Pulp and paper industry: An overview on pulping technologies, factors, and challenges

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Abstract. The pulp and paper sector currently plays important part in the world’s economy. In this paper, we present a review of pulping technologies to convert logs or wood chips and non-woody materials into pulp for use in papermaking which consist of mechanical, chemical and semi-mechanical. It also talks about the history of papermaking and various important factors involved in producing high quality pulp and paper such as H-factor (time and temperature), alkaline charge, liquor to wood ratio, and sulphidity. This paper also discusses about challenges facing by the pulp and paper industry or processes, namely high use of energy and chemicals, as well as generation of liquid and solid wastes of large quantities. This paper will be handier for those who are new to the field of pulping research for paper production.

1. Introduction

Modern paper making evolved from an ancient art in Egyptian civilization which used papyrus as writing media around 3000 BC. The characteristics of the papers in this era are not the same as the papers used today. A more skillful papermaking later was reported from a Chinese named T’sai Lun in 100 AD, utilizing a wide variety of materials such as bamboo or mulberry fibers. This method of papermaking was then spread throughout Middle East and Rome in the Mediterranean Sea after several centuries until it reached Europe, England, and America at the beginning of 15th century. In 1799, the first continuous papermaking machine called Fourdrinier machines was patented by a Nicholas Louis Robert from France [1]. The milestones in the pulp and paper industry continued further with the invention of cylinder paper machine by John Dickinson in 1809, leading to a rise in Fourdrinier machines usage for making thin paper. Seventeen years later, steam cylinder was introduced for drying the papers. The United States began to use the Fourdrinier engine only in 1927. Mechanical process of making pulp from wood of low quality was discovered in 1814 by Friedrich Gottlob Keller, whereas soda process was just introduced in 1854 by Charles Watt and Hugh Burgess. Sulphite process was found three years later by Benjamin Chew Tilgh, an American chemist, through his British Patent. This process was able to produce a good and ready bleached pulp. Finally, Kraft or sulphate process was discovered from a basic experiment of Carl Dahl in Danzig in 1884 which is a dominant method used today [2]. Those milestones provided the basis for modern pulp and paper industry.

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1.1. Wood Composition and cooking liquor

There are two types of raw materials for paper making, namely wood (Acacia, Eucalyptus, etc.) and non-wood (banana, kenaf, bamboo, etc.) materials. Of these two types, the pulp and paper industry uses wood raw materials. Wood is part of the stem or branches and twigs of plants that is harden due to lignification. Wood is available in large quantities, easily cultivated, cheap, and contains a lot of cellulose. Wood as raw materials are divided into long fiber (softwood) and short fiber wood (hardwood) (Table 1). Each type of wood produces different types of pulp [2]. Cooking liquor is another component in pulp making and divided into three categories: (i) white liquor, which is the main cooking chemical consists of caustic (NaOH), sodium sulphite (Na₂S), and sodium carbonate (Na₂CO₃); (ii) black liquor, which is a washing liquid containing lignin and dissolved chemicals and is used to meet the needs of cooking fluid in the cooking process, and; (iii) white chemicals, which contain chlorine dioxide (ClO₂) for increasing the whiteness of pulp.

| Component       | Hardwood (%) | Softwood (%) |
|-----------------|--------------|--------------|
| Cellulose       | 45           | 42           |
| Hemicellulose   | 30           | 28           |
| Lignin          | 20           | 27           |
| Extractive      | 5            | 3            |

1.2. Manufacturing of pulp and paper

Pulp manufacturing starts with transporting wood coming from the forest to the wood piling place called wood yard. This is then followed by wood skin peeling using debarking drum, which is a paring tool drum containing a lifting bar by turning motion. Peeled skin will fall through holes in the wall slot. After exfoliation, the bark is converted into chips called the chipping process. Chips that have met the standard will proceed to the next process, which is cooking process. Aim of this process is to dissolve the lignin component in wood using chemical and heat. The cooking process takes place in a large pressurized vessel called a digester by addition of white liquor. Subsequently, washing is carried out to separate fibers from water-soluble pliers, which consists of organic compounds i.e. lignin and also organic compounds as leftovers from cooking chemicals. Screening using a filter followed to separate fibers or impurities based on size. These components can reduce the quality of pulp and can cause waste of chemicals in the bleaching processes. Bleaching is the next step which is applied by the pulp and paper industry in four sequential stages, namely Initial Dioxide Stage (D0), Oxidation-Resistant Extraction (EOP) stage, Chlorine Dioxide stage 1, and Chlorine Dioxide stage 2. D0 is gradation and separation of lignin, whereas EOP is elimination of lignin. Chlorine Dioxide stage 1 is aimed to increase brightness and Chlorine Dioxide stage 2 is the final stage to perfect the level of bleaching stage. Finally, the pulp goes to paper production stage in which the products can be traded for use as stationery, office supplies, and others. In addition to paper, pulp can be directly sold to investors who need to change it into new products such as cardboard, tissue, etc.

