Puu-0.4110: Conventional and Non-Conventional Pulping as a Basis for Biorefinery (7 cr)

Lecture 21: Lecture wrap-up
Products from extractives
High-yield pulping processes
Lecture wrap-up and general issues concerning the course
## Course lectures 1

<table>
<thead>
<tr>
<th>Course practicalities &amp; introduction</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General concepts of pulping and biorefinery (Total: 14 h)</strong></td>
<td></td>
</tr>
<tr>
<td>2 Raw materials for biorefineries: availability and structure</td>
<td>2</td>
</tr>
<tr>
<td>3 Principles of conventional and non-conventional pulping methods</td>
<td>2</td>
</tr>
<tr>
<td>4 Biomass pretreatment: Debarking, chip production, screening and storage</td>
<td>2</td>
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<td>5 Biomass fractionation: Part 1 – Principles of impregnation and pulping</td>
<td>2</td>
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<tr>
<td>6 Biomass fractionation: Part 2 – Oxygen delignification and bleaching</td>
<td>2</td>
</tr>
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<td>7 Biomass fractionation: Part 3 – Batch and continuous digesters</td>
<td>2</td>
</tr>
<tr>
<td>8 Principles of recovery cycles and effluent treatment</td>
<td>2</td>
</tr>
</tbody>
</table>
# Course lectures 2

## Pulping methods (Total: 18 h)

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Credits</th>
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<tbody>
<tr>
<td>9</td>
<td>Mass &amp; energy transfer and reaction kinetics in biorefineries. Part 1.</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Mass &amp; energy transfer and reaction kinetics in biorefineries. Part 2.</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>Kraft pulping: Pulp washing I</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>Kraft pulping: Pulp washing II</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>Kraft pulping: Recovery of chemicals and energy I</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>Kraft pulping: Recovery of chemicals and energy II</td>
<td>2</td>
</tr>
<tr>
<td>15</td>
<td>Acid sulfite pulping</td>
<td>2</td>
</tr>
<tr>
<td>16</td>
<td>Research insights: Ionic liquids / Hydrothermal fractionation</td>
<td>2</td>
</tr>
<tr>
<td>17</td>
<td>Organosolv and other non-conventional processes</td>
<td>2</td>
</tr>
<tr>
<td>18</td>
<td>Modified alkaline pulping processes</td>
<td>2</td>
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</table>
## Course lectures 3 (Gross total: 44 h)

### Products (Total 6 h)

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Duration</th>
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</thead>
<tbody>
<tr>
<td>19</td>
<td>Group work instructions – Carbohydrate and lignin based products:</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Pulp (papermaking &amp; dissolving), viscose &amp; other fibres;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hemicellulose-based products;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lignin extraction &amp; gasification, syn-gas, other products</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Group work: Presentations</td>
<td>2</td>
</tr>
<tr>
<td>21</td>
<td>Lecture wrap-up</td>
<td>2</td>
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### Practice (Total: 4 h)

<table>
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<tr>
<th></th>
<th>Description</th>
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<tbody>
<tr>
<td>22</td>
<td>Toihan OY: a start-up company from industrial waste water treatment</td>
<td>2</td>
</tr>
<tr>
<td>23</td>
<td>Dissolving pulp manufacture for viscose process – case Stora Enso</td>
<td>2</td>
</tr>
</tbody>
</table>
Feedback & questions

Opinions on "flipped classroom" – summary

• Mostly positive feedback
• Advantages (times mentioned)
  – Enhances working according to your own schedule (6)
  – Time in class used more efficiently for discussions than lecturing (3)
  – Teaching by professionals which otherwise might be unavailable (2)
  – Variety to normal lectures
• Disadvantages:
  – Technical problems (4)
  – Not possible to ask questions immediately (3)
  – Active work required (2)
  – The lecture times are already booked in the students’ schedules, therefore no advantage due to watching the videos on you “own time”
  – Exercises not graded or compulsory
  – New method in Aalto – practice needed
Feedback and questions

After this week's lectures I want to ask...

