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Energy Technology
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ENERGY PRODUCTION IN PULP AND PAPER INDUSTRY

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Supervisor:  Professor Esa Vakkilainen

Lappeenranta, 2019
The aim of this thesis is to find and study key energy indicators that have a huge influence at steam generation efficiency in pulp and paper industry. Determination of the efficiency of heat and electricity production is a prerequisite for stable and efficient operating conditions. In description part basics of technological processes in the pulp and paper mills are explained. In research part heat transfers in fluidized bed boiler and recovery boiler were calculated. As the result some graphs were plotted and several dependences were identified.
ACKNOWLEDGEMENT

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Prokhorskii Gleb

Lappeenranta, 2019
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ABBREVIATIONS

CaO  Calcium oxide
CaCO₃  Calcium carbonate
Ca(OH)₂  Calcium hydroxide
Cl₂  Chlorine
ClO₂  Chlorine dioxide
CO₂  Carbon dioxide
H  Hypochloride
H₂O  Water
H₂O₂  Hydrogen peroxide
KCl  Potassium chloride
K₂CO₃  Potassium Carbonate
K₂SO₄  Potassium Sulfate
NaBO₂  Sodium metaborate
Na₃BO₃  Sodium Borate
NaClO₃  Sodium chlorate
Na₂CO₃  Sodium carbonate
NaOH  Sodium hydroxide
Na₂S  Sodium sulfide
Na₂SO₄  Sodium sulfate
Na₂S₂O₃  Sodium thiosulfate
NOₓ  Nitrogen oxide
O₂  Oxygen
O₃  Ozone
SO₂  Sulfur dioxide

Bar  Bars
GJ  Gigajoule
kgDS  Kilogram dry solids
kWh  Kilowatt-hour
MW  Megawatt
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pa</td>
<td>Pascal</td>
</tr>
<tr>
<td>tDS</td>
<td>Ton dry solids</td>
</tr>
<tr>
<td>BAT</td>
<td>Best available techniques</td>
</tr>
<tr>
<td>BFB</td>
<td>Bubbling fluidized bed boiler</td>
</tr>
<tr>
<td>BL</td>
<td>Black liquor</td>
</tr>
<tr>
<td>BLI</td>
<td>Black liquor impregnation</td>
</tr>
<tr>
<td>CFB</td>
<td>Circulating fluidized bed boiler</td>
</tr>
<tr>
<td>CTMP</td>
<td>Chemi-thermomechanical process</td>
</tr>
<tr>
<td>CTO</td>
<td>Crude tall oil</td>
</tr>
<tr>
<td>D₀</td>
<td>First bleaching stage</td>
</tr>
<tr>
<td>D₁</td>
<td>Second bleaching stage</td>
</tr>
<tr>
<td>DC</td>
<td>Direct contact</td>
</tr>
<tr>
<td>DD washer</td>
<td>Drum displacer washer</td>
</tr>
<tr>
<td>E_{op}</td>
<td>Alkaline extraction stage</td>
</tr>
<tr>
<td>EMCC</td>
<td>Extended modified continuous cooking</td>
</tr>
<tr>
<td>ESP</td>
<td>Electrostatic precipitator</td>
</tr>
<tr>
<td>GW</td>
<td>Groundwood</td>
</tr>
<tr>
<td>HBL</td>
<td>Hot black liquor</td>
</tr>
<tr>
<td>HHV</td>
<td>High heating value</td>
</tr>
<tr>
<td>HVLC</td>
<td>High volume low concentration gas</td>
</tr>
<tr>
<td>HP steam</td>
<td>High pressure steam</td>
</tr>
<tr>
<td>HWL</td>
<td>Hot white liquor</td>
</tr>
<tr>
<td>IPPC</td>
<td>Integrated pollution prevention and control</td>
</tr>
<tr>
<td>ITC</td>
<td>Isothermal cooking</td>
</tr>
<tr>
<td>LAC</td>
<td>Latin America and the Caribbean</td>
</tr>
<tr>
<td>LHT</td>
<td>Liquor heat treatment</td>
</tr>
<tr>
<td>LHV</td>
<td>Low heat value</td>
</tr>
<tr>
<td>LP steam</td>
<td>Low pressure steam</td>
</tr>
<tr>
<td>LVHC</td>
<td>Low volume high concentration gas</td>
</tr>
<tr>
<td>MC pump</td>
<td>Medium consistency pump</td>
</tr>
<tr>
<td>MCC</td>
<td>Modified continuous cooking</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>MP steam</td>
<td>Medium pressure steam</td>
</tr>
<tr>
<td>NA</td>
<td>North America</td>
</tr>
<tr>
<td>Paa</td>
<td>Peracetic acid, CH$_3$COOOH</td>
</tr>
<tr>
<td>PGW</td>
<td>Pressure groundwood</td>
</tr>
<tr>
<td>RCF</td>
<td>Refractory ceramic fibre</td>
</tr>
<tr>
<td>RDH</td>
<td>Rapid displacement heating</td>
</tr>
<tr>
<td>SCM</td>
<td>Semichemical pulping</td>
</tr>
<tr>
<td>TMP</td>
<td>Thermo-mechanical pulping</td>
</tr>
<tr>
<td>WBL</td>
<td>Warm black liquor</td>
</tr>
<tr>
<td>WL</td>
<td>White liquor</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

In present, modern pulp and paper mills can provide all heat and electricity they consume and almost always there is electricity surplus that can be sold. It is important due to steady price growing for conventional fuels (as natural gas, coal etc.). In order to didn’t have to buy additional fuel for BFB boiler or electricity from the grid efficiency and steam generation processes should be under control.

Energy provides a great opportunity for reduction of operating cost due to energy intensity of pulp and paper industry (share of energy costs are 10-15% of total manufacturing costs and can reach under 40% in total cost of production). That’s why it is profitable to build own power plant near pulp mill to provide its own electricity.

Pulp and paper industry is a complex system with including of huge number of different power-hungry processes. Also many factors can influence on energy consumption: quality management, energy management, type and age of equipment, method of processing raw materials etc. It means that not only production chain should be under quality control but also production scheme should operate without any decreasing efficiency conditions.

Currently to assess the energy utilization in pulp and paper industry energy audit procedure might be carried out. One of ways of efficiency measuring is use of energy indicators that could be expressed as ratio of different types of energy.

In the beginning of this thesis is small review of current trends in pulp and paper mills. Then the general methods and processes of wood processing and paper making are described. Further also some information about every unit is given for clear understanding of the whole process of making paper.

The first question that is raised in this paper is the search for the causes of reduction steam generation and boiler efficiency. It should be clear how energy is producing and how boilers are operated.
The second step is to change every value that could be variable during operating and to find the most important of them and to explain the dependence of efficiency and steam production on variable values. In operating time big number of indicators is changing and all of them anyway are influencing on steam production efficiency that’s why the main aim of this thesis is to find the most significant changes of them.