2. Overview of pulping technology

Pulping process is the separation of lignin to obtain fiber or cellulose from fibrous material. Thus, cellulose must be clean from lignin so that the quality of the paper obtained does not change colour during use. Mechanical, Chemical, and Semi-Mechanical Pulping are three general classes of turning wood into pulp [3]. Mechanical pulping is entirely dependent on physical action whereas chemical pulping needs chemicals to release the fibers. Semi-Mechanical Pulping combined mechanical and chemical actions to obtain the fibers. Results from this process is called pulp, which will then be processed into paper in the paper machine [4].
2.1. Mechanical Pulping
A tool such as grinding is used for scraping in mechanical pulping. First, the wood is skinned and then cut and crushed to produce chips. Then, the raw materials are milled to release fibers, followed by filtering these materials so that cellulose is separated from the others [3]. The yield from this process is around 90-98%. Mechanical slurries contain high lignin and short fibers which make it fragile. There are several methods of mechanical pulping namely Mechanical Pulp Refiner (RMP), Pressure Groundwood (PGW), Stone Groundwood (SGW), Thermomechanical Pulp (TMP) and Chemi-Thermomechanical Pulping (CTMP), in which the main difference is whether the pulp produced from a refiner or stone grinder [5]. Other advantages of mechanical pulping are low production costs and suitable for printing paper due to good ink absorption, compressibility, opacity, high bulk density, and more environmentally friendly. Nonetheless, drawbacks arisen from this process are: high loads of shive and knots; yellow color of paper when exposed to bright lights due to high lignin content, and; high fiber damage and low pulp strength due to shorter fiber. Figure 1 illustrates the CTMP process.

![CTMP PROCESS DIAGRAM](image)

**Figure 1.** Illustration of the Chemi-Thermomechanical Pulping process [5].

2.2. Chemical Pulping
Pulping with a chemical process aims to damage and dissolve the fiber binding agent consisting of lignin and pentose using chemicals. This process of damaging and dissolving is called cooking. The process of cooking raw materials with chemical solutions is carried out in a reactor called digester. During cooking, lignin reacts with chemical solutions and forms dissolved compounds that are easily washed. Some cellulose also reacts, producing a low pulp yield. Chemical pulping can be divided into three types, namely soda, sulfite and Kraft pulp making [5]. Soda and sulfate processes use alkali chemicals in cooking liquids, so composting pulp follows. Compared to mechanical method, chemical process usually produces higher pulp strength and paper quality, reuse chemicals and energy more efficiently, and products can be used for making viscose [3]. However, several drawbacks arisen from this process are a lower yield and greater production cost (40-52%), a pungent odor from the pulp, and more pollution to the environment due to chemicals used.
2.2.1. Soda pulping
The cooking solution used in soda pulping is sodium hydroxide (NaOH). The soda solution function in the process is for hydrolysing lignin and other fiber binding agents so that the fiber contained in the raw material will be released. Lacking of cooking chemicals will result in darken pulp and difficulty in bleaching. However, excessive cooking chemicals can reduce yield by degradation of cellulose fibers. Cellulose degradation with concentrated sodium hydroxide solution can occur at temperatures above 1000 °C. If the temperature is too high, amount of degraded carbohydrate will be greater than dissolved lignin, which will reduce the yield and thickness of the pulp. Nonetheless, it is easy to recover sodium hydroxide from liquor as an advantage from this process [6]. Soda-Anthraquinone (Soda-AQ) has also been used to make pulp made of mostly non-woody plants, in which the anthraquinone acts as a redox catalyst resulting in increased yield [7].

