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ISBN 978-3-031-47284-8 ISBN 978-3-031-47285-5 (eBook)
https://doi.org/10.1007/978-3-031-47285-5

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

This book is dedicated to Teresa, my life's accomplice, to our sons, and grandsons.

Preface

Pulp refining is one of the most fundamental operations in paper manufacturing. Although this fact is fully recognized by the great majority of papermakers, the ways to evaluate and to optimize quality and performance in pulp refining are poor in most paper mills. This situation is mainly due to the weak understanding of the effects of refining variables on fibers and the corresponding impacts on paper properties, when refiners are in operation. The knowledge of refining machinery variables for better results on the pulp quality developments is also another point to deserve improvements. Even the most important operation and quality parameters to evaluate refining behavior are not fully understood, not only by papermakers, but also by researchers on this field. Refining control is generally based on applied/consumed energy and pulp freeness development: something recommended just for beginners and not compatible to the overall demands for obtaining the most appropriated performances in paper machine runnability and paper sheet quality. The lack of technical knowledge and orientation to corrective actions by technicians both do impact costs, paper machine performance, and final product quality.

These fragilities in pulp refining knowledge by people working in refining rooms over the world surely are to be reduced by reading this amazing book has been written thanks to Professor Vail Manfredi's expertise. Master Manfredi is one of the most renowned experts on the theories and practical applications of pulp refining for papermaking purposes.

I know Vail Manfredi since the early days of his academic studies with the purpose to become forest engineer with a major in pulp and paper science and technology. During 1975/1976, I had the privilege to be his teacher and to advise him as undergraduate student and also as trainee on his initial practical studies with pulp and paper in the P&P laboratories at the School of Agriculture "Luiz de Queiroz" from the University of Sao Paulo/Brazil. Our first published technical article in partnership between we both and Professor Luiz Ernesto Barrichelo and Regina Fazanaro (another trainee student) was related to measure fiber population and fiber coarseness using very simple and immediate laboratory techniques. The title of that article, translated to English, is: "Quantitative Analysis of Cellulosic Fibers," published through the Brazilian magazine O Papel, in September 1976. Since those early times, I maintain in my mind the figure of Vail Manfredi as a dedicated, keen, and responsible person and an excellent professional, what has been proved along his career. After his graduation in 1978, Vail was also my graduate student, when working for his Master of Science degree at the same university. He has always shown to have a great ability, capacity, and understanding to face practical and theoretical issues. His master thesis was oriented to evaluate the changes of wood quality and kraft pulping ability along the stem heights of *Eucalyptus* planted trees.

From the university to the industry was an easy jump. Vail Manfredi had a fast growth in his career by developing R&D innovations in some Brazilian eucalyptus pulp/paper manufacturing companies (Ripasa, Aracruz, Bahia Sul, and Suzano). At Aracruz Celulose (from 1983 till 1992), he had his first challenge with pulp refining, thanks to the project and operation of a pilot plant to evaluate and to optimize *Eucalyptus* bleached kraft pulp refining in comparison to other pulp fibers. This project had also a strong marketing orientation, since the aim was to help *Eucalyptus* pulp users to take the most from this recent product made available in the world pulp markets. When Vail changed jobs from Aracruz Celulose (market pulp mill) to Bahia Sul (market pulp and printing and writing paper mill) in 1992, he had as initial tasks some similar challenges as before in Aracruz: responsibility for projecting the technical area for R&D studies, including the development of the design and operational issues for another pulp refining pilot plant. In both cases, the pilot plants had been built to be very close "to the real life" and to represent pulp refining in industrial operations. These studies were so important, that pulp refining has become a passion technical issue on Vail's professional life.

Vail Manfredi has also an admirable personal profile for sharing knowledge through articles, speeches, courses, and participation in technical associations (TAPPI/USA as a member of the IRMC – TAPPI International Research Management Committee; ABTCP/Brazil, etc.). I feel proud on this because his behavior is very similar to mine, and for this reason, I keep a happy and hidden feeling that my initial guidance in his career has been approved and taken as a simple example.