The last step is to compare the results and explain why these indicators influence more than other and conclude how decrease of the efficiency could be prevented.
2. TRENDS IN PULP AND PAPER PRODUCTION

2.1. Forest industry structure

Global forest industry divided into two categories: chemical forest industry and mechanical forest industry. The chemical industry produces pulp. In turn, pulp can be divided into chemical, mechanical, semi-chemical and non-wood pulp production. Also in paper production recovered paper can be used. In case of mechanical forest industry it produces plywood, sawn goods, fiberboard etc. (Figure 2.1) (Finnish Forest Association, 2016)

![Forest Industry Diagram](image)

Figure 2.1 – Scheme of the forest industry

Chemical pulping process dissolves the most of lignin and hemicelluloses from the wood that’s why the result of chemical pulping is high-quality paper. Chemical pulping presented by sulfite and sulfate wood pulping. Sulfite cooking process takes place in sulfurous acid combined with limestone for producing calcium bisulfite. Just mixture of sulfurous acid and calcium bisulfite dissolves the lignin and frees the cellulose fibers. (Printwiki, 2007a)

In case of sulfate process it is the most widely uses chemical pulping method. It is known as “kraft” process ("kraft" is the German and Swedish word for "strength"). In this type of pulp production an alkaline cooking liquor is used with sodium hydroxide (NaOH) and sodium sulfide (Na₂S) which are active cooking chemicals. (Printwiki, 2007a)
There are two main processes in mechanical pulping: grinding and refining. Grinding provides the paper great optical properties such as high opacity. (Vakkilainen, 2017) In turn, refining gives the pulp good strength properties. Mechanical pulps are mainly used in newsprint, as well as papers used in telephone directories, catalogs, magazines, paper towels and tissues. (Printwiki, 2007b) Also mechanical pulping has some advantages such as high pulp yield, low cost and this pulp possesses some great qualities suitable for its usage: ink absorbency, compressibility, bulk. (Printwiki, 2007b)

Semichemical pulping is combination of chemical and mechanical pulping. The main idea of this process is to separate fibers from non-fiber wood components, in particular, lignin that binds cellulose fibers together. (Printwiki, 2007c) Semichemical pulping is in middle between wholly mechanical and wholly chemical pulping, because mechanical – big yield, low lignin dissolving, while chemical – low yield, high lignin dissolving. At first wood chips expose to mild cooking in mixture of sodium sulfite and small quantity of alkaline salts (Na₂CO₃, NaOH). Then this bulk goes to disk refiner for separating the individual cellulose fibers. (Printwiki, 2007c)

Recycled fiber could be defined as a recovered paper. This type of paper plays the important role in paper industry in several developed countries, such as USA. Also use of recycled paper is better and more ecological for the environment than use of virgin paper. It helps to preserve forests due to decreased demand. Producing recycled paper uses less energy than producing virgin paper. Thus recycled paper can be used for the same purposes as paper from virgin wood. Also there are no indications that recycled paper is dangerous and harmful to humans. (Bajpai, 2014.)

2.2. Fibre material production and consumption

Fiber material production in the world is steadily increased during 1961-2016. This grow is presented in Figure 2.2. Since 1961 chemical wood pulp is the most important and developed pulp. The difference between chemical and mechanical pulping was raised from 2 times to more than 5 times. (FAO, 2018)
The fibre material global production was about 410 million tons in 2017. (FAO, 2018)

Volume of every pulp and paper production is represented in table 2.1 below.

<table>
<thead>
<tr>
<th>Recovered paper</th>
<th>Chemical wood pulp</th>
<th>Mechanical wood pulp</th>
<th>Semi-chemical wood pulp</th>
<th>Other fibre pulp</th>
</tr>
</thead>
<tbody>
<tr>
<td>229 million tons</td>
<td>139 million tons</td>
<td>25.5 million tons</td>
<td>8.7 million tons</td>
<td>12.3 million tons</td>
</tr>
</tbody>
</table>

The global fiber material consumption in different regions is represented in Figure 2.3 (FAO, 2018):

- America 25%
- Asia 48%
- Europe 25%
- Oceania 1%
- Africa 1%
Figure 2.3- Global consumption of different fibre materials in 2015 (FAO, 2018)
2.3. Paper and board production

Global paper and board production in 2016 was about 409 million tons. This number has been increasing from about 70 million tons in 1961. Since the 1980s annual growth had been reached 3% per year. While annual growth of China’s paper and board production reached 9% per year (Figure 2.4) (FAO, 2018)

![Paper and board production in the world](image)

Figure 2.4 – Global paper and board production (FAO, 2018)

Asia became a largest producer of paper and board in the world by 2000. Also Asia had reached a bit less than 50% share of world’s paper and board production till 2016. While Europe and America (NA and LAC) both accounted 25.4% share. (FAO, 2018)

According to FAO all countries have made a big lip forward since 1961 year, but some countries as USA and Japan had a sharp decrease of production in 2009. Also according to FAO some countries can be highlighted due to the most production of paper and board that are presented on Figure 2.5 below (FAO 2018):
According to FAO, paper and board production could be categorized into 3 categories, such as: newsprint, printing and writing papers, other paper and paperboard. Figure 2.6 represents their shares in whole production of paper and board. (FAO, 2018)
2.4. Paper and board consumption

Paper and board consumption is closely linked with Gross National Product and living standards of each country individually. That’s why there is huge difference between countries. While world’s average is about 55 kg per capita, in Europe it is 125 kg per capita.

The table 2.2 below is representing consumption of paper per capita in different regions with one of countries with the highest, average and lowest consumption per capita. (FAO, 2016) The consumption difference between countries much higher than between regions due to each region has one or more country with relatively great consumption.

Table 2.2 – The consumption of paper and board per capita in 2016 (FAO, 2018)

<table>
<thead>
<tr>
<th>Region</th>
<th>Countries</th>
<th>Consumption per capita</th>
<th>Average region consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>USA</td>
<td>218</td>
<td>211</td>
</tr>
<tr>
<td></td>
<td>Canada</td>
<td>151</td>
<td></td>
</tr>
<tr>
<td>Europe</td>
<td>Slovenia</td>
<td>354</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>France</td>
<td>134</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Albania</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Asia</td>
<td>Japan</td>
<td>203</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>Lebanon</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bangladesh</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Latin America</td>
<td>Costa Rica</td>
<td>111</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Peru</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Venezuela</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Oceania</td>
<td>New Zealand</td>
<td>151</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>Fiji Islands</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solomon Is.</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Africa</td>
<td>Swaziland</td>
<td>53</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Kenya</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Uganda</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
2.5. Development of capacity of pulp mills

During last years the capacities of pulp mills have been grown slightly especially LAC and Asia where bleached hard kraft mills (BHKM) have been put into operation. The aim of increasing capacity of new mills is lower price per ton of core product. The world’s biggest pulp and paper plant is situated on a 1750 hectare site in Indonesia with 2 million tons per year capacity. (Figure 2.7)

Figure 2.7 – APRIL pulp and paper mill (Aprilasia, 2015)

In the world development of pulp and paper mills capacities could be represented by Figure 2.8

Figure 2.8 – The development in capacity of pulp mills (Vakkilainen, E, 2017)
2.6. Pulp and paper mills cost structure

Figure 2.9 below shows shares of different components in forest industry manufacturing cost. In Nordic countries as Finland and Sweden recovered paper is not available that’s why its share is the smallest one but share of virgin wood is the biggest. Other components have approximately the same shares excluding small shares of market pulp and fuel in Sweden.