2.2.2. Sulphite pulping
This process uses active chemicals as follows: sulphite acid, calcium bisulphite, sulphur dioxide expressed in solution as Ca (HSO₃)₂ with excess of H₂SO₃. Softwood is the common raw material and SO₂ and Ca (HCO₃)₂ are the cooking solution (equations 1 and 2) [6]. Lignin which is bound to cellulose will react with a solution of Ca (HSO₃)₂ (equations 3-5). The process produces a high yield in certain kappa numbers, higher white degree of pulp that is not bleached, and pollution of less than 1. However, this process is rarely used in industry due to the high costs.

\[
\begin{align*}
S + O_2 &\rightarrow SO_2 \\
2SO_2 + H_2O + CaCO_3 &\rightarrow Ca(HSO_3)_2 + CO_2 \\
Ca(HSO_3)_2 &\rightarrow Ca^{2+} + 2HSO_3^- \\
Lignin + HSO_3^- &\rightarrow SO_2 + LigninOH^- \\
LigninOH^- + HSO_3^- &\rightarrow LigninSO_3^- + H_2O
\end{align*}
\]

2.2.3. Kraft pulping
Kraft technology found by Carl Ferdinand Dahl is chief and superior in pulp production [6]. This process combines sodium hydroxide and sodium sulphide at a temperature of 160-180 °C (320-356 °F) and pH>12, producing fibrous material resulted from destruction of bonds of lignin macromolecules. The following cooking reaction can be shown for Kraft process (equation 6).

\[
NaOH + NaS_2 + Wood \rightarrow Na - org. + S - org. + NaHS
\]

2.2.4. Semi-mechanical pulping
Semi-mechanical pulping is a method of combining chemical process with mechanical process. The chemical used in this process is sodium sulphate to remove cellulose lignin bonds and get perfect fiber separation. Included in this process is Chemi-Thermo Mechanical Pulping (CTMP) which uses heating to degrade lignin so that the pulp has a lower yield but with better quality than pulp with the mechanical process [4]. Following are the advantages of semi-mechanical pulping: a fairly bright color pulp, a longer pulp resistance, and 65-85% of yield. On the contrary, several disadvantages noted are a more complicated process and large production costs.

2.2.5. Other chemical pulping methods
Other methods in pulp production are organosolv and hydrotropic methods. Organosolv is a method of separating fibers using organic chemicals such as methanol, ethanol, acetone, acetic acid and others. In this process, decomposition of lignin is caused by breaking of ether bond. This process does not use sulphur so that it is safer for the environment and recycling black liquor can be done easily [4]. It also requires relatively low capital infestation due to less waste and easy refining of alcohol [8]. Printing
paper and dissolving pulp are examples products of organosolv process which have lower strength property than the Kraft process. With respect to hydrotropic method, fibers separation is carried out using water-soluble and environmentally friendly reagents known since the middle of last century [9]. Hydrotropic is an aqueous salt solution that at the same temperature, could provide greater volubility for substances that are slightly soluble (such as lignin) than water. Example of commonly used hydrotropic salt is sodium xylene sulfonate. Relatively pure lignin can be recovered by deposition and used for conversion to other chemical products [10].

2.2.6. Biopulping
Biopulping is the process of separating fibers (cellulose) with other substances to produce pulp using certain microorganisms. There are two biopulping processes namely lignin depolymerisation and esterification of oxalate. These processes are resulted from fungal penetration on wood chip’s lumen and cells, increasing saturation of water fiber as one of the results [4]. Fungi from Basidiomycetes class have been known able to degrade lignin in the wood weathering process. Lignin degradation involving the activity of the ligninolytic enzyme produced by the white root fungi, namely lignin peroxidase, manganese peroxidase, and laccase [11]. The third enzyme is a multi-extracellular enzyme that involves in the lignin depolymerization process. Some research results show that biopulping is relatively superior to the Kraft process because it is environmentally friendly [12]. Nonetheless, this process is slow compared to chemicals and requires biological control in a complicated process.

3. Cooking equipments, parameters, and pulp analysis
The pulp cooking process is usually carried out using a tool called digester. Digester is a cook container that must withstand high temperature, alkaline or chemicals with high concentration and large pressure. Digester is an upright cylinder-shaped chips/chip-in-shape cookware that is designed for high pressure and temperature. There are two filter strainers in the digester, one is located at the top of the digester called relief strainer and the other one is located in the middle of the digester called middle strainer. The function of strainer is to keep the wood fibers that are being cooked not out of the digester at the time to circulate the cooked fluid and at the time of wasting the existing gases in the digester. There two types of digesters, namely batch and continuous digesters.