- is there a difference between oven dried and air dried pulp, when we talk about effects of drying on pulp (e.g. hornification)?
- if you think it's reasonable to use fossil fuels for generating steam, respectively process heat in general, in biorefinery concepts?
- do we have more of those video lectures in this course?
- There is a large multitude of different cooking and impregnation processes used in different plants around the world. Are there certain regions where certain processes are favoured, is this because of raw material or local expertise with technology?
- is it possible to remove heartwood from logs cost efficiently?
Feedback & questions

Continue the sentence:

One thing which has surprised me during this course is...

- the amount of recent innovations in pulping technology, as the technology is over 100 years old, much of the chemical understanding of the process has come after 1970s.
- the amount of new information for me.
- During my studies and work experience at a pulp mill I've understood that pulping is not a simple process but haven't been able to realise how many chemicals are included especially in the bleaching phase.
- how efficiently chemicals are recycled during Kraft pulping.
- the possible extreme importance of energy efficiency in creating new economically feasible bioproducts. Earlier I thought that it's only very important.
- how difficult processes can be that look quite simple at first glance.
Simulation exercise

• Please register to a tutorial ASAP!
  – In the tutorial, I will show how to use the principal functions of the WG software – still, most of the learning you will do on your own during the simulation work
  – In the tutorial, we will transfer a kraft base case model (HW) to a prehydrolysis mill

• On week 47, I will upload to the wiki pages an example of material and economical balance calculations for kraft and prehydrolysis kraft base cases
  – You will have to provide similar calculations for your processes (as a part of the report)
  – Not everything can be included, e.g. salary costs will be missing (still, comparisons between different processes are possible)
  – If problems occur, contact your instructor
Toihan OY’s lecture: Monday, November 23rd

- 10:15-12 AM, Puu 1, L1
- Topic: Toihan Oy - business from industrial waste water treatment
- Lecturers: Sakari Toivakainen & Heikki Hannukainen
- Students will write a one-page summary of the lecture
  - Those who cannot attend will have to write a three-page essay with three references (topic: Effluent treatment in biorefineries)
Stora Enso lecture: Monday, November 30th

- 10:15-12 AM, Puu 1, L1
- Topic: Dissolving pulp manufacture for viscose process – case Stora Enso
- Lecturer: Sirpa Välimaa
- Students will write a one-page summary of the lecture
  - Those who cannot attend will have to write a three-page essay with three references (topic: Viscose production process)
Exams

• December 7th, 2015, 9:00 AM – 1:00 PM
  – Other options: January 12th, 2016, 1 – 5 PM
  May 25th, 2016, 9 AM – 1 PM

• 5 questions, à 5 points
  – Extra points from quizzes and from answering the feedback questionnaire (online form), max. 5 points

• Example questions from previous years (shown here!)
  – New questions will be prepared for each exam!

• Remember to register!

• Some hints: correct calculation of white liquor properties (EA, AA,S), definition of washing loss
  – Quizzes: Week 40 – q2, q5, q9; Week 41 – q5, q2
### Important dates and deadlines

- **27 November:** Course feedback survey opens (open until 17 December)
- **23 November:** Lecture – Toihan OY
- **30 November:** Lecture – Stora Enso dissolving pulp
  - DL of the Toihan lecture summaries
  - DL of registration for the exam
- **7 December:** DL of the SE lecture summaries
  - Exam
- **20 December:** DL for simulation files and reports
  - DL for group members’ assessment
- **19 January (2016):** Course grades available (the latest)
Products from extractives
High-yield pulping processes
Learning outcomes

After this lecture the student
• can describe the chemical reactions and separation of extractives during pulping
• recognises the chemical composition of the extractive-derived products, such as turpentine and crude tall oil (CTO)
• can name several end uses for CTO
• is able name some high-yield pulping processes, their products, and chemicals used in these processes
• can assess the suitability of the high-yield pulping processes as a basis for biorefinery
Extractives

• A very diverse group of substances with low molecular mass found in wood
  – What can you remember of their properties and role in trees?
• The extractives react during pulping and in the best case can be collected as side products
  – Which kind of products?
• Typical contents of extractives in wood species (% of dry weight):
  – Scots pine (*Pinus sylvestris*): 2.5-4.5
  – Norway spruce (*Picea abies*): 1.0-2.0
  – Silver birch (*Betula pendula*): 1.0-3.5
Properties of extractives

- Terpenoids, terpenes and steroids
- Fats, waxes and their components
- Phenolic substances
- Extractives: hydrophilic to some extent, lipophilic
- Inorganics

Fats and fatty acids

- In wood fats occur mainly as triglycerides.
- Free fatty acids (FA) are present only in heartwood.
  - The amount of free FAs increases when logs are stored.