Figure 2.9 – Share of different components in Forest industry manufacturing cost (Vakkilainen, E, 2017)
3. PROCESS DESCRIPTION

3.1. Chemical pulping

Chemical and mechanical processes are two main ways of pulp production. In this chapter full process of chemical pulping is described. In chemical pulping are used four principal processes: kraft, sulfite, neutral sulfite semi chemical and soda. Currently share of the kraft process is over 80% of the chemical pulp produced. (Cheremisinoff, 2010) The first chemical pulp mills were implemented in 1850s in England. It was caustic soda type pulp mill. The first sulfite pulping mills was introduced in 1867. It is more complex solution that uses sodium, calcium, magnesium and ammonia salts of sulfurous acid. (Vakkilainen, 2017)

In this chapter chemical pulping is described more deeply. Chemical pulping is named “chemical” because during this process chemicals are used for removing lignin and other impurities. After removing the most of impurities the pulp becomes stronger and brighter. Then it got name “kraft” due to kraft means strong in several languages. This technology was implemented in 1884 in Germany. In this process wood chips are “cooked” in a digester with help of white liquor that consists of NaOH and Na₂S. (Nilsson, 2007)

There are several technological processes in kraft pulp mills which represented on Figure 3.1. Kraft process has a number of advantages among other processes:

- There no any restrictions about specific kinds of wood
- High quality pulp due to lack of lignin
- Energy efficient chemical regeneration
- Valuable of by-products (Getrevising, 2016)
Kraft pulp mill processes can be divided into two lines: fibre line (the main raw material and product line) and chemical recovery line (consists of liquor and lime cycles) (Figure 3.2).

### 3.1.1. Wood handling

The department of wood handling deals with intake, storage, de-icing, debarking, chipping, chip screening delivery of wood between the mill gate and the digester plant. Commonly wood is delivered by trains, trucks or ships. Arrived wood can go directly into mill process or to the storages. Volume of storages depends on wood type that is used in mill. With regard to storage time it should be as short as possible due to moisture absorption that’s why wood should be fresh. Normal storage time is among 2-7 days. Also wood chips require being the same size.
Figure 3.2 – Chemical pulping process (Vakkilainen, 2017)
Debarking process is very important for pulp and paper industry for quality maintenance of final product due to bark in pulp decrease its brightness and strength. Bleaching does not influence at bark particles in pulp. This process takes place in special debarking drums that main purposes are not only removing bark but also removing sand and other small particles. Many types of drums exist they can be dry, wet, semi-wet. Dry drums are commonly used in areas where de-icing is not necessary. In this type of debarking water is used only for log washing. In turn, water sprays at the feeder end of the drum in wet or semi-wet debarking. Principle of action of debarking drums is moving of logs through the drum while drum is rotating. In this time logs rub against each other and become debarked. (Gullichsen, 1999)

Not all bark can be removed with help of drum. Small quantity of bark goes with logs to chipper. In this way logs meet special roll conveyor for separation bark from logs. (Gullichsen, 1999)

The main purpose of chipping is to reduce the size of logs for increasing the penetration ratio of chemicals, water and heat. Also it influences at efficiency of process and quality of pulp. The most widely used type of chippers is disc chipper (Figure 3.3) (Gullichsen, 1999)

Figure 3.3 – Disc chipper (Acrowood, 2018)
The next step after chipping is chip screening. The aim of its process is to ensure homogenous chips for coking. If any chips are oversize they returned into main chip flow. Currently the most widely used screen is a hole screen. This screen consists of 3 decks. Chips from top deck are removed to a re-chipper. (Gullichsen, 1999)

The last step of fuel preparation is a chip storage. It is connected with screener with help of belt conveyors that have some advantages such as: low power demand, easy maintenance and easy capacity increasing. But it requires relatively high investment cost compared with pneumatic conveyor. In case of storages there are two types of storages: open piles and silos. During comparison between this types it can be seen that pile storage do not have any restrictions in storage size, while silos prevents impurities from mixing with screened chips, but is has higher investments cost. (Gullichsen, 1999)

3.1.2. Cooking

Three different types of cooking exist:
- Batch cooking
- Continuous cooking
- Conveyor cooking

The most common pulping processes are batch and continuous cooking. Conveyor cooking is more often used for sawdust. Batch cooking was the first cooking method for kraft pulping. Continuous cooking method was implemented in 1960s due to high energy consumption. Development of energy efficient continuous pulping method displaces batch cooking in 1980s. (Gullichsen, 1999)

The main aim of cooking is to remove so much lignin as possible with help of chemicals and heat, because the cooking chemicals cheaper than bleaching. However, so deep lignin removal damages fibre, decreases pulp strength and yield of end product. To prevent it kappa number was considered that represent how much lignin should left in the pulp. One kappa unit is equal to 0.165% lignin. If this number is known workers are familiar with exact quantity of lignin. (Gullichsen, 1999)
As it was said earlier, cooking liquor (white liquor) used to dissolve lignin. The main active substances in it are NaOH and Na₂S. It also contains a number of alkalines, chlorides and calcium compounds.

The chemical properties and compositions of cooking liquors are defined with following terminology (Table 3.1):

Table 3.1 – names and compositions of cooking liquors (Gullichsen, 1999)

<table>
<thead>
<tr>
<th>Total alkali</th>
<th>All Na compounds (NaOH, Na₂S, Na₂CO₃, Na₂SO₄, Na₂S₂O₃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active alkali</td>
<td>Concentration of NaOH and Na₂S in white liquor: NaOH + Na₂S</td>
</tr>
<tr>
<td>Effective alkali</td>
<td>Concentration of NaOH and Na₂S in white liquor: NaOH + 1/2Na₂S</td>
</tr>
<tr>
<td>Sulfidity</td>
<td>Sodium sulfide concentration in white liquor Na₂S [\text{NaOH} + \text{Na₂S} ] * 100</td>
</tr>
<tr>
<td>Causticity</td>
<td>Chemical efficiency of white liquor production in causticizing: NaOH [\text{NaOH} + \text{Na₂CO₃} ] * 100</td>
</tr>
<tr>
<td>Reduction</td>
<td>Sodium sulfate Na₂SO₄ reduction to sodium sulfide Na₂S in recovery boiler: NaS [\text{Na} + \text{Na₂SO₄} ] * 100</td>
</tr>
</tbody>
</table>

3.1.2.1. Batch cooking

There are two ways of batch cooking process: traditional and displacement methods. Traditional batch cooking method used to produce the pulp in at least four different digesters, this guarantee uniform product for the pulp mill.
This cooking type consists of next order:

- Chip filling
- Chips pre-steaming
- White and black liquors filling
- Heating
- Cooking
- Blowing