This present book on pulp refining may be considered as his masterpiece, crowning his professional career. The book has been written in his retirement period, what represented available time for reading, studying, thinking, and making reflections and comparisons for building the text.

As a researcher and professor in many courses on pulp refining, it is possible to observe that Professor Vail Manfredi had as purpose to guide the book readers through the history of paper and this essential product manufacturing process, finally reaching, with a lot of details, the process of pulp refining: and the consequences of refining in papermaking. The texts are very complete, associating the theoretical points of how refining happens with operational conditions, pulp fiber changes, and paper quality requirements. He pays attention to the different concepts and principles of the refining operation, trying to get the most from the different theories, basing his writing on deep thinking and interconnected reflections.

As a talented forest engineer with a rich career on pulp and paper technology, his book is written searching for associations among changes in pulp anatomical elements, refining variable operations, machinery devices, and the corresponding effects on paper quality. It is my understanding that the chapters about refining variables control, optimizations, and measures to evaluate refining performance were outstanding and very useful to technical people. Also, students and young engineers, devoted to pulp and paper manufacturing, are to have a great chance to upgrade their knowledge by a careful reading of all book chapters, since the book searches for connections from fibrous raw materials to final paper products. The young people, beginners in the P&P sector, are invited to reflect and to imagine how someone can be able to significantly improve his knowledge by reading the available technical literature. I was invited to follow Vail's writings, and I'm quite sure that he has done complete reading of over 1400 technical references obtained from the world technical and scientific literature. From the range of age for these technical materials, I'm also sure that this collection of knowledge has been gradually accumulated along his close to 50 years of dedication to the pulp and paper science and technology.

For all these points (and many others not mentioned by my own forgetfulness), I recommend this book to all those interested on learning about pulp refining and its connections with paper manufacture, behavior, and performance. I'm very confident that this book is to become an important part of the global history of papermaking technology.

Porto Alegre, Rio Grande do Sul, Brazil Celso E. B. Foelkel

Acknowledgments

I thank the authors and associations below for permission, as a courtesy, to use photos or illustrative figures from their publications in the text of this book.

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Dr. Herbert Sixta – Aalto University, Finland
Dr. Huan Liu – Shaanxi University of Science & Technology – China
Dra. Patrícia Kaji Yasumura – Instituto de Pesquisas Tecnológicas – Brazil
Pulp and Paper Technical Association of Canada – PAPTAC Canada
REGMED Indústria Técnica de Precisão Ltda – Brazil

Special thanks to
Dr. Celso E.B. Foelkel
for the conviction, encouragement, and support given in the elaboration of this book.

Contents

Chapter 1
Introduction

Pulp refining is defined as the mechanical treatment applied to fibers in suspension to develop the desired properties in the paper. Since the most remote times (T'sai Lung, 105 AD), the treatment is carried out through successive cycles of mechanical impacts on the fibrous materials.

The treatment is done on fibers in suspension, promoting hydration of the fiber cell wall leading to their delamination, making it porous, flexible, and less resistant, or, depending on the amount of applied energy, leading to its complete destruction causing fiber rupture (reduction in the average fiber length).

The process is a stress fatigue one in which the fibers are subjected to compressive and shear forces that reduce the cell wall intrinsic resistance. The fibers tend to collapse becoming more flexible; deformations of the fibers and fines are generated which increase the specific surface available for the connections between fibers. The process is characterized by high energy consumption.

In the production of most commercial papers, after the selection of the pulp to be used, refining is the main determinant of the quality of the finished product, as it is the only unit operation that irreversibly modifies the morphology of the fibers.

The process, however, has some unwanted side effects, such as the reduction of both specific volume (bulk) and opacity of the paper, in addition to increasing the difficulty of removing water in the areas of paper formation and pressing in paper machines.

Nowadays, with paper machines operating at speeds of up to 2000 m/min, it is essential that refining is properly conducted so that productivity is not affected, and manufacturing costs are not exceeded beyond what was planned.