Composition and amount of lipophilic extractives of fresh and water-stored logs of Norway spruce.
Extractives in pulping

• Low-molecular fraction
  – The volatile organic compounds (predominantly mono-, sesqui-, and di-terpenes) can be collected during chip steaming and early stages of the cook ‡ turpentine
  – Hardwoods contain mostly higher terpenes ‡ no turpentine

• Larger molecules
  – Chemical reactions during pulping
    • Hydrolysis of esters (saponification or acid hydrolysis)
    • Acid sulfite: some compounds lead to harmful condensation reactions
  – Separation
    • In softwood kraft process: soap separates
  – Large quantities of extractives or their poor separation leads to fouling of the equipment
    • Especially a problem in acid sulfite process
Turpentine composition and usage

- Pine kraft turpentine yield is typically 2-15 kg/Adt of pulp
  - For spruce: 2-3 kg/Adt
- The collected turpentine is normally sold out from the mill
  - Raw turpentine is purified into fractions by distillation
- Turpentine is used as a solvent or diluent for varnish, in pharmaceutical industry, and as a perfume additive

<table>
<thead>
<tr>
<th>Compound</th>
<th>Weight fraction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>α-pinene</td>
<td>60-83</td>
</tr>
<tr>
<td>β-pinene</td>
<td>2-7</td>
</tr>
<tr>
<td>Δ³-karene</td>
<td>11-28</td>
</tr>
<tr>
<td>Others</td>
<td>2-6</td>
</tr>
</tbody>
</table>

J. Gullichsen & C.-J. Fogelholm, Chemical Pulping 6B, Fapet OY, 2000, p. 375
Extractive content of wood

- Extractive content of wood depends on
  - Tree species
  - Tree age
  - Sampling place (bark and heartwood contain more extractives than sapwood)
  - Growth area
  - Sampling season (highest in the spring)

- Storage time affects negatively the extractive content

**Graph:**
- TURPENTINE LOSS, %
- STORAGE TIME, WEEKS
-CHIP PILE
  - INTERIOR
  - SURFACE
  - ROUNDWOOD

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Kraft process: Soap

• Due to the alkaline hydrolysis of the fatty acid esters, soap is formed during kraft cooking
  – Soap = Na (and Ca) salts of fatty and resin acids
• Tall oil = acidified kraft soap
  – From Swedish "tall olja" (tall = pine)
• Soap contains impurities (e.g. black liquor, fibres)

Resin acids (tricyclic diterpenes): abietic acid and pimaric acid
Kraft process: Soap recovery

- Soap rises on top of black liquor (BL) storage tanks
  - Collected by skimming
- Maximum soap particle rising rate obtained by optimising the density difference of soap and BL, soap particle diameter, and BL viscosity
  ✩ Rising rate affected by BL dry solids content and temperature
- Soap solubility at its lowest at BL dry solids of 26%

STOKES FORMULA:
\[
\nu = \frac{(\rho_2 - \rho_1) \cdot R^2}{9\mu}
\]

The soap separates as micelles

- The fatty and resin acid salts formed during alkaline cooking are *surface active* compounds (a.k.a. *surfactants*)
  - Contain a polar *hydrophilic* and a non-polar *hydrophobic* part

- As the surfactant concentration reaches *critical micelle concentration* (cmc)
  - formation of *micelles*

- The cmc is dependent on the fatty acid (FA) resin acid (RA) ratio and other conditions (i.e. temperature, ionic strength)

- In addition to FAs and RA, the micelles incorporate neutral extractive components, such as sterols

- No resin acids in hardwoods
  - soap separation hindered
  - To improve soap separation, resin acids are added to birch BL

T. Nousiainen, Crude Tall Oil Production Improvement, Master’s thesis, Aalto University, 2012
Acidulation of soap \( \equiv \) CTO (Crude Tall Oil)

