tr>
<th>Technique</th>
<th>Energy reduction potential</th>
<th>Commercial viability</th>
<th>Scalability</th>
<th>Open process compatibility</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulp/cellulose in supercritical solution</td>
<td>Estimated low as high pressure and temperature are involved. Beneficial is the one-step process. Energy use is stated as comparable to conventional solvent-solid extraction [78]</td>
<td>Techniques available, solely based on product properties.</td>
<td>For scalable production, large pressure tanks are required.</td>
<td>The current setup only shows recrystallisation in expansion vessel.</td>
<td>2</td>
</tr>
</tbody>
</table>

Sources [74], [75], [77], [79]–[84]
CASE 6 SUPERCritical DRYING

Introduction

To remove liquid from a suspension super criticality can be used. Super criticality means that the substance temperature and pressure are brought above the critical point. In this state the distinction between gas and liquid disappears, the density of the liquid and gas phase becomes equal. Super criticality is advantageous because it has a lower viscosity and diffusivity than liquid. The literature describes two methods using super criticality: supercritical drying and supercritical extraction.

Application to papermaking

Supercritical (carbon dioxide) drying is a relatively new process to remove liquids (e.g. water) from solid (porous) materials. Water can also be used in supercritical drying however it has a high critical point requiring high pressure and temperature (22MPa, 647K [82]). To reduce energy use in aqueous drying the water can be washed out with ethanol or acetone which is subsequently removed by CO₂ under high pressure [82], [85]. Four supercritical drying methods could be applied for water removal in the papermaking process [86], [87]:

- Supercritical gas drying (SCGD) uses liquid CO₂ to replace the water after which it is raised to supercritical level.
- Supercritical organic solvent drying (SCOD) where the organic solvent with CO₂ is raised to a supercritical state.
- Supercritical mixture solvent drying (SCMD) in which solvent is mixed with CO₂ (g) and raised to the supercritical state of the mixture.
- Spray drying with the assistance of supercritical gas (SASD) is a combination of the supercritical state and spray drying wherein the substance is sprayed in a chamber and dried.

Potential partners

- Waters
- Suflux
- CO₂dry / Feyecon

<table>
<thead>
<tr>
<th>Energy reduction potential</th>
<th>Technology Readiness Level</th>
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</thead>
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<tr>
<td><img src="image" alt="Energy reduction leaves" /></td>
<td><img src="image" alt="Technology Readiness Level" /></td>
</tr>
</tbody>
</table>
Requirements table

<table>
<thead>
<tr>
<th>Method</th>
<th>High-speed process</th>
<th>Low CO₂ emissions from process</th>
<th>Cost-effective</th>
<th>Safety</th>
<th>Energy reduction</th>
<th>High paper strength</th>
<th>Closed / open system</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supercritical -</td>
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<td>• gas drying (SCGD)</td>
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<td></td>
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<tr>
<td>• organic solvent drying (SCOD)</td>
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<tr>
<td>• mixture solvent drying (SCMD)</td>
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<tr>
<td>• spray method supercritical drying (SASD)</td>
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<tr>
<td>Depending on technique drying times can be long or short.</td>
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<tr>
<td>CO₂ can be reused, although some amount is lost during depressurisation.</td>
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<tr>
<td>Is a standard dehydration technique, applied in many industries. However, operation and equipment costs are high. CO₂ dry claims up to 30% lower investment costs. Scalability required.</td>
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<tr>
<td>Working under high pressure may oppose risks in production</td>
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<tr>
<td>CO₂ drying energy depends on operating temperature and pressure required. CO₂Dry claims up to 50% energy reduction (compared to freeze-drying)</td>
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<tr>
<td>Nanopaper is three times stronger than normal. Structure remains intact</td>
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<tr>
<td>Sources [85], [86], [88]–[100]</td>
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</tr>
</tbody>
</table>

Figure 9 Schematic visualization of supercritical drying techniques © Zheng et al. [86]
CASE 7 ELECTRO DEWATERING