In this book, we present a brief history of papermaking followed by comments regarding wood as a source of fibers, including its chemical and anatomical characteristics and, also, the influence of these aspects on the quality of the pulp produced as well as the effects of the pulping process, mainly chemical process, on pulp quality, in addition to addressing how these wood characteristics influence both the refining process and the quality of the final paper.

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https://doi.org/10.1007/978-3-031-47285-5_1

For the refining treatment, in addition to presenting its history and development of the equipment involved, we will approach the evolution of refining models, the so-called “refining theories,” developed with the aim of expanding the understanding of the whole process, especially how the treatment influences the characteristics of the fibers and how they influence the economy of the process and the quality of the final products.

We also present a broad discussion, based on experimental results, on the contribution of the main operating refining variables, as well as the main strategies that can be used industrially to optimize the operating results. From this evaluation, the parameter that complements the specific edge load theory was identified. This parameter is related to the retention time of the fiber flocs inside the refiner.

This evaluation also confirmed that refining cannot be adequately characterized using only two operating parameters, as is traditionally done. Four operating parameters are required: refining energy, refining intensity, consistency, and the pulp to be refined.

A specific chapter discussing the refining process optimization is also presented. In this chapter, a new proposal for disc configuration, which should allow considerable gains in refining energy, is discussed. The suggestion is the adoption of channels with variable width in the refining discs.

We hope, in this way, to contribute to improve the understanding of the refining process and, also, help students and technicians working in this extremely important topic in the paper manufacture.

Chapter 2
The Beautifull History of Paper

Before the invention of paper, various types of materials were used as a means of recording written information. Different cultures have used clay, wood, bark, leaves, stone, metal, papyrus, parchment, and cloth as recording media at one time or another. As a curiosity, around the fifth century, in Central America the Aztec and Mayan peoples also developed their appropriate and durable writing supports, which were made from birch (*Betula alba* L. and *Betula nigra* L.) and from the bark of the fig tree (*Ficus* sp.), being called huun and amate, respectively [1–3].

In antiquity, the Egyptians developed a way of using papyrus, soaking it with water and kneading it until it formed a parchment shape, with a thickness like a fabric. The oldest papyrus scrolls, on which we have something written, are over 5000 years old. Papyrus helped to shape and strengthen Egyptian society and was the support of writing in current use until the first centuries of the Christian era throughout Europe, Asian regions, and, of course, Africa, where it originated. Without the papyrus, the course of Mediterranean history and literature would have been quite different. The same is true for the effect on European history [1, 3].

The word paper originates from the Latin “papyrus,” an aquatic plant that exists in the delta of the Nile River and is considered sacred because its flower resembles the rays of the sun, the maximum deity of the ancient Egyptian people [2].

Although there is evidence that paper, as we know it today, has an earlier origin, the first known record of a papermaking process dates back 105 AD. Tsai Lun, an official at the court of the Chinese Emperor Ho Ti, directed some workers to crush mulberry bark together with pieces of bamboo and old fishing nets. The crushed raw materials were dipped in water and boiled for a long period of time, being reduced to a pulp that was beaten and dispersed in vats with water. From these vats, samples were collected on a sieve, with a bamboo frame and a stretched cloth, and placed to dry in the sun in a natural drying process [1–11].

Thus, the first sheet of paper was born, whose basic principle of production remains almost unchanged after almost two thousand years of its invention.

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https://doi.org/10.1007/978-3-031-47285-5_2

In addition to being easier to produce than parchment, paper had other advantages such as less possibility of breakage and better ink absorption, making it difficult to erase or alter what was written, important aspects when it came to preserving official documents and records. Following the commercial routes of the great caravans, the use of paper extended through the four corners of the Chinese Empire. Paper became the preferred vehicle for maps, battle plans, and astronomical charts, as well as for books, architectural plans, and scientific, musical, religious, and mathematical notes, which facilitated experimentation in each discipline [2, 3, 6] (Fig. 2.1).