- *Crude tall oil* (CTO) is prepared through acidulation of soap
  - Results in liberation of FAs, RAs, and unsaponifiables (e.g. sterols), as well as separation of impurities
  - The soap quality affects the CTO quality
- The reported requirements for the soap prior to acidulation
  - CTO content in soap > 50% of wet sample
  - Lignin content in soap < 1% of wet sample
  - Fibre content in soap < 1% of wet sample and < 50% of the lignin amount
  - Calcium content < 0.3% or 750 mg/kg wet sample
- CTO yield greatly affected by e.g. wood species, log and chip storage time, soap skimming system
  - Typical yields (kg CTO/ADt): 18-45 (USA, slash pine), 45 (southern Finland), 60 (northern Finland)

\[ \text{Corresponding to 50-70\% of the initial amount in the raw material} \]
CTO manufacture

*Hydrodynamic separator (HDS)*

### Composition of CTO

**Example**

<table>
<thead>
<tr>
<th></th>
<th>Southeastern USA (pine)</th>
<th>Northern USA &amp; Canada</th>
<th>Scandinavia (pine &amp; birch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid number</td>
<td>165</td>
<td>135</td>
<td>132</td>
</tr>
<tr>
<td>Resin acids, %</td>
<td>40</td>
<td>30</td>
<td>23</td>
</tr>
<tr>
<td>Fatty acids, %</td>
<td>52</td>
<td>55</td>
<td>57</td>
</tr>
<tr>
<td>Unsaponifiables, %</td>
<td>8</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>

- Acid number (AN) depicts the CTO quality
  - Only pine ‡ AN = 160-165
  - 50% or more hardwood ‡ AN = 125-135
  - AN is expresses the amount of KOH (in mg) required to neutralise one gram of CTO

*J. Gullichsen & H. Lindeberg, Byproducts of Chemical Pulping, in J. Gullichsen & C.-J. Fogelholm, Chemical Pulping 6B, Fapet OY, 2000, p. 379*
Crude tall oil (CTO) components

- CTO is normally sold out from the mill to a separate company
  - In Finland: Forchem (Rauma), Arizona Chemicals (Oulu)
- CTO is fractionated by distillation
  - TOFA & TOR are called saponifiables, other fractions are unsaponifiables (e.g. sterols)

<table>
<thead>
<tr>
<th>CTO fraction</th>
<th>Amount</th>
<th>Compounds</th>
<th>Possible usages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled tall oil (DTO)</td>
<td>10-15%</td>
<td>Easily distillable compounds</td>
<td>Industrial oils</td>
</tr>
<tr>
<td>Tall oil fatty acids (TOFA)</td>
<td>20-40%</td>
<td>E.g. oleic and linoleic acids</td>
<td>Paints, soaps, inks, industrial oils</td>
</tr>
<tr>
<td>Tall oil resin (TOR)</td>
<td>25-35%</td>
<td>E.g. abietic acid</td>
<td>Paints, glues &amp; sizing, soaps, inks</td>
</tr>
<tr>
<td>Tall oil pitch (TOP)</td>
<td>20-30%</td>
<td>E.g. sterols</td>
<td>Pharmaceuticals, biofuels</td>
</tr>
</tbody>
</table>
Reactions during acid sulfite pulping

- Sulfite turpentine traditionally the only extractive-derived product
  - p-cymene separated from the digester gas relief
- Fatty acid esters are hydrolyzed to a great extent
- Resin droplets adhere to metal surfaces or to fibrous material
  - Pitch problems connected to acid pulping of coniferous wood
    † only certain softwood species (esp. spruce) can be used
  - Pitch also causes specks or holes on the paper surface and in high concentration has a negative effect on the viscose process
- Pinosylvin (from the heartwood of pine species) is harmful, even at low concentration
  - Condensates with lignin (phenol-formaldehyde condensation)
    † larger lignin structures with a lower degree of sulfonation
      (lower solubility) † inhibition of delignification
- Gallic acid and its derivatives (ellagotannin)
  - Major extractives of Eucalyptus species
  - Also cause condensation
  - The effect not as severe as with pinosylvin
High yield (chemical) pulps
Pulping can be mechanical, chemimechanical, semichemical