Firstly, chips are loaded into the digester from the top and here process of pre-steaming of the chips begins. Pre-steaming helps to avoid air in the composition of chips (and also to take it out from the digester vessel). Thus, with the help of pre-steaming it is possible to achieve bigger absorption rate of the chemical to chip. After this step, digester is filled with white and black liquor. The amount of liquor must be determined prior to the process, based on the ratio of liquor-to-wood. Then, liquor starts to heat with the help of circulation through the heat exchanger, after that process of cooking begins. Usually cooking continues until desired value of the H-factor. H-factor illustrates relative rate of full dissolution of lignin. Finally, cooking process is instantly completed by cooling the ambient temperature to 10-20 degrees by degassing of digester. (IEF, 2015a)

Traditional batch cooking method was displaced with more efficient displacement batch cooking method. This method is based on heat usage from the previous to following cooks. Also, reusing of liquor from preceding cook helps to reduce steam consumption and enrich quality of the pulp in comparison with conventional batch cooking method. (IEF, 2015a)

Figure 3.4 represents that this method includes several white and black liquors accumulators and some number of digesters which amount depends on production rate. Also on figure 3.4 the cooking process is described. The whole process consists of:

- Chip fill and impregnation
- Hot liquor fill
- Heating and cooking
- Displacement
- Pump discharge
Firstly, the digester is filled with chips, which in turn are packed with help of low-pressure steam. The process of impregnation liquor filling starts in the same time as chips filling. Also in the same time air is removed from the digester, this forces white liquor soaking into chips. This process took place until the digester is full. During next step digester is filling of black and white liquors and it increases temperature until 150-165 °C. The cooking process takes place by using medium-pressure steam and pumping out of the liquor. Heat consumption is twice decreased due to black liquor usage in the next steps. The last step is the discharging of the pulp from the digester at atmospheric pressure. (IEF, 2015a)
3.1.2.2. Continuous cooking

Continuous cooking could be represented by 4 types of alternatives:

- Single-vessel hydraulic
- Single-vessel steam/liquor phase
- Two-vessel hydraulic
- Two-vessel steam/liquor phase

As we can see there are two digester types: hydraulic and steam/liquor phase. The difference between them is in different liquid level. In hydraulic digester the level of chips always below the liquid level, in turn, in steam/liquor liquid level is below than chips level. (IEF, 2015b)

Also these digester types are divided into single and two-vessels. Single-vessel has impregnation point at the top of the digester, in turn, two-vessel has impregnation vessel where chips are impregnated and through digester vessel they are introduced to the top. (IEF, 2015b)

The digester can be divided to several zones, where the flows can be concurrent or countercurrent. Impregnation zone where common temperature is 115-125°C is at the top of the digester. In heating zone the final cooking temperature is reached. After cooking process liquor is removed from the system and its pressure and temperature are decreased in flash tanks. In the bottom of the digester chips are cooled by use of wash water and discharged from it. (IEF, 2015b)

Some kinds of modified continuous cooking are exist. They are:

- MCC (Modified Continuous Cooking)
- EMCC (Extended Modified Continuous Cooking)
- ITC (IsoThermal Cooking)
- BLI+ITC (Black Liquor Impregnation + IsoThermal Cooking) - Low-Solids
- EAPC (Enhanced Alkali Profile Cooking)
3.1.3. Washing and screening

The main targets of washing are to wash the pulp for the next stages and to recover black liquor. That’s why during this process black liquor is separating from pulp. The pulp that comes from the digester consists of both fibres and black liquor. In turn, black liquor consists of inorganic chemicals and organic lignin. (IEF, 2015c)

The more efficient washing decreases the black liquor flow with the pulp to next stages that decreases bleaching chemicals consumption. Black liquor separating makes possible to reuse cooking chemicals in energy production. Separated black liquor is evaporated and burnt in recovery boiler. (IEF, 2015c)

Some kinds of devices are included into washing process:
- atmospheric diffuser
- pressure diffuser
- drum washers
- gas-free filters
- press washing (IEF, 2015c)

The first step of washing takes its place in atmospheric diffuser where pulp is washed after big number of operations as cooking, oxygen delignification and bleaching. As we can see from its name, atmospheric diffuser operates at atmospheric pressure. In turn, pressure diffuser operates at any pressure and could operate with more than 100°C temperature. (IEF, 2015c)

Screening is needed to separate pulp from harmful impurities as: raw materials (branches, bark) and process impurities (sand, ash, metals). Process of separation is based on size and weight difference of particles. In case of size, separation screens are used. In turn, weight separation centrifugal force helps to divide particles. (IEF, 2015d)
The full screening process consists of two stages: coarse screening where large impurities such as uncooked chips are removed to a knotter and fine screenings where small particles such as shives, fibre bundles and sand are removed. (IEF, 2015d)

### 3.1.4. Oxygen delignification

The next step after cooking and washing is oxygen delignification. This step is needed to remove remaining lignin from pulp. This process occurs with more selective chemicals. The most part of lignin is removed in cooking process, but remaining in pulp lignin could not be removed from pulp without yield losses. Also oxygen delignification helps to decrease flow of bleaching chemicals. (Nepenin, 1994)

On figure 3.5 common places of every single process in pulp production are shown. The normal place of oxygen delignification in order of priority is after screening and before bleaching. It is important to wash pulp after oxygen delignification stage due to need to remove reaction products and COD.

![Diagram of pulp production stages](image)

Figure 3.5 – Possible locations of every pulp production stage (Vakkilainen, E, 2017)

Nowadays two types of oxygen delignification are widespread: medium- and high-consistency. After previous stages such as cooking, screening and washing, pulp goes to oxygen mixer in which inlet alkali, oxygen and steam are added. There are single- or double-stages reactors. In case of one-stage reactor, pulp directly heated by using steam before oxygen mixer. In double-stage reactor the temperature in the first stage is lower than in second. After reactor, pulp is supplied to blow tank where pulp is separated from gases and then discharged to the washer. Then washing water goes to liquor recovery system. (Gullichsen, 1999)
3.1.5. Bleaching

Increase of pulp brightness is the main target of bleaching. Residual lignin can decrease pulp brightness. Up to 90 per cent of lignin is removed during cooking process.