In China, paper was essential for the evolution of woodblock printing, and in the Tang dynasty (618–906 AD), thousands of religious and secular books were produced [6]. The first reported use of paper for toilet purposes also comes from China in the sixth century, where it was made from rice straw [3].

The Chinese kept the secret of papermaking for many centuries until, in the sixth century, their invention was taken to Japan by Buddhist monks. The Japanese first used paper only for records and official documentation, but with the rise of Buddhism, the demand for paper grew rapidly [2, 3, 11].

In the eighth century, the papermaking technique arrived in Korea, when the country was invaded by the Chinese. The pulp used to make paper was prepared by grinding fibers from hemp, rattan, blackberry, bamboo, rice straw, and even seaweed [3, 10, 11].

Fig. 2.1 Production of manual paper sheet in the ancient China [16]

Over time new raw materials were introduced, such as lime, to help with the defibration, ramie, silk, and textile fibers from rags and old clothes, an excellent raw material because due to the processing already received for fabrics, they could be easily prepared, with little mechanical treatment in pestles. Pressing the wet paper before sun drying as well as finishing techniques, such as coating the paper surfaces with a thin layer of a wheat starch dissolved in boiling water, were introduced [2, 6–11].

Taught by Chinese papermakers, Tibetans began to make their own paper in place of their traditional writing materials, a large palm leaf. Even though they adopted paper, Tibetan books traditionally still reflect the long, narrow format of the original palm-leaf books [3].

Through trade routes, the papermaking process was introduced to Central Asia, Persia, and India. In 751, during the Battle of Talas, when the Arab army attacked the city of Samarkand, an important outpost of Chinese trade caravans in Central Asia, prisoners were taken who knew the techniques of papermaking and exchanged secrecy for freedom. Samarkand quickly became known for the excellent quality paper it produced, mainly due to the flax and hemp used as raw materials and the quality of the water used in the manufacturing process [2–4, 10–12, 28].

In Baghdad, paper production began in 795, with the first factory already using hydraulic energy to crush the raw materials used [2–4, 12, 28]. In the Arab world, paper was used not only for books and documents, but also as wrapping material and napkins [3].

From then on, the diffusion of knowledge about paper production followed the Muslim expansion along the North African coast and from Alexandria, Tripoli, and Tunisia. Furthermore, in the eleventh century, trade routes involving Italian ports that maintained active trade relations with the Arab world and land routes from Spain to France were vehicles that disseminated papermaking techniques throughout Europe [2, 10, 12, 14, 28].

Outside of Arab, Japanese, and Chinese jurisdictions, paper began to be manufactured in Italy, in Fabriano, in 1276, where the identification of paper was also created using watermarks. In France, manufacturing began in the city of Troyes, in 1348, and in Germany, in 1390, in the city of Nuremberg. In England, the first record of papermaking occurred in 1494 [2, 3, 10].

Western Europeans were initially suspicious of the paper. The Christian world probably thought of this as a manifestation of Muslim culture and rejected it. In fact, in 1221, Holy Roman Emperor Frederick II declared all official documents written on paper invalid. This decree also helped protect the interests of powerful European landowners who monopolized the parchment markets. It was not until the introduction of printing in the fifteenth century that Western Europeans would fully embrace paper [3].

The raw material chosen by European manufacturers was, most of the time, cotton or linen fiber rags that were separated, cleaned, and heated in an alkaline solution, first in an open vat and later under steam pressure. The rags were then washed and macerated until they formed a pulp that was used in the manufacture of paper [3, 11].

Most paper mills at the time used mills powered by water wheels for this task. The flow of water would turn a wheel and its energy would be transferred to a hammer mill that would break apart the rags [3].

In Europe, the main medium for writing during most of the Middle Ages was parchment. Even though it is much more resistant than paper, as it is animal skin, it was gradually replaced by paper because it is also more expensive. But writing by hand was a slow and laborious process, both to produce the original of a work and to reproduce it.