<table>
<thead>
<tr>
<th>Pulping Method</th>
<th>Chemicals</th>
<th>Yield</th>
<th>Pulp Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwood (GW)</td>
<td>-</td>
<td>&gt;98%</td>
<td>Paper</td>
</tr>
<tr>
<td>Thermomechanical (TMP)</td>
<td>-</td>
<td>&gt;97%</td>
<td>Paper</td>
</tr>
<tr>
<td>Chemi-thermo-mechanical (CTMP)</td>
<td>Na$_2$SO$_3$ (NaOH)</td>
<td>&gt;90%</td>
<td>Board, paper, fluff, tissue</td>
</tr>
<tr>
<td>Alkaline peroxide mechanical (APMP)</td>
<td>H$_2$O$_2$, NaOH, Mg-salts, chelant</td>
<td>&gt;90%</td>
<td>Paper, board</td>
</tr>
<tr>
<td>Neutral sulfite semi-chemical (NSSC)</td>
<td>Na$_2$SO$_3$, NaOH/Na$_2$CO$_3$ (*)</td>
<td>~80%</td>
<td>Fluting board</td>
</tr>
<tr>
<td>Green liquor pulping</td>
<td>Na$_2$CO$_3$, Na$_2$S</td>
<td>&gt;80%</td>
<td>Core board</td>
</tr>
<tr>
<td>High-yield kraft pulping</td>
<td>NaOH, Na$_2$S</td>
<td>55-70%</td>
<td>Liner board</td>
</tr>
</tbody>
</table>

*) Also NH$_4$ as a base is possible
High yield kraft pulping

- Main raw material softwood
- Kraft (or sulfite) delignification and mechanical treatment with defibrators
  - typically unbleached pulp
- Yield 55-70% (kappa number >60)
- Tailor-made pulps for certain end-use
  - kraft liner base pulp: good tensile strength, bursting strength, tearing strength, and stiffness
  - liquid packaging board (middle or base layer): high bending stiffness, bulk, bursting strength, density and cleanliness
Neutral sulfite semi-chemical (NSSC) pulping

- Na$_2$SO$_3$ cooking: sulfonation and hydrolysis (sulfitolysis) at near neutral pH (ensured by an HCO$_3^-$/CO$_3^{2-}$ buffer)
- Generally, hardwood
- Short, thin chips to ensure good impregnation
- Residual lignin content: 15-20% on pulp (Kappa number 100 – 120)
- Softened chips are refined at high pressure and temperature to form a raw pulp
- Regeneration of chemicals either separately or together with a kraft (sulfite) pulp mill (cross-recovery)
- Most common application is for corrugating medium (fluted material in the middle of corrugated board): Good fiber stiffness
Green liquor pulping is used for core board production

• Main raw material birch, typical yield 80-85%
  – Yield loss is from dissolving lignin and hemicelluloses
• Green liquor: Na$_2$CO$_3$ and Na$_2$S, ~180 °C
• Mechanical treatment with defibrators and refiners
• Typically unbleached pulp
• End-use: **core board**
  ⇒ the wanted fibre properties: stiffness, good bonding abilities
Do you think that the mentioned processes are suitable for biorefineries?

- Why? Why not?
Summary

- The most important byproducts in conventional pulping are turpentine and crude tall oil (CTO)
  - Extractive-derived products, used e.g. for producing chemicals or as a solvent (turpentine)
- In softwood kraft pulping, lipophilic extractives separate as soap
- Soap is cleaned and acidulated ‡ CTO
  - The chemical components in CTO are fatty acids (FA), resin acids (RA), and unsaponifiables (mostly steroids)
- In high yield (chemical) pulping mechanical refining is necessary for fibre separation
  - Used mostly for special paper and board products
Extra material on CTO & high-yield pulping
General classification of terpenoids

Hemiterpenoid (1 isoprene unit)
- isoprene

Monoterpenoid (2 isoprene units)
- limonene

Sesquiterpenoid (3 isoprene units)
- codinene

Diterpenoid (4 isoprene units)
- abietadiene

Sesterterpenoid (5 isoprene units)

Tetraterpenoid (8 isoprene units)
- obhiobolin

Polyterpenoid (>8 isoprene units)

Terpenoids

Tetraterpenoid
- carotene

Rubber and gutta-percha

Fats, waxes and their components

**Triglycerides**

**Fatty acids:**

- palmitic acid C16
- oleic acid C18
- linoleic acid C18
- linolenic acid C18
- pinolenic acid C18