The common bleaching process consists of some stages such as:

- Chemical and the pulp mixer
- Bleaching reactor
- Washing equipment (Nepenin, 1994)

The mostly widespread chemicals which used in bleaching process are: chlorine dioxide, oxygen, ozone and peroxide. Some of these chemicals could be manufactured on directly on pulp and paper mill, while some of them such as oxygen, peroxide and alkali could be transported from definite chemical factories. (Nepenin, 1994)

On figure 3.6 below the bleaching process example is represented. Full bleaching process consists of three or four stages. At first, pulp goes to first bleaching stage (D₀) where chlorine dioxide is used as bleaching chemical. The next stages are washing stage and alkaline extraction stage (Eₒp). The main purpose is to remove all reaction products which been created in D₀ stage. Then pulp heads to a second bleaching stage (D₁) where the main component is chlorine dioxide. Chemical consumption depends on kappa number (wood type in other words). (European commission, 2014)

Figure 3.6 – Bleaching process (CNBM, 2018)
3.1.6. Drying

Drying process required only in non-integrated power plants, because it is not necessary to dry pulp mass if transporting distance is not very big. (Nepenin, 1994)

Drying process divided into three sections:
- Wire
- Press
- Drying

It is very important to efficiently dewater of pulp to decrease heat consumption in drying section. (Ek, 2009)

There is the most widespread web drying method. Airborne dryer of cylinder is used for drying in this method. For airborne drying convective heat transfer is used, in turn, cylinder drying is based on contact heat transfer. Nowadays cylinder dryers are not cost effective that’s why they would not been constructed anymore. (Ek, 2009)

3.1.7. Chemical recovery

As it was said in 3.1.1 chapter pulp production consists of two lines: pulp line and chemical recovery line (Figure 3.7). The purposes of chemical recovery line are:

- Pulping chemicals recovery
- Burning of organic materials of black liquor in recovery boiler to produce electricity and heat
- Organic by-products recovery

Nowadays in modern plants dry solids concentration is about 80 per cent. While after pulp washing it is only 14-18 per cent and should be increased.
3.1.7.1. **Evaporation**

Increase of dry solids can be reached by drying. Drying can be implemented by evaporator. Also evaporator serves for methanol, turpentine and soap separation. These chemicals can be found in black liquor after cooking stage.

On figure 3.8 below falling film evaporator and its arrangement are represented. These evaporators typically installed in multiple effect systems (figure 3.9). This system usually contains from five to seven evaporators that are set up in a series. Multiple effect means effective use of steam energy for multiple times evaporation water from black liquor. Every “effect” is operated on different saturation pressure and temperature which increases along the way of liquor.
Figure 3.8 – Falling film evaporator (Sumitomo, 2019)

Figure 3.9 – Black liquor evaporation series (Convergence, 2015a)
3.1.7.2. **Recovery boiler**

Recovery boiler is one of the most important equipment in pulp and paper mill due to it makes these functions:

- Inorganic chemicals recovering from black liquor
- Energy and heat generation by producing high pressure and temperature steam
- Getting rid of odorous gases that appears during cooking process

Dry solids of black liquor include cooking chemicals (as inorganic part) and lignin (as organic part). Recovery boiler can be divided into two zones: oxidizing zone and reducing zone. Reducing zone is in the bottom of boiler while oxidizing is in the top. The Black liquor gets into boiler through nozzles in the bottom of boiler (reducing zone). Droplets of liquor are dried and burnt while flying to char bed.

Recovery boilers usually have from three to five air levels. Primary air is blown into the bottom part of boiler through ports on walls. Secondary level can be divided into several levels and can be blown through different walls. Secondary air is very important due to it influences at combustion performance. (Mikkanen P., 2000)

In the char bed smelt is formed and it consists of sodium sulphite and sodium carbonate. Sodium sulphite is very important chemical due to it is used in cooking. This smelt flows to dissolved tank where is mixed with weak white liquor for obtaining green liquor which goes to recausticizing plant to become suitable for cooking. (Vakkilainen, 2018a)

Nowadays modern recovery boiler’s capacity reached almost 5000 tDS/day while typical boiler’s average capacity over 2400 tDS/day. Also operating temperature and pressure was increased from 480 °C till 505°C and 80 bar to 110 bar respectively. (Vakkilainen, 2018b)
3.1.7.3. Causticizing and lime kiln

The main purpose of recausticizing step is to convert green liquor to white liquor; it means to transform sodium carbonate into sodium hydroxide for cooking usage. The main target of this process is to create as strong liquor as possible. Also the primary target of recausticizing plants is to convert lime mud (CaCO$_3$) into lime (CaO). (Metso, 2011)

The process of recausticizing is represented in figure 3.11 below. At first green liquor is clarified from dregs. After clarifying, green liquor is pumped with lime to a slaker, where calcium hydroxide is formed. After these processes caustic soda (NaOH) and lime mud are produced. The next step of white liquor production is green to white liquor reaction which
takes place in several mixing tanks. In these tanks white liquor (NaOH) is separated from CaCO₃ with help of “lime milk”. (Metso, 2011)

Last step of recausticizing process is lime mud converting into lime in special kiln. Lime kiln uses heat, motion and air flow to convert lime mud to lime. This process is named “calcining”. The common lime kiln is inclined and rotated tube. The burner at the lime outlet is needed for “calcining” reaction (Figure 3.12)

![Figure 3.11 – Recausticizing process (Convergence, 2015b)](image1)

![Figure 3.12 – Lime kiln (Convergence, 2015c)](image2)
3.2. Mechanical pulping

Mechanical pulping process is based on wood fibres separation from one another with help of using mechanical energy. Mechanical pulping is represented be groundwood pulping (GW), pressure groundwood pulping (PGW), thermo-mechanical pulping (TMP), chemi-themomechanical pulping (CTMP). All species of these processes are represented in table 3.2 below. Also on figure 3.13 are represented the main mechanical pulping processes.

Table 3.2 – Description of main pulping processes (CNMB, 2019)

<table>
<thead>
<tr>
<th>Pulping process</th>
<th>Raw materials</th>
<th>Yield</th>
<th>Typical end use</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW</td>
<td>Spruce and fir</td>
<td>95-98.5%</td>
<td>Printing and writing papers and newsprint</td>
</tr>
<tr>
<td>TMP</td>
<td>Spruce and fir</td>
<td>93-97.5%</td>
<td>Printing and writing papers and newsprint</td>
</tr>
<tr>
<td>CMP</td>
<td>Spruce, aspen, beech</td>
<td>80-90%</td>
<td>Printing and writing papers, tissue and packaging board</td>
</tr>
<tr>
<td>CTMP</td>
<td>Spruce, aspen, beech</td>
<td>90-94%</td>
<td>Printing and writing papers, tissue and packaging board</td>
</tr>
</tbody>
</table>
3.2.1. Groundwood

At first groundwood is made of debarked in barking drum logs. Then these logs get in grinders where forced by the grinding stones. After this step wood is warmed for lignin softening and releasing of fibres. In case of pressure groundwood the grinding process occurs with overpressure (commonly 3 bar). Operating with overpressure not only increases pulp strength, but also improves groundwood quality.

3.2.2. Thermomechanical pulping

Wood chips are the main material in thermomechanical pulping process. During this pulping process, at first, wood should be debarked, chipped and washed to remove impurities. The next step is steam warming and refining between discs of refiner (Figure 3.14). Steam warming of chips helps for better fibre separation in refiner. The refining process can be single- or two-stage. Also nowadays refiners are operated under overpressure.
3.2.3. Chemi-mechanical pulping

This is another one pulping process which is situated between chemical and mechanical pulping. Chemi-thermomechanical pulping can be reached by increasing the chemical treatment in thermomechanical pulping process. Chemical pretreatment of chips increases optical and strength properties of pulp. There are two wood types: softwood and hardwood. In case of softwood, the main chemical is sodium sulphite, in turn, hardwood requires alkaline peroxide. These chemicals are commonly added before preheating step and introduced by impregnation. In this pulping process chips are preheated until 70-170°C and cooked from fifteen minutes until two hours.