The Chinese had already invented xylography, a technique in which graphic signs were carved in relief on wooden boards and applied to the paper as if they were a stamp. This process reached Europe and, in 1450, was perfected by the German Johann Gutenberg, who created movable types made of metal, which could be regrouped to print different texts, better adapting to the reduced European alphabet in relation to the thousands of Chinese characters.

The texts considered important were, until then, handcrafted by copyist monks through long and laborious processes, they were produced much faster, and the dissemination of information became much faster and accessible to all, which required increasing amounts of paper [2, 9, 11–14]. The papermakers faced two major problems: the supply of adequate fibrous material and the tedious artisanal papermaking process. Solving these problems took centuries, but when it did, it profoundly impacted the industry's technology development [7-10, 13].

In Europe, the use of white cloth rags, mainly those made of linen and hemp, gave rise to what became known as rag paper, and for several centuries these inputs were the fundamental raw materials for the paper production in the West. With the increase in the demand for paper, the great demand for this raw material created an international trade in rags. Great Britain, in addition to having its own stocks of rags, receives them from Japan, South America, and the Canaries. But its main suppliers were Germany, France, Russia, Italy, Egypt, Turkey, Belgium, and Holland [10].

The rags were separated, torn, and then crushed using a pestle system with hammers, moved initially manually activated and then by the water wheels, forming a paste that was placed in a vat with water, allowing the introduction of a screen capable of retaining a layer of fibers, and allowing the water to drain. After removing the frame from the vat, the water was pressed out and the remaining pulp was left to dry. The frame could not be reused until the previous sheet of paper was removed from it [10–12].

It was a completely handmade and time-consuming process in which a good worker could not make more than 750 sheets a day, which explains the high value of all literary pieces of the time and their little use. The process remained artisanal and time-consuming until the nineteenth century when, in December 1798, when the French mechanical engineer Louis-Nicolas Robert invented the first papermaking machine (Fig. 2.2) [2, 11, 12].

The machine could produce wet paper 12–15 m long by about 40 cm wide. It consisted of a movable screen that received a continuous flow of suspended fibers

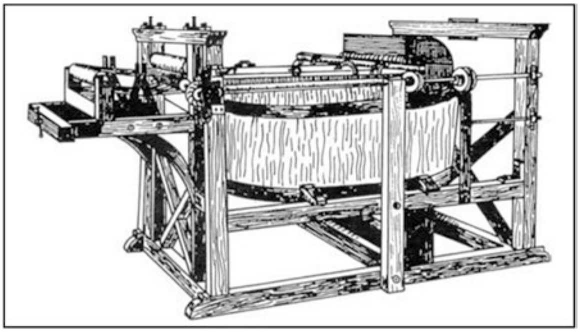

Fig. 2.2 Diagram of Didot's paper machine [5]

and delivered an entire sheet of damp paper to a pair of pressure rollers. When the continuous strip came out of the machine, it was manually hung over a series of cables or bars to dry. This sheet was cut into sheets [2, 12].

Two English industrialists, Henry de Fourdriner and his brother, perfected the invention by transforming it into a continuous production machine, known as the Fourdrinier Machine [2, 7, 8, 11–14]. The machine basically consisted of an endless screen moving on a horizontal table on which the suspended fibers were applied at one end through an inlet box. Drainage occurred when the forming fabric was moved to the other end, where the wet sheet was removed after pressing. Continuous paper drying came later.

This was probably the most important invention in the history of papermaking, having a great impact on the development of modern civilizations.

With the invention of the printing press, allowing linotype printing on paper and the industrialization of paper manufacturing, the dissemination of information became much faster and accessible to all. The books, newspapers, and magazines appeared, in an increasingly democratized process in which generalized culture, science, faith, terror, and printed advertising have since spread [2, 4, 14].

America's first paper mill was founded in 1690 by William Rittenhouse near Germantown, Pennsylvania. The first newspaper in the North American colonies was the Boston, published in 1705; the second was the Boston Gazette, first published in 1719. The third, also dated 1719, was Bradford's Mercury, published by Andrew Bradford, son of the printer William Bradford. To supply paper for the New York Gazette, William Bradford opened a paper mill in New Jersey around 1726 [11].