Introduction

Electrical assisted mechanical dewatering, known as electro-dewatering, is considered as one of the most effective hybrid processes for the improvement of wastewater sludge dewatering efficiency. The operating conditions of the electric field and pressure used in the electrically assisted mechanical dewatering are sufficient to remove a significant proportion of the water that cannot be removed using mechanical dewatering technologies alone. Thus electro-dewatering has the potential to be viable for a range of slurries, which either could not be sufficiently dewatered or would otherwise require extreme conditions using conventional dewatering devices. [101]–[104]. Some research showed the occurrence of electrolysis when applying sufficient high electrical fields. Electrolysis of water can be of interest as it produces H₂ and O₂. However, electrolysis is a high energy consuming process. With 100% theoretical efficiency it requires 13,2 GJ/t of water. This is, in comparison with the energy consumption during the current drying section (3,6 – 6,2 GJ/t of water [105]) 2 to 3,5 times higher. The current industrial state of the art show 70% electrolysis efficiency. The maximum theoretical efficiency of a fuel cell is 83%. Calculating with these numbers (18,9 GJ input and 11,0 GJ recovery per ton of electrolysed water) the net energy consumption will be 7,9 GJ/t of water. Electrolysis will therefore not yield a profit in terms of energy use. However, it can be an interesting option from an economic point of view.

Application to papermaking

Electro dewatering has the potential to assist in the press section of the current paper production process. Research on the efficiency of the technique is mainly done in the field of wastewater sludge dewatering. It has been shown that electro dewatering can be used to remove a significant proportion of the inherent water from conditioned activated wastewater sludge. It can remove from 10 to 24% of additional water, which cannot be accessed by the conventional mechanical dewatering process alone. The energy used to reach the additional dryness is significantly lower (10–25% lower) than that required for thermal drying techniques [102]. Research on the dewatering of cellulosic pulp and paper waste sludge shows a long dewatering time to get moisture content (55%) similar to the one obtained in the factory by mechanical methods. However, this comparison is difficult and non-concluding because of the difference of the applied mechanical compression forces. Advantage seems to be that the cake is better prepared to be hot air dried [105].

Table: Energy reduction potential

<table>
<thead>
<tr>
<th>Energy reduction potential</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Leaf icons]</td>
<td>![Triangle]</td>
</tr>
</tbody>
</table>

Figure 10: Mechanical dewatering and electro-dewatering with the different mechanisms © Mahmoud et al. [1]
As no research is found on the effect of electro dewatering in paper production, the ability to predict possible enhancements is limited. As seen in the waste sludge experiments the process speed will be a challenge to keep up with the current paper production speed.

**Potential partners**

- Energos
- Bluewin
- The Laboratory of Thermal, Energetic and Processes, University of Pau, France

**Requirements table**

<table>
<thead>
<tr>
<th>Technique</th>
<th>Potential Energy Reduction</th>
<th>Substantial Water Removal</th>
<th>Speed of Process</th>
<th>Water Reusability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro Dewatering</td>
<td>10 – 25% of additional dryness compared with thermal drying technique</td>
<td>10 – 24% additional water than mechanical dewatering</td>
<td>20 – 250 minutes contact time for waste sludge</td>
<td>Same as current mechanical press process</td>
</tr>
</tbody>
</table>

Sources [101]–[106]
CASE 8 ULTRASONIC DEWATERING

Introduction

Ultrasound is sound waves (ultrasonic waves) with frequencies higher than the upper audible limit of human hearing (from 20 kHz up to several gigahertz). It is no different from 'normal' (audible) sound in its physical properties. The applications of ultrasonic waves are divided into two groups: low and high intensity. Low-intensity ultrasonic waves are those wherein the objective is to obtain information about the propagation medium without producing any modification in its state. On the contrary, high-intensity applications are those wherein the ultrasonic energy is used to create permanent changes in the treated medium [107]. High-intensity ultrasound is suitable for dewatering and drying of moisture containing solids (ultrasonic dewatering) without the introduction of heat. Studies to ultrasonic dewatering are mainly in the field of food processing, and more recently some research is done in the field of fabric drying.