3.3. Semi chemical pulping

Semi chemical pulping process consists of two main processes: chemical softening and refining in mechanical pulper. One benefit of this pulping type is the higher pulp yield due to lower chemical use. Sulphite semi-chemical pulping is the most common process of SCM. This process often use for hardwood or sawdust for producing pulp for board manufacturing. (Printwiki, 2007c)
3.4. Paper and paper board manufacturing

3.4.1. Raw materials

For paper and paper board production raw materials which consists of fibrous material, variety of additives and chemicals are used. In turn, fibrous materials are recycled fibres and also chemical or mechanical pulp. The properties of raw material depend on end products. Table 3.3 shows raw materials needed for every end product.

Table 3.3 – Used raw materials for paper and paper board production

<table>
<thead>
<tr>
<th>End product</th>
<th>Raw material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newsprint</td>
<td>Few added chemicals, sometimes pigments, very little color, mechanical pulp or RCF</td>
</tr>
<tr>
<td>Kraft wrapping</td>
<td>Unbleached kraft pulp</td>
</tr>
<tr>
<td>Kraftliner or testliner</td>
<td>Unbleached kraft pulp and RCF or RCF only</td>
</tr>
<tr>
<td>Board</td>
<td>All fibre types including RCF</td>
</tr>
<tr>
<td>Writing and printing</td>
<td>All grades of fibre, mainly bleached, fillers, sizes, colors, brighteners, may be coated</td>
</tr>
<tr>
<td>Tissue</td>
<td>Chemical pulp and RCF in different mixture</td>
</tr>
<tr>
<td>Specialty paper</td>
<td>Specific fibre processing</td>
</tr>
</tbody>
</table>

3.4.2. Paper machine

Water from fibre is removed in paper machine so the content of moist less than 10%. Main principles of removing water are: drainage, pressing and evaporation.

The paper machine includes head box, wire and press sections, drying section and reel (Figure 3.15). At first, head box is needed to getting a uniform dispersion of fibres to obtain a uniform paper formation. Next is wire section where water is drained out from all suspension layers. This section drains the paper to around 17-20% of dry solids. After this section, press section drains paper to 37-55% depending on press section. Drying sections
help to reach 90% of dry solids in paper. The widespread method of drying consists of steam-heated cylinders for drying paper and board (Table 3.4). (Youtube, 2012)

Table 3.4 – Different types of drying (Vakkilainen, 2017)

<table>
<thead>
<tr>
<th>Dryer type</th>
<th>Tissue, %</th>
<th>Paper, %</th>
<th>Board, %</th>
<th>Coating, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder</td>
<td>5</td>
<td>95</td>
<td>95</td>
<td>35</td>
</tr>
<tr>
<td>Yankee</td>
<td>84</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Infrared</td>
<td>1</td>
<td>1</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Impingement</td>
<td>4</td>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Through-air dryer</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condebelt</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Impulse</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4. STEAM AND ELECTRICITY PRODUCTION

Traditionally energy is produced by burning of black liquor in recovery boiler and burning of wood residues in fluidized bed boiler (Figure 4.1). Commonly wood bulk and black liquor satisfy plant’s needs. But if plant requires more energy – more wood residues can be bought.

Wood includes small amount of potassium (K) and chlorine (Cl). These elements get into black liquor during cocking process. In recovery boiler they enrich fly ash and increase corrosion activity of flue gases.

Grow of temperature increases corrosion activity of potassium and chlorine. That’s why steam temperature in recovery boiler is determined by corrosion activity of potassium. This limit for superheated steam is between 400-490 °C depending on the potassium and chlorine content. After removal of these elements, temperature can be increased up to 510-520°C.

Figure 4.1 – Boilers scheme of pulp and paper plant (Fogelholm, 1999)
For bark and wood residues combustion are commonly used grate boilers and fluidized bed boilers. In case of fluidized bed boilers the common types are circulating fluidized bed boilers (CFB) and bubbling fluidized bed boilers (BFB). In comparison of grate and fluidized bed boilers the second type has several advantages:

- Low-grade fuels could be burnt with high ash content or moisture by fluidized beds
- Lot of types of fuels could be burnt a low emission of NOx and high combustion efficiency at the same time
- If a limestone is injected in a furnace it is easily and cheaply to remove sulphur
- A faster steaming rate’s change and a better turn down rate are the most important practical advantage (Huhtinen, 1999)

Examples of power production and steam flows are represented on figure 4.2.
5. METHODOLOGY

5.1. BFB boiler

At first we need to assume initial values, all of these values will be changed to estimate the impact of any of them:

- Properties of fuel
  - Low Heat Value
  - Content of carbon
  - Content of hydrogen
  - Content of nitrogen
  - Content of sulphur
  - Content of ash
  - Content of oxygen
  - Moisture content

- Temperatures
  - Ambient temperature
  - Primary air temperature
  - Secondary air temperature

- Air shares
  - Primary air
  - Secondary air
  - Water in air
  - Excess air
  - Infiltration air

- Mass flows
  - CaCO₃ mass flow
  - Sootblowing
  - Blowdown

- Live steam and feedwater properties
  - Pressure
  - Temperature
The next step is balance calculations. During this step amount of air per kgDS have to be calculated. It can be calculated by making combustion table. The fuel composition, mass molar mass and the moles are usually written in the combustion table. Additionally, we can include there the amount of oxygen required and the produced amount of flue gases.

Then to make combustion equations such as \( C + O_2 = CO_2 \) for every element. As a result of multiplying the quantity of oxygen by the combustion reaction coefficient for each reaction we will get amount of needed oxygen. This is because one mole of oxygen always weighs the same, and therefore the sum of all molar quantities of oxygen needed, will give the overall amount of oxygen needed on a mole basis. The amount of oxygen tells us the number of moles needed theoretically to complete the reaction. This is called the stoichiometric \( O_2 \). In reality, an excess air is added to the boiler to ensure the complete combustion of all elements.

The oxygen and nitrogen amounts we have now are the stoichiometric quantities in the air. In other words, the amount required to make the necessary reactions take place theoretically. In reality, more air is supplied in order to ensure the combustion process is as complete as possible. Incomplete combustion can lead to undesirable carbon monoxide and hydrocarbons in the flue gases. Additionally, soot can be formed.