When paper production grew in volume, the availability of raw materials became a serious problem. At the time, rag overcoats were used, but the clothes available were not enough to meet demand, as there was strong competition with the textile industry in addition to export bans by some sovereigns. Rags became scarce and the search for alternative and abundant raw materials began [2, 4, 11].

In 1719, Reamur suggested using wood instead of rags. American papermakers began experimenting with alternative raw materials as early as the 1790s by testing local fiber sources such as bark, straw, and corn stalks. In search of something to replace the rags, Mathias Koops edited, in 1800, a book printed on straw paper [2, 11].

In Brazil, currently the world's largest producer of eucalyptus pulp, the first paper mill emerged with the arrival of the Portuguese royal family. Located in Andaraí Pequeno, in the city of Rio de Janeiro, it was founded in 1808 by Henrique Nunes Cardoso and Joaquim José da Silva, Portuguese industrialists transferred to Brazil [2]. In 1809, Friar José Maurício da Conceição Velloso was then allowed to open a paper mill embira, a shrub from which a very resistant fiber is extracted, as raw material [2, 10].

In 1837, André Gaillard opened a paper factory in Rio de Janeiro with machines imported from France, and, in 1841, another factory was opened in Engenho Velho by the sculptor Zeferino Ferraz. Both factories produced low-quality paper, which was used only for packages and packaging [2, 4].

In the mid-nineteenth century, the development of coffee culture brought great progress to the then Province of São Paulo and, with the arrival of European immigrants, it began to experience a great industrial development that generated several enterprises. One of them, idealized by the Baron of Piracicaba, in the city of Itú, intended to create conditions for the installation of industries taking advantage of the hydraulic energy possible in the region due to the existence of the waterfall on the Tietê river. In this place, in 1889, the company Melchert & Cia started the construction of the Salto Paper Factory, which operates until today, duly modernized, producing special papers, being one of the few factories in the world that manufactures money paper [4].

In 1844, Friedrich G. Keller made fiber pulp, using wood by the griding process, but still adding rags to the mixture. The pulp was obtained by rubbing pieces of wood against a rotary grinder in the presence of running water (Fig. 2.3).

Heinrich Voelter bought Keller's invention in 1847 and, in 1848, hired Johann Matthäus Voith to build the first wooden grinder, allowing, from 1850, the installation of the first machines to obtain wood fiber for paper production.

The fibers were separated and transformed into what came to be known as "mechanical pulp." In 1852, the Voith spindle grinder appeared and, soon after, in 1859, the Voith refiner was introduced to improve the quality of the paste obtained by shredding the tailings [2, 14].

In 1854, a process for producing cellulosic pulp was discovered in England through treatment with chemical products, giving rise to the first "chemical pulp." Seeking to separate the cellulose fibers from the lignin, several processes were discovered: such as the soda process, the sulfite process, and the sulfate process ("kraft process").

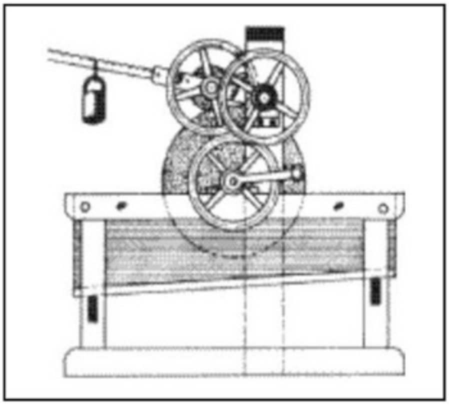

Fig. 2.3 Equipment to obtain pulp from wood developed by Keller [5]

From the second half of the nineteenth century onward, wood began to replace rags in papermaking in Europe, and is currently the main fibrous raw material used in the production of a large types of paper and paperboard [2, 8-10, 13, 16–21].

The use of wood as a raw material, although relatively recent, was one of the most important facts in its history, having an effect comparable only to the development of continuous production in paper machines [7–9, 23].