Application to papermaking

Ultrasonic dewatering can be of interest in reducing the moisture content of paper before entering the drying section or to replace the drying section completely. Two different ultrasonic dewatering techniques are identified.

**Ultrasonic Assisted** convective (hot air) drying resulting in an acceleration of heat and mass transfer and reduction of the drying time without a significant increase in product temperature [108]. The drying time for the convective drying of clipfish can be reduced by 43% with the application of airborne ultrasound at an intensity 25 W kg$^{-1}$. The change in the drying rate is more significant at the beginning of the drying process than at the end [109]. However, one of the main difficulties in the application of ultrasonically assisted drying is to achieve efficient generation and transmission of ultrasonic energy from the transducers to the product while ensuring easy adaptability to conventional drying processes [107], [110].

**Direct Contact Ultrasonic** drying involves placing the ultrasonic transducer in direct contact with the material. A high-frequency vibration atomises water turning it into a cold mist [111]. The good acoustic impedance matching between the vibrating plate of the transducer and the material favours the deep penetration of acoustic energy and increases the effectiveness of the process [107]. A demonstration unit was fabricated to show the efficacy of the process and its energy saving compared to the thermal drying process. The preliminary results showed that the energy consumption of the direct contact ultrasonic press drier which was made of the metal mesh-based transducer was five times less than the latent heat of evaporation at water contents greater than 20% [112].

<table>
<thead>
<tr>
<th>Energy reduction potential</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image.png" alt="Leaf Icons" /></td>
<td><img src="image.png" alt="Technology Icons" /></td>
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</table>
Potential partners

- Herrmann Ultrasonics + Video
- Oak Ridge National Laboratory (ORNL)

Requirements table

<table>
<thead>
<tr>
<th>Technique</th>
<th>Potential Energy Reduction</th>
<th>Scalability</th>
<th>Paper Quality Affection</th>
<th>Continuous Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonic Assisted</td>
<td>30%</td>
<td>Challenge to achieve efficient transmission of the ultrasound on large scale</td>
<td>Not tested on paper</td>
<td>Yes</td>
</tr>
<tr>
<td>Direct Contact</td>
<td>Up to 80%</td>
<td>No restriction on the ultrasonic surface</td>
<td>Not tested on paper</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Sources [107]–[113]
CASE 9 OSMOTIC DEWATERING

Introduction

Osmosis is the movement of a solvent through a semi-permeable membrane into a region with a solution of higher osmotic value (e.g. higher dissolved salt concentration), in the direction to equalise the solute concentration (osmotic value) of the two sides. Osmosis may thus be used for separation of water from a solid/water mixture. The process results in a concentration of the feed stream and dilution of the highly concentrated stream (referred to as the draw solution).

Application to papermaking

Forward osmosis is an engineering process utilising natural osmosis whereby the water from the feed stream passes through a semi-permeable membrane which has the advantages of low energy requirements. The method can potentially be used to assist in the press section of the current paper production process to reduce the moist amount before entering the drying section. Research on this technique focusses on wastewater sludge dewatering, water treatment and food processing. As the process will dilute the draw solution and reduce its osmotic value, Reverse osmosis can be used to restore the needed osmotic value. Reverse osmosis uses pressure to force the water through a semi-permeable membrane from an area of high osmotic value to an area of low osmotic value. Research in the field of sludge dewatering has shown a solids level of 70-80% with a process speed of 8 L/h per m2 of membrane surface [114].

As no research focuses on the effect of forwarding osmosis in paper production, the ability to predict possible enhancements is limited. As seen in the waste sludge experiments the process speed will be a challenge to keep up with the current paper production speed.