Batch digester is a large digester with a total filled volume of chip and cooking liquor range between 70 and 350 m³. Usually a factory has six to eight batch digesters so while some cook, others can fill up, go into the blow tank, and so on. Steam provides heating of digester and dilution of cooking liquid, which can be directly or indirectly. When steam passing the inside of the digester tubes, steam recycling and more uniform heating can be obtained. A continuous digester is a tubular digester in which the chip enters and exits the digester continuously, passes over a stream containing five major stages (presteaming-impregnation-heating-cooking-washing). This type of digester has been considered more efficient in terms of space, control, energy, and chemical usage. A special feeder is often used to allow chips entering the commonly pressurized digester with the help of a rotary valve. After passing through the high-pressure feeding, the cooker will take the chips to the digester. Conditions for impregnation are usually 45 minutes at 130 °C, allowing uniform cooking of chips at these process conditions [4]. Below are influencing parameters in Kraft pulping.

3.1. Alkali Strength
Alkali strength for softwoods is normally about 12 to 14% effective alkali on dry woods, whereas the requirement is typically lower (8 to 10%) for hardwoods with active alkali about 21%. Providing sufficient composition of alkali is very important for completion of cooking and adjustment of reaction rate. The common employed method is to utilize the minimum practicable alkali charge and vary the cooking temperature to achieve the desired rate. Higher alkali charge could cause a slight reduction in hemicellulose retention at given kappa number and changes the composition of retained hemicellulose [6]. Alkali in the cooking liquor is basically consumed for three different reactions: lignin reaction, neutralisation of organic acids, and resin reaction in the wood [13].
3.2. H-factor
The H-factor is the cooking time-temperature needed to achieve a certain kappa number, which is described by the area under the Kappa number (K) curve versus time (in hr) (Fig. 2). For instance, a value of the H-factor of 925 is proportional to a one-hour isothermal cooking at 170 °C, considering other cooking conditions (effective alkali concentration, liquor-to-wood-ratio, etc.) are maintained constant. This will result in a sufficient precision of the predicted kappa number [5]. However, the cooking process can not eliminate the lignin perfectly without damaging the pulp. Therefore, it will be followed by an advanced process that is bleaching to prevent reject pulp.

3.3. Liquor to wood ratio
For adequate penetration, it is essential to supply sufficient liquor for wetting chips’ surfaces. For batch cooking, three-quarter filled digester is normally employed at the beginning. Gradual rising in the liquid level due to chip moisture and lignin in the liquid phase during cooking [6]. Sufficient white liquor is supplied in the digester to provide the specified alkali charge. Balance of the liquid requirement is typically made up with black liquor. Liquor to wood ratio is a ratio between all liquids contained in the digester with a dry wood chip, usually at ratio of 3:1 to 5:1. A greater dilution would decrease the concentration of active chemical and thereby reducing the reaction rate.

3.4. Sulphidity
Delignification selectivity (yield vs. kappa number; viscosity vs. kappa number) is also primary and important parameter. High selectivity requires concentration of sulphide as high as possible, especially during transition from initial to bulk delignification [14]. A carbon–carbon bond cleavage of the b-c-linkage yielding formaldehyde and styryl aryl structures could present during insufficient supply of sulphide ions, reducing the selectivity. Effects of Na2S in Kraft pulping of softwoods are prone until 15% sulphidity, resulting in higher yield and a stronger pulp, but the benefits are less dramatic at higher sulphidities [6].

3.5. Impregnation
In each process of chemical pulping, it is very important to ensure alkali distributes uniformly in all parts of the wood. Impregnation process goal is to optimize penetration of chemical substances into wood so that the resulting pulp is uniform, high quality and does not leave the wood that does not react with liquor. Ideally, the cooking should take place with the same concentration in all parts of wood and with a uniform temperature as well. Penetration is defined as transfers of liquid and associated chemicals into

Figure 2. Effect of H-factor on kappa number and yield (Spruce/Pine = 1:1; liquor to wood ratio = 3:8:1; maximum temperature = 170 °C; effective alkali charge = 19%; sulphidity = 38%) [5].
air-filled cavities of the wood chips caused by hydrostatic pressurization until saturation of fibers. Liquid diffuses into the pores while entrapped air dissolves into water or diffuse out pores [5]. Impregnation process is usually done by inserting hot steam or hot black liquor into wood chip.