Finally, we get the amounts of all components of the flue gases and calculate the final composition of the gas on a mass basis. (Table 5.1, Table 5.2, Table 5.3)

Table 5.1 – Flue gas calculation example

<table>
<thead>
<tr>
<th></th>
<th>g/kgBD</th>
<th>g/kgBD</th>
<th>g/kgBD</th>
<th>g/kgBD</th>
<th>g/kgBD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>As fired</strong></td>
<td>1666.67</td>
<td>666.67</td>
<td>545.000</td>
<td>59.000</td>
<td>364.100</td>
</tr>
<tr>
<td><strong>Molar weight</strong></td>
<td>18.0152</td>
<td>12.0110</td>
<td>2.0158</td>
<td>31.9988</td>
<td>28.0134</td>
</tr>
<tr>
<td><strong>Biomass fuel</strong></td>
<td>1666.7</td>
<td>37.000</td>
<td>45.375</td>
<td>29.269</td>
<td>11.379</td>
</tr>
<tr>
<td><strong>Recycle ash</strong></td>
<td>0.0</td>
<td>0.000</td>
<td>-</td>
<td>-</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Steam to preheater</strong></td>
<td>0.0</td>
<td>0.000</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>As fired</strong></td>
<td>1666.7</td>
<td>37.000</td>
<td>45.375</td>
<td>29.269</td>
<td>11.379</td>
</tr>
<tr>
<td><strong>Recycle ash</strong></td>
<td>0.0</td>
<td>0.000</td>
<td>-</td>
<td>-</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Cham. loss to stack</strong></td>
<td>0.0</td>
<td>0.000</td>
<td>-</td>
<td>0.000</td>
<td>-</td>
</tr>
<tr>
<td><strong>To ash and flue gas</strong></td>
<td>1666.7</td>
<td>37.0</td>
<td>45.367</td>
<td>29.269</td>
<td>11.379</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td>0.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total to ash</strong></td>
<td>0.000</td>
<td>0.008</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total to flue gas</strong></td>
<td>1666.7</td>
<td>37.000</td>
<td>45.367</td>
<td>29.269</td>
<td>11.379</td>
</tr>
</tbody>
</table>
Table 5.2 – Flue gas calculation example

<table>
<thead>
<tr>
<th></th>
<th>Air</th>
<th>Dry Gas</th>
<th>Water vapour</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mol</td>
<td>m3n</td>
<td>g</td>
</tr>
<tr>
<td>C</td>
<td>45,367</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S</td>
<td>0.669</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H2</td>
<td>20.269</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Qreq(required)</td>
<td>0.051</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Qreq in BD</td>
<td>11.379</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>O2 from air</td>
<td>0.002</td>
<td>1.090</td>
<td>1537.770</td>
</tr>
<tr>
<td>N2 in BD</td>
<td>9.431</td>
<td>0.010</td>
<td>13.000</td>
</tr>
<tr>
<td>H2O from air</td>
<td>0.324</td>
<td>0.072</td>
<td>58.577</td>
</tr>
<tr>
<td>Excess wet air</td>
<td>343.856</td>
<td>5.354</td>
<td>6735.634</td>
</tr>
<tr>
<td>Stoich. wet air</td>
<td>234.466</td>
<td>5.254</td>
<td>6735.634</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.3 – Flue gas calculation example

|                          |          |              | Flue gas |
|--------------------------|----------|--------------|
|                          | mol      | m3n         | g        |
| excess O2                | 12.171   | 0.273       | 389.443  |
| excess N2                | 45.645   | 1.023       | 1278.659 |
| excess CO2               | 0.017    | 0.000       | 0.767    |
| excess H2O               | 0.006    | 0.018       | 14.519   |
| Excess wet air           | 58.639   | 1.314       | 1683.388 |
| Stoich. wet air          | 234.556  | 5.254       | 6733.624 |
| Total wet air            | 293.196  | 6.568       | 8417.012 |
| H2O in stoich. air       | 3.224    | 0.072       | 58.077   |
| H2O in excess air        | 0.006    | 0.016       | 14.519   |
| Total water in air       | 4.030    | 0.090       | 72.596   |
| Total dry air            | 289.166  | 6.478       | 8344.415 |
| Mass flow (wet)          | 77.716   | 101.044     |          |
| Mass flow (dry)          | 77.732   | 100.133     |          |
| Theor. dry FG            | 228.541  | 5.114       | 7131.168 |
| excess dry air           | 57.833   | 1.296       | 1668.808 |
| Dry flue gas             | 286.374  | 6.409       | 8800.036 |
| H2O comb                 | 66.275   | 1.485       | 1193.950 |
| H2O air                  | 4.030    | 0.090       | 72.596   |
| H2O sum                  | 70.304   | 1.575       | 1266.646 |
| Sootbls.                 | 356.678  | 7.985       | 10066.582 |
| Scrubber                 | 4.026    | 0.104       | 83.333   |
| Wet FG                   | 361.304  | 8.088       | 10149.915 |
| Mass flow (wet)          | 97.061   | 121.799     |          |
| Mass flow (dry)          | 76.912   | 105.600     |          |

Next step is calculation of total heat input:

\[
Q_{tot} = LHV + W + UDA + HDA + IDA + M + H
\]  
(5.1)

Where,

- \( LHV \) – Low Heat Value
- \( W \) – Water in fuel
- \( UDA \) – unheated dry air
- \( HDA \) – heated dry air
- \( IDA \) – infiltration dry air
- \( M \) – moisture in air
- \( H \) – heat credits
After this total heat loses have to be calculated:

\[ Q_{loss} = Q_{man} + Q_{rad} + Q_{CO} + Q_{FG} + Q_{ash} + Q_{dust} + Q_{refr} + Q_{calc} + Q_{sulf} \]

(5.2)

Where,
- \( Q_{man} \) – manufacturers margin
- \( Q_{rad} \) – radiation/convection losses
- \( Q_{CO} \) – loss due to unburnt CO
- \( Q_{FG} \) – flue gas losses
- \( Q_{ash} \) – C in ash
- \( Q_{dust} \) – loss due to dust after ESP
- \( Q_{refr} \) – correction of HV to reference temperature
- \( Q_{calc} \) – loss due to calcination
- \( Q_{sulf} \) – credit due to sulfation

The last step efficiency calculation:

\[ \eta = \frac{Q_{tot} - Q_{loss}}{Q_{tot}} \]

(5.3)

Using these calculation steps, key indicators will be highlighted and final results with theirs descriptions are represented in chapter 6.

**5.2. Recovery boiler**

Recovery boiler calculation is divided into two steps: mass balance calculation and energy balance. Main initial values for mass balance calculation are black liquor properties and purification:

- heating value (HHV), carbon, hydrogen, nitrogen, sulfur, sodium, potassium, chlorine, borate, oxygen, NPE (Inert)
- Dry solids
- \( \text{SO}_2, \text{HCl} \)
• Reduction for sulphur and borate
• Air ratio
• Mass flow of sootblowing steam

Calculation is started from incoming black liquor properties mass per kgds.