Potential partners

- HTI Water
- CSIRO

<table>
<thead>
<tr>
<th>Energy reduction potential</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="leaves.png" alt="Leaves" /></td>
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## Requirements table

<table>
<thead>
<tr>
<th>Technique</th>
<th>Potential Energy Reduction</th>
<th>Substantial Water Removal</th>
<th>Speed of Process</th>
<th>Water Reusability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward osmosis</td>
<td>N/A</td>
<td>70-80% solids level with sludge waste</td>
<td>Slow. Up to 15 L/h per m² of membrane surface</td>
<td>Water reusable with the use of reverse osmosis</td>
</tr>
</tbody>
</table>

Sources [114]–[118]
CASE 10 MICROWAVE DRYING

Introduction

Microwaves heat up materials by dielectric heating. The dipole moment of water enables molecular friction when radiated with microwaves. Therefore, products heat up homogenously and efficiently, especially when consisting of water. The advantages of microwave heating are efficient heating of materials in a very short timeframe (up to 10 times faster than convection heating) and requiring little space (10% of floor space [119]).

Application to papermaking

Microwave drying is explored in many fields, and therefore a lot of different set-ups exist. Four categories have been distinguished that could be applied: Continuous microwave dryer (belt technology), Microwave vacuum based dehydration, Microwave-osmotic dehydration and microwave-assisted hot air drying.

1. Continuous microwave dryer (belt technology) is a drying technique where multiple microwave generators are placed perpendicular to a drying belt. The technique is used to dry materials like wood, board and ceramics [120].
2. In microwave vacuum (MWV) based dehydration microwave technology is combined with a vacuum system. In vacuum, water vaporises at much lower temperatures with better heat distribution. Energy consumption is estimated 2.98-7.7 MJ/kg while 4.45-6.50MJ/kg is the estimation of conventional air-drying energy use [121].
3. Microwave-osmotic dehydration (MWOD) uses osmotic dehydration to increase moisture loss speed of, especially fruit products. The moisture loss compared to other techniques was 30 to 94% faster [122].
4. Microwave-assisted hot air drying (MWHA) is a combination of hot air ventilation and microwave power [123].

The general challenge with the microwave technique for drying is defining the optimal values for parameters like frequency (Hz), power (W) and assistive drying techniques (hot-air, vacuum, osmotic, freeze).

Potential partners

- Romill
- Pueschner
- Process technologies

<table>
<thead>
<tr>
<th>Energy reduction potential</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
</table>
## Requirements table

<table>
<thead>
<tr>
<th>Concept</th>
<th>Scalability</th>
<th>Paper quality</th>
<th>Attainability</th>
<th>Continuous</th>
<th>Energy reduction potential</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave: Microwave belt drier, Continuous microwave dryer, Microwave-Osmotic Dehydration, Microwave-Vacuum-Based Dehydration, Microwave-assisted hot air drying</td>
<td>Yes, is industrially applied in many industries and uses less than 10% of convection drying floor space. However, the optimal characteristics for large-scale paper application need to be developed.</td>
<td>All properties were found to be either enhanced or at the same level. Microwaves enhance bonding strength between fibres [124].</td>
<td>Needs to be tailored and experiment ed with microwave suppliers</td>
<td>Yes, using a belt drying system</td>
<td>Microwave drying is regarded as an efficient technology. Heat is generated principally in the product and a significant time reduction can be achieved. In research has been estimated that microwave technology can achieve 20% energy reduction.</td>
<td>6+</td>
</tr>
</tbody>
</table>

Sources [119]–[123], [125]–[135]
CASE 11 HYGROSCOPIC DRYING

Introduction

Hygroscopic materials are materials that extract moisture from their surroundings. The effect can be viewed as a similar process to osmotic extraction; the moisture is directed to the regions with high adsorption potential until the vapour pressure inside the hygroscopic material/desiccant is in equilibrium with the outside air. Hygroscopic materials function at room temperatures making them ideal for in-house dehumidifiers [136]. Materials that are known for their hygroscopic behaviour are cellulose, salts, silica gels, activated carbon, borax, alum and zeolites [137]. The primary downside for desiccants is their slow adsorption speed (hours) [138], [139].

Application to papermaking

Desiccants adsorb moisture from air based on the difference in vapour pressure. Therefore, to apply desiccants in papermaking, water needs to be turned into moisture enabling a vapour pressure difference. To facilitate the moisture extraction water could be moisturised using a continuous dry air flow. This air flow can be combined with a desiccant wheel system [140]. The desiccant wheel is a circular system where dry air can be used to moisturise water from, for example, paper that subsequently is dehumidified by the desiccant in the rotary wheel. When the desiccant is saturated, it can be dehumidified itself by a stream of heated air or using microwave technology [141].