**Triglycerides:**

- glycerol moiety
- trilinolein

Fats, waxes and their components

Waxes and steryl esters

Fatty acid esters:

- **Waxes**
  - $R_1$ = fatty acid chain
  - $n$ = 19-23

- **Steryl esters**
  - $R_2$ = chains of saturated and unsaturated C14-C20 fatty acids

- **Triterpenyl esters**
  - $R_2$ = triterpenyl alcohol

R1= fatty acid chain, R2 = chains of saturated and unsaturated C14-C20 fatty acids

Kraft process: Soap separation

- One example of soap separation tanks on the left
  - Every mill has its own tailor-made tank farms
- Soap is settled in a soap tank
  - BL pumped out from the bottom
  - Mixing improves the separation

J. Gullichsen & H. Lindeberg, Byproducts of Chemical Pulping,
in J. Gullichsen & C.-J. Fogelholm, Chemical Pulping 6B, Fapet OY, 2000, p. 381
Mechanical pulping I

Groundwood (GW)

- Objective: *defibration by mechanical force & heat*
  - wood heated due to friction
  - *avoiding the dissolution of wood material*
    - $\Rightarrow$ high yield: 94-98%
  - due to high lignin content fibres are stiff (not flexible)
  - fibres break
    - $\Rightarrow$ fibres shorter than in chemical pulps
    - $\Rightarrow$ formation of *fines* (small particles derived of wood material: e.g. pieces of wood cell wall)
  - relatively bright pulp
Mechanical pulping II
Thermomechanical pulping (TMP)

- Defibrating wood chips mechanically in a refiner
  - steamed wood chips fed between grooved rotating metal disks
  - high yield: 94-98%
  - stiff fibres (high lignin content)
  - higher temperatures than in groundwood process
  $\Rightarrow$ fibres more intact, less fines formation, relatively bright pulp

- The process has a high energy consumption

Mechanical Pulping, Fapet 1999
Combined chemical and mechanical treatment

- Semi-chemical pulping
  - yield 65-85%; e.g. NSSC (neutral sulfite semi-chemical pulp → corrugated board) and green liquor cooking → core board
- High-yield chemical pulps
  - yield 55-70%; e.g kraft liner base pulp, liquid packaging board, sack paper
- Chemimechanical pulping
  - yield 85-95%; e.g. CTMP, APMP, CMP, DWS, OPCO, LFCMP, CTMP

![Graph showing delignification degree vs. yield](image-url)
CTMP PROCESS DIAGRAM
Conveyor-type NSSC cooking produces fluting board pulp

### Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steaming</td>
<td>min</td>
<td>2 – 3</td>
</tr>
<tr>
<td>Time</td>
<td>°C</td>
<td>75 - 95</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impregnation time</td>
<td>min</td>
<td>4 - 5</td>
</tr>
<tr>
<td>Cooking</td>
<td>min</td>
<td>12 – 16</td>
</tr>
<tr>
<td>Time</td>
<td>°C</td>
<td>180 - 185</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooking liquor</td>
<td>g/L</td>
<td>72 – 78</td>
</tr>
<tr>
<td>Na₂O conc</td>
<td>% odw</td>
<td>6.5 – 7.0</td>
</tr>
<tr>
<td>SO₂ conc</td>
<td>g/L</td>
<td>60 – 65</td>
</tr>
<tr>
<td>pH</td>
<td>% odw</td>
<td>5.5 – 6.0</td>
</tr>
<tr>
<td>Initial</td>
<td></td>
<td>9 – 10</td>
</tr>
<tr>
<td>end</td>
<td></td>
<td>5 - 6</td>
</tr>
<tr>
<td>Yield</td>
<td>%</td>
<td>78 - 82</td>
</tr>
<tr>
<td>Cooking liquor</td>
<td>m³/t p</td>
<td>0.8 – 1.0</td>
</tr>
<tr>
<td>Steam demand</td>
<td>GJ/t p</td>
<td>2.2 - 2.4</td>
</tr>
</tbody>
</table>

Chemical Pulping Part 1, book 6, Papermaking Science and Technology, 2011, p249-251