3.6. Pulp Analysis
Kappa number, viscosity, and alpha cellulose are three important components in pulp analysis. Kappa number is often used in mill control work to achieve degree of delignification and chemical requirement for bleaching, in which the percentage lignin approximately equals to K x 0.15. Kappa number is commonly determined from reactions of lignin and other non-cellulosic constituents of pulp fibers with acidic permanganate. Kleppe [15] reported that total pulp yield in Kraft pulping of southern pine and southern mixed hardwoods is influenced by kappa number (Fig. 3). A good indication of cellulose degree of polymerization can be obtained by measuring the viscosity of cellulose solution of known concentration. Alpha cellulose (the long-chain molecular fraction of the holocellulose) is defined chemically as that portion which resists solubilization of the shorter-chain cellulose and hemicelluloses in strong caustic solution. The chemical determination is carried out through pulp extraction under specified conditions. The soluble portion is then measured by oxidation with potassium dichromate, and the alpha cellulose fraction is calculated by its difference [6].

![Figure 3. Total pulp yield versus kappa number in Kraft pulping of southern pine and southern mixed hardwoods [14].](image)

4. Challenges to face
4.1. Energy usage in pulp and paper mills
The characteristics of energy technology used for the pulp and paper industry depend on the type of process used. Each process requires certain energy that may use fuels such as coal, gas and oil, or electricity. The fuel is mainly used for steam generation and the main electricity user in an industry is an electric motor. Regarding mechanical pulping, the process requires considerable electrical energy. In contrast, chemical pulping requires large amounts of steam and most of the energy consumed is for pulping and paper drying. However, this process produces a by-product in the form of black liquor. This by-product can be used to generate steam and electricity in an incinerator. Black liquor can produce energy about 22 GJ per tonne of pulp produced. Thus, it can result in energy surplus depending on the configuration of process in the pulp mill. Gasification technology has also an opportunity to increase efficiency in the use of black liquor. In the gasification process, hydrocarbons are converted into synthetic gas (syngas) in the form of carbon monoxide and hydrogen mixture. This synthetic gas can be used as raw materials in chemical industry or for driving gas turbine used in the power plant. This technology is often called black liquor gasification combined cycle (BLGCC) which fuelling can also
use biomass such as leather and wood chip. With respect to biopulping, reducing the environmental impact and production costs due to small use of chemicals and energy are the main goals of this process. However, the process is slower compared to the mechanical and chemical processes and requires proper control when working with biological material.

4.2. Waste generation and management
The wastes produced from the pulp and paper production can be divided into three categories, namely liquid, solid and air or gas. Liquid waste is generally processed using a Waste Water Management Installation (WWTP). The WWTP system classifies and combines its operating units (physical, chemical, and biological). Operation unit associated with physical is screening. Screening is used as an efficient and inexpensive way to set aside large sized suspended materials (e.g. fiber) and weak black liquor filtration. Fibers and weak black liquor are not desired in cooking and the concentration unit, respectively. Regarding to chemical process, chemicals addition to waste water is usually carried out to remove particles that are difficult to settle. Some examples of wastes or processes that use chemicals are remaining liquid from the bleaching results using chemical chlorine dioxide, caustic soda extraction, and chemical solution from cooking. With respect to biological process, the main objective of waste water treatment is to collect and eliminate or decompose dissolved organic matter which is biodegradable by microorganism activity.

The pulp and paper industry generally produces solid waste in the form of stone from lime and contains soda. This must be disposed of in a safe and comfortable environment. Solid waste must be disposed of at the place of final disposal that is secure. There are two other types of solid wastes in the industry processed using bark boilers and lime kilns. Bark boilers are used to burn bark, while lime kilns are used for processing lime sludge. The air emission produced from the pulp production process is usually recycled using a tool such as blow gas treatment. Electrostatic dust precipitator and wet scrubber are two examples of air emission units available in recovery boiler and recaustizing unit, respectively. Some wastes or processes that produce air emissions along with their handling are polluted condensate from the digester process, non-condensable gas, high pressure steam produced from burning organic matter, evaporation of the rest of chemicals due to the heat from washing units, and wastes containing solid particles from boiler chimney.

5. Conclusion
The history of making pulp and paper starts from ancient method using bamboo as the main ingredients and now in a modern way using Acacia and Eucalyptus along with technological advances in paper products of higher quality. There are several technologies known in papermaking process, namely mechanical, chemical, and biological pulping, with chemical Kraft pulping as the most dominant method. In the Kraft process, high quality pulp is produced using temperature of 160 to 180 °C with 120 minutes of cooking and 60 minutes of heating time, liquor to wood ratio of 3:1 to 5:1, and active alkali of 21% of dry chip. The chemical process unavoidably has drawbacks to the energy usage and environment. Therefore, more advanced technologies and continuous improvement are needed pertinent to environment and energy controls for the benefit of industries and society.

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