Potential partners

- Atlas Copco
- Hoval
- Novatec

Figure 15 Schematic visualization of desiccant setup. © Zhang et al. [144]

Figure 146 Picture of solid silica gel desiccant © Tradekorea.com

<table>
<thead>
<tr>
<th>Energy reduction potential</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
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<td>![leaf icons]</td>
<td>![technology icons]</td>
</tr>
</tbody>
</table>
### Requirements table

<table>
<thead>
<tr>
<th>Concept</th>
<th>Sustainable energy reduction</th>
<th>Doesn’t affect quality of paper</th>
<th>Scalability</th>
<th>Cost-effective</th>
<th>“Easy” water absorption</th>
<th>Re-usability of the crystal</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desiccant drying</td>
<td>A significant energy</td>
<td>The technique is</td>
<td>Is a low-</td>
<td>Desiccants are</td>
<td>The desiccant was reused</td>
<td>1-2 (for paper)</td>
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<td>consumption reduction can</td>
<td>applied to dry delicate and</td>
<td>cost drying</td>
<td>applied as</td>
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<td>be achieved when</td>
<td>heat sensitive structures</td>
<td>method</td>
<td>dehumidifiers and</td>
<td>without loss of</td>
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<td>combined with fluidised bed</td>
<td>as flowers and as a means to</td>
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<td>do not have a rapid</td>
<td>functionality.</td>
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<td>and solar</td>
<td>conserve product</td>
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<td>adsorptive power of</td>
<td>The desiccant can be</td>
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<td>characteristics. It is</td>
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<td>water in the liquid</td>
<td>regenerated using a stream</td>
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<td>therefore assumed that the</td>
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<td>of hot air that</td>
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<td>quality of paper is not</td>
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</tbody>
</table>

Sources [69], [136], [138]–[140], [142]–[146]
CASE 12 SUPERHEATED STEAM

Introduction

Superheated steam is steam at a higher temperature than its vaporisation point with the corresponding pressure and is generated by heating the saturated steam obtained by boiling water. Drying with superheated steam have some advantages over conventional convective drying; Lower energy use due to the possibility of reusing the latent heat of evaporation, higher heat transfer coefficient that leads to a reduction in drying time and the potential of new product quality specifications [147], [148].

Application to papermaking

Superheated steam drying is not a new concept in paper drying and is an alternative to replace the current drying section.

Superheated Steam Impingement Drying is one of the possible future designs for the paper industry. This technique is in development and advantages are expected in energy savings, reduction in equipment size and paper quality properties [149]. Research on paper quality dried with superheated steam reports an increase in strength, toughness and tensile index [150]. The lower temperature of superheated steam caused by the vaporisation of water during the drying process will not result in condensation, as the temperature is higher than the saturation temperature and stays in superheated condition. The excess steam can be recovered with the use of mechanical compression of vapour [147]. Suggestions are made to combine superheated steam drying with a supplementary heat source (e.g. microwave) to speed up the drying rate [151].

Potential partners

- Fraunhofer
- CDS

<table>
<thead>
<tr>
<th>Energy reduction potential</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Leaves" /></td>
<td><img src="image" alt="Icons" /></td>
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</tbody>
</table>
### Requirements table

<table>
<thead>
<tr>
<th>Technique</th>
<th>Potential Energy Reduction</th>
<th>Steam regeneration</th>
<th>Scalability</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superheated steam impingement drying</td>
<td>Up to 50%</td>
<td>Mechanical vapour recompression</td>
<td>Tests in pilot scale</td>
<td>Process at atmospheric pressure</td>
</tr>
</tbody>
</table>

Sources [147]–[152]
CASE 13 FOAM FORMING

Introduction

The role of water is undisputable in the papermaking process. Water is used as a swelling agent; it increases the contact area between fibres, it is used as a solvent for additives, it is the suspending and dispersing medium, and it facilitates the creation of hydrogen bonds [71]. Therefore, completely removing water from the papermaking process requires technology that needs to replace all the functions of water. Instead of completely removing water from the process there might also be solutions that enable web-forming using a reduced amount of water. The benefit of such a technique would be that water can still be used to enable hydrogen bonding and as a swelling agent, while less drying energy is required. Techniques that facilitate such a forming system are foam forming and the use of strength additives like zwitterions that increase the coulombic interaction between the fibres.