Table 5.4 – Black liquor properties

<table>
<thead>
<tr>
<th>Incoming black liquor</th>
<th>mass, g/kgds</th>
<th>kmol/kg</th>
<th>mol/kgd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>C</td>
<td>325,0</td>
<td>12,011</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H</td>
<td>33,0</td>
<td>2,016</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N</td>
<td>0,9</td>
<td>28,013</td>
</tr>
<tr>
<td>Sulfur</td>
<td>S</td>
<td>61,0</td>
<td>32,060</td>
</tr>
<tr>
<td>Sodium</td>
<td>Na</td>
<td>200,0</td>
<td>45,980</td>
</tr>
<tr>
<td>Potassium</td>
<td>K</td>
<td>30,0</td>
<td>78,197</td>
</tr>
<tr>
<td>Chloride</td>
<td>Cl</td>
<td>2,5</td>
<td>35,453</td>
</tr>
<tr>
<td>Borate</td>
<td>B</td>
<td>5,0</td>
<td>10,811</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O</td>
<td>341,6</td>
<td>31,999</td>
</tr>
<tr>
<td>Water</td>
<td>H₂O</td>
<td>250,0</td>
<td>18,015</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td>1249,0</td>
<td>75,183</td>
</tr>
</tbody>
</table>

Second step is balance of every element calculations:

• Sulphur
  o SO₂, S in dust, ash and smelt

• Chloride
  o NaCl and KCl in dust and ash
  o HCl in flue gas
  o Cl in smelt

• Borate
  o borate in dust and ash
  o borate, Na₃BO₃, NaBO₂ in smelt

• Sodium
  o Na₂SO₄, NaCO₃, NaCl in dust and in ash
  o Na₂SO₄, Na₂S, Na₃BO₃, NaBO₂, NaCl in smelt

• Potassium
  o K₂SO₄, K₂CO₃, KCl in dust and in ash
  o K₂SO₄, K₂S, KCl, K₂CO₃ in smelt
• Carbon
  o NaCO₃, K₂CO₃ in dust and ash
  o NaCO₃ in smelt
  o CO₂

• Oxygen
  o CO₂
  o CO₃, SO₄ in dust and ash
  o SO₂
  o Na₂SO₄, NaCO₃, K₂SO₄, K₂CO₃, Na₃BO₃, NaBO₂ in smelt
  o H₂O

The last step of mass balance calculation is calculation of all mass flows per kgds and flue gas mass flow is the sum of all of components: black liquor, air, dust, ash, sootblowing, direct preheating and smelt.

When flue gas mass flow is already known steam mass flow can be calculated by assuming the same components as in BFB boiler with additional of:

• Black liquor heat capacity and temperature
• Flue gas heat capacity

The first step is heat input calculation and losses calculation. After these steps, it will be possible to calculate efficiency and steam production.
6. RESULTS OF CALCULATION

6.1. BFB boiler

After making several kinds of calculations, some of the key parameters have been received. In this chapter these parameters are shown and their influence is described.

The first parameter is moisture content percentage. This indicator has great influence at steam boiler efficiency and steam flow. Due to barks and other residues are very moist this parameter was checked first. As it represented on figures 6.1 and 6.2 boiler’s efficiency has a rapid drop between sixty and eighty per cent exactly as in case of steam flow. It can be described by increasing heat consumption for water evaporation and decreasing useful heat of steam.

Figure 6.1 – Dependence of boiler efficiency on moisture content
The next parameter is low heat value of fuel. As it can be predicted, grow of LHV increases efficiency and steam flow. On graphs 6.3 and 6.4 one can see slight grow of efficiency and linear dependence of steam flow.
In case of feed water temperature boiler’s efficiency is constant that’s why I have not considered it in my calculations. In turn, steam flow has a steady grow depending on feed water temperature (Figure 6.5). It can be described by constant heat value from gases to steam and redistribution of consumed heat.
Next in turn is amount of unburned CO. Unburned CO can appear due to mistakes or problems in combustion modes. Availability of this content testifies about constant decline in efficiency (figure 6.6) and steam flow (figure 6.7) not mentioned about harmful gases which can be emitted into environment.

![Eff(unburned CO)](image)

**Figure 6.6 – Dependence of boiler efficiency on unburned CO**

![Steam flow(unburned CO)](image)

**Figure 6.7 – Dependence of steam flow on unburned CO**
The last parameter which has tangible impact is outlet temperature. Grow of exit temperature decreases efficiency (figure 6.8) due to efficiency dependence:

\[ Q = 1 - \Sigma q \]  

(6.1)

Where \( \Sigma q \) is sum of each loss.

In case of steam flow its decline is due to decrease of useful heat.

Figure 6.8 – Dependence of boiler efficiency on boiler outlet temperature

Figure 6.9 – Dependence of steam flow on boiler outlet temperature
6.2. Recovery boiler

First and the most important parameter in recovery boiler maintenance are content of dry solids. Due to little changes it can cause significant effects. Dry solids content influences at high heat value and amount of burnable contents in black liquor (dependence 6.2):

\[
HHV = 25.04 \cdot C_s + 0.1769 \cdot C_z - 2.582 \cdot C_{Na} + 48.92 \cdot C_H + 42.31 \pm 0.41 \quad (6.2)
\]

Where,
- \( C_s \) – the sulphur content of the dry solids
- \( C_{Na} \) – the sodium content of the dry solids
- \( C_H \) – the hydrogen content of the dry solids (Vakkilainen 1999)

On figure 6.10 dependence of steam flow on dry solids.

![Steam flow vs Dry solids](image)

Figure 6.10 - Dependence of steam flow on dry solids content

The next parameter is smelt temperature. Result of calculations is represented on figure 6.11. Smelt temperature linearly influences at steam flow due to higher temperature of
smelt decreases used heat. The same description but with increase of steam flow can be related to black liquor inlet temperature (Figure 6.12)

Outlet temperature in recovery boilers has the same trend as in BFB boiler (Figure 6.13)
Air preheating temperature has more impact than in BFB boilers due to air is preheated by steam extracted from turbine. It means, that additional heat is growing and steam flow is also growing (Figure 6.14), but in the same time it decreases power generation.
Excess air has a slight decrease of steam flow on operational range because it increases needed heat to enlarge temperature of air from inlet temperature to burning temperature (Figure 6.15).

Figure 6.15 - Dependence of steam flow on excess air
CONCLUSION

Pulp and paper industry is one of the most important industries in many countries over the world. Production of qualitative end product requires huge amount of produced energy that’s why to prevent of additional resources use all processes have to be effective as possible.

As it was said in introduction chapter, costs of energy resources in pulp and paper industry are reached 15 per cent of total manufacturing costs and also under 40 per cent in total production costs. That’s why it should be mentioned that more energy effective processes have a great impact on reducing total costs of production.

The main aim of this thesis work was to calculate possible energy production in modern pulp mills and find out production indicators which have a great influence at steam production and boiler efficiency. To answer on this question, calculations of BFB boiler and recovery boiler were done. Then each indicator was checked and the main ones, which can be changed during operation, were selected. At the last step in accordance with objectives steam flow and boiler efficiency dependence graphs were plotted and described.

Methods of calculation which I used have several advantages and disadvantaged and few of them should be noticed. The most significant advantage is visibility. These graphs show how much steam boiler can produce per kg fuel. And behavior of these lines is visible. In every situation approximate changing percentage can be calculated. But as every method it has drawbacks. One of them is approximate results. Boilers operating modes were taken as approximate average in this industry and they are not related with any of certain mill. Also this calculation may include age of auxiliary and main equipment, pipes condition, insulation conditions etc. to provide more accurate results.

In general the problem of finding key indicators of pulp mills is a complex action which has to include huge data bases of every plant normal operation modes and equipment conditions. But with calculation that I have made it is easier to understand which processes have to be improved to reach better efficiency.
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