Application to papermaking

Foam forming is a technique developed by VTT that uses microbubbles to create a very dense foam. The foam can be laid on an adapted papermaking machine. As air is combined with water, less water is required to suspend pulp while maintaining the creation of paper-like materials. Expected savings will be up to 30% in drying energy and overall 20% in energy reduction while using less raw materials [153].

Zwitterions are not a forming technique but rather an additive that can be used to increase the paper strength. Zwitterions increase the coulombic interaction between the fibres. The coulombic interaction in paper strength has been researched extensively as the primary bond for paper strength. Zwitterions could be added to the mixture when paper is formed with low water content (using steam formation) after a waterless laying technique [73], [154].

Potential partners

- VTT
- Valmet

<table>
<thead>
<tr>
<th>Energy reduction potential</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Energy Reduction Icons]</td>
<td>![Technology Icons]</td>
</tr>
</tbody>
</table>
# Requirements table

<table>
<thead>
<tr>
<th>Concept</th>
<th>Speed of process</th>
<th>Cost-effectiveness</th>
<th>Energy reduction</th>
<th>Scalability</th>
<th>Emission reduction</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foam forming</td>
<td>1000m/min</td>
<td>60-85% of current cost</td>
<td>20%</td>
<td>Yes</td>
<td>Up to 30% reduction in drying energy</td>
<td>6 (pilot stage)</td>
</tr>
</tbody>
</table>

Sources [153], [155]–[157]
APPENDIX I: COMPLETE TECHNOLOGY LIST

1. **Air-laying**: A technique very common in papermaking for paper products like napkins and tissues. In contrast to the “wet” papermaking process, in air-laid production of paper air is used as the medium to create the nonwoven. Challenges will be in creating paper with similar strength and characteristics as normal paper. [158] [159] [6]

2. **Carding**: A technique to create non-woven sheets with mechanical force. Fibers are mechanically placed in interlocking positions with needle-like structures. Likewise to air-laying, the challenge will be to use binders that strengthen the paper. [158] [159] [160] [161]

3. **Centrifugal Force spinning**: A technique that use a centrifugal force to position the fibers in a web that are extruded or sprayed at the center of the centrifuge. The technology is primarily used for specialist nonwovens like membranes. Not yet commercially applied. [162]

4. **Cross-linking additives**: This technique can be applied to reduce the amount of water required as additional ingredient to papermaking techniques. The cross-linkers can be added to increase paper strength and entangle the web structure. [163] [158] [164] [165] [166]

5. **Electrospinning**: This technique uses electric force to create charged fibers from a polymer melt or a polymer solution. The fibers can be sprayed to create a nonwoven mesh that can be interconnected. The challenge will be to dissolve kraft pulp in a sustainable process to create cellulose fibers. [167] [168] [169] [170]

6. **Gel-spinning**: This technique comprises a gel that is pressed through a nozzle (spuitmond) to create fibers. The raw material needs to be fed in a gel. The challenge will be to create a raw material that can be used by a gel-spinning system. [52]

7. **Spunbonding I/S**: Spunbonding is a process similar to the gel spinning process where the raw material is fed as a polymer solution or a polymer melt that is pressed through a set of nozzles to create a nonwoven web. The technique is already commercially applied in the creation of polymer nonwovens. [171] [158]

8. **Melt/solution blowing**: The melt/solution blowing technique forces the creation of fibers accompanied by air onto a carrier. Due to the spray-like flow a fiber web is created on the carrier. Similar to other melt spinning techniques the challenge will be to dissolve the kraft pulp in order to create the web. [158] [172]

9. **Needlepunching**: Like carding needle punching uses a somewhat similar strategy. Needles are used to entangle the fibers to form a web. Unlike carding the fibers are not rolled but pressed with needles perpendicular to the web. Although this is a very old technology the application to paper will depend on the ability to handle smaller size fibers. [158] [173]

10. **Sonication to entangle fiber network**: Sonication is a technique that use “waves” to disorder the state of materials. The technique can be used to fibrillate the fibers. [174]

11. **EPSON Paperlab**: The Epson paper lab is an example of a complete “dry” paper recycling technique. It uses waste office paper as input and creates a reusable sheet of paper as output. It goes through the stages of fiberizing-binding-forming without additional water use. A binder is introduced in the binding stage to bond the paper.

12. **Alcohols (Methanol, Ethanol, N-propanol, N-butanol)**: Replacing water with alcohol as solvents. Challenge will be to overcome the lower dipole moment of the alcohols. Tear strength and breaking length are substantially lower for alcohols. [72]
13. **Supercritical and near-critical fluids**: Not directly introduced as a solvent to replace water. However, the use or supercritical and near critical fluids are claimed to have high success rates in enabling production processes and reaction. Besides, they are sustainable alternatives. [175]

14. **Ionic liquids**: Ionic liquids are fluid salts that are used as a medium to increase reactions and change the characteristics of the materials dissolved in the liquids. They can dissolve cellulose (and kraft pulp) enabling new applications in web formation. This is discussed in the results of case 1. Challenge will be the regeneration of the solvent and application in bulk. [176]

15. **SO2-ethanol-water (cellulose dissolving)**: Similar to the role ionic liquids have. However, a safer and less toxic solvent than acid sulfate that is currently used for dissolving cellulose in the Lyocell (rayon) process. [177]

16. **Spray coating (airbrushing, e.g.):** Spray coating is a technique where a solution or melt is forced through a nozzle to create a homogeneous spray. The coating technique can be used to replace the relatively wet size press process. [178] [179] [180]

17. **Brushing**: Is the technique where a brush is applied to spread a viscous fluid on a surface. [180]

18. **Casting**: Casting can be applied in two ways. The first is by casting the film or coating on the surface itself. The second is to pre-cast the coating in a mold and then apply it on the surface. This results in a two-component system. [181] [182] [183]

19. **Centrifugal powder coating**: In this technique, centrifugal force is applied to spray a powdered coating on a surface. The challenge will be to adopt the centrifugal system in the current paper process. [184]

20. **Coating materials, as a replacement for starch**: This is not a technique but merely a water-use mitigation option by enabling other (bio-based) materials as a replacement for starch that has similar characteristics but less water use (higher solid content). Materials from the food and medicine industry are introduced. [185]

21. **Electrostatic coating**: This is a technique that create a spray that adds a charge to the coat. If the to be coated surface is charged as well with an opposite charge the coat and surface attract each other. The challenge will be to apply this in the papermaking process and the negative effects of electrostatic forces that may occur. [186] [187] [179]

22. **Hot-melt coating**: Coatings (like waxes) can be applied as a hot melt to mitigate the use of solvent and therefore the drying process. [184]

23. **Increase solid content**: An approach to reduce the water content in the coat and thereby to reduce the amount of water required. [188] [189]

24. **Knife coating technique**: This technique is somewhat similar to the size-press technique. However, the knife coating technique allows to dose the amount of coat applied. Also, it allows application of more viscous fluids. [190]

25. **Bar coating**: This technique uses a metering rod that “scrapes” excess coating of the surface. Changing the diameter of the wire tunes the quantity of the applied coating. [191]

26. **Crosslinkers**: Cross linkers can be applied to the mixture of the paper to strengthen the paper internally and can be added to the starch coating. [192]

27. **Dry lamination**: A technique that applies a “dry” second layer on the substrate. [193]

28. **Dry powder coating (e.g., mechanofusion)**: A coating that is applied as a dry substance by force (air or press) [194] [195]

29. **Extrusion lamination/coating**: Similar to dry lamination, although the coating is applied as a hot melt and extruded in the process. [193] [196]
30. Hot-melt laminating (e.g., compress): This technique shows similarities to dry lamination, a second roll with the laminate is combined with the substrate roll. When combined, heat is applied to bond the laminate with the substrate. [191] [193]

31. Photocurable coating (UV, cross-linking): This coating is cured using a light source like UV. [197] [198] [199] [200]

32. Plasma pre-treatment and flash evaporation treatment: This technique uses a two-component system. A plasma pre-treatment is required to change the surface characteristics. The flash evaporation treatment applies a thick coating. The challenge will be to apply the batch-process in the continuous papermaking process. [201]

33. Water-based self-drying, fast curing coating: An additive added to the coating suspension allows quick drying at room temperature in 1-3 hrs. [202]

34. Chemical Vapor Deposition (CVD): A batch coating technique in a vacuum that allows depositing high-quality coats. This technology is state of the art. The challenge will be to implement the technique in the continuous, high speed, papermaking process. Systems are the developed towards continuous CVD. [203]

35. Electrostatic dry powder coating: This is a technique that create a spray that adds a charge to the coat. If the to be coated surface is charged as well with an opposite charge the coat and surface attract each other. The challenge will be to apply this in the papermaking process and the negative effects of electrostatic forces that may occur. [204]

36. Heat Exchanger - Is a device that transfers the heat from the exhaust air to the fresh inlet air. The air streams are separated by a solid wall. Where are lots of different designs but the principle is the same. [205]

37. Membrane Heat Exchanger - The principle of this device is the same as a normal heat exchanger. The exhaust air and the inlet air are separated by a semi-permeable membrane, which will recover the exhaust air moisture into the inlet air. [206] [207]

38. Heat Exchanger with Heat Pump - The principle of this device is the same as a normal heat exchanger. The separated heat pump will compress pre-warmed gasses into a hot liquid which will extra heat the inlet air. [208]

39. Mechanical Vapor Recompression - Is a device that recompressed the exhaust air. It involves taking vapor (usually water vapor) at, or a little above, atmospheric pressure and adding energy to it by compression. The result is a smaller volume of vapor, at a higher temperature and pressure, which can be used to do useful work. [209]

40. Heat recovery steam generator - An energy heat exchanger that recovers heat from a hot gas stream. It produces steam that can be reused in the process. [210]

41. Self-heat Recuperation - Is a technology that facilitates recirculation of not only latent heat but also sensible heat in a process, and helps to reduce the energy consumption of the process by using compressors and self-heat exchangers based on exergy recuperation. [211] [212] [213]

42. Infrared Drying - A technique that use the infrared spectrum of light to heat objects. [214] [215]

43. Microwave Drying - A technique that use electromagnetic radiation with high frequencies to create friction of the water molecules. [216] [108]

44. Ultrasonic Drying - A technique that basically works like a humidifier. An ultrasonic humidifier uses a ceramic diaphragm (piezoelectric transducer) vibrating at an ultrasonic frequency to create water droplets. [217] [113] [218]
45. Osmotic Dewatering - A technique that is based on the principle of osmosis. Osmosis is the spontaneous movement of solvent molecules (through a semi-permeable membrane) into a region of higher solute concentration, in the direction that tends to equalize the solute concentrations on the two sides. [219]

46. Electro Dewatering - A technology in which a conventional dewatering mechanism such as pressure dewatering is combined with electro kinetic effects to realize an improved liquid/solids separation. [104] [220] [221]

47. Heated Press Section - Preheating the paper (and water) before the press section will lead to increased dewatering efficiency. [222]

48. Freeze Drying - A technique that works by freezing the material and then reducing the surrounding pressure to allow the frozen water in the material to sublime directly from the solid phase to the gas phase. [223]

49. Belt Press Dewatering (Vacuum & Mechanical) - Is an industrial machine, used for solid/liquid separation processes. The process of filtration is primarily obtained by passing a pair of filtering cloths and belts through a system of rollers. [224] [225]

50. Superheated Steam Drying - The superheated steam acts both as heat source and as drying medium to take away the evaporated water. [149]
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