Although technology has significantly changed, the basic operations remain the same. Papermaking involves a five-step process in which the fibrous material is broken down and the suspended fibers are drained through a screen to form a fiber sheet. The sheet is pressed, dehydrated, and modified according to their final use [3].

Chapter 3
The Wood Pulping Processes

The purpose of the pulping process is to release the constituent fibers of the wood, which can be done either mechanically or chemically. These two processes have considerably different yields and fibers are produced with different inherent properties. In general, chemically produced fibers have a longer average length, are less damaged, are more flexible, and are more hydrophilic than mechanical pulps [24–27].

An efficient pulping process depends on the uniformity of the wood's characteristics and must extract the maximum benefits that wood can offer. In these two cases, both the production cost and the quality of the pulp obtained are related to the characteristics of the used wood [29–31].

However, wood is a naturally variable material, and, to maintain relative uniformity, several authors [18, 20, 31] have proposed the classification of woods be used according to their characteristics, looking to optimize both pulping and the quality of the resulting pulps. This procedure also opens up opportunities to develop pulps with different characteristics for specific uses. Thus, there must be a close connection between the forest and the pulping process. It is worth remembering that it is possible to produce bad pulp from good wood, but the reverse is not true [23].

3.1 Mechanical Pulping

Mechanical pulps are produced by the separation of wood fibers by abrasion (shearing), in the presence of water, from the application of mechanical energy in a friction device.

The processes are characterized by high yield (90–98%) and energy consumption (1000 kWh/t). Yield is high because only a few carbohydrates and extractives are dissolved during the process [34, 267].

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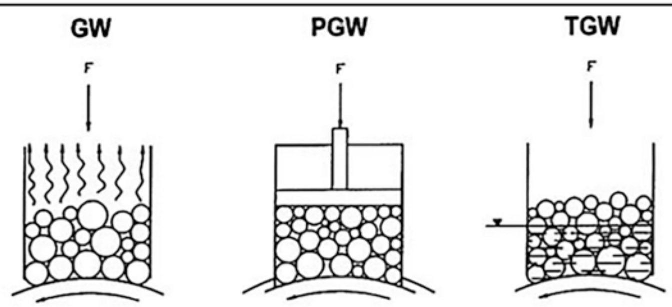
https://doi.org/10.1007/978-3-031-47285-5_3

There are two basic types of equipment used: the "grinders," which evolved from the initial equipment using millstones, and the refiners.

Friction damages the fibers producing a wide range of particle sizes. However, the extent of these damages can be partially controlled by altering the elasticity of the wood through heat pretreatments associated or not with chemicals [27, 34]. Figure 3.1 illustrates the various types of mechanical pulping processes available for using wood as a raw material. The process is called "refining" when friction occurs in refiners where high rectangular bars in the plates compress and cut the woody material, causing the fibers to separate [34].

The mechanical pulping processes per refiner currently in use are: thermomechanical pulping (TMP), chemo-thermomechanical pulping (CTMP), and high-temperature thermomechanical pulping, more commonly referred to as the medium density fiber (MDF) process [27].

For the TMP and CTMP processes, fiber separation is mainly achieved at low temperature (100–140 °C) by physical crushing and rupture of the S1/S2 layers interfaces of the cell wall (TMP process). Additionally, the temperature can be reduced if the chips are pretreated in a solution of sodium hydroxide followed by preheating with steam. The lignin becomes sulfonated, and the process is called chemo-thermo-mechanical (CTMP). These fibers contain microfibrillar structures from the secondary layers of the cell wall and some remaining middle lamella



GW *SGW*	*Groundwood* *Stone groundwood*	*Grinding under atmospheric pressure, shower water temperature normally 70 °C – 75 °C*
PGW	*Pressure groundwood*	*Grinding under pressurized conditions (2.5 bar), shower water temperature below 100 °C*
PGW-S	*Super pressure groundwood*	*Grinding under pressurized conditions (4.5 bar), shower water temperature above 100 °C*
TGW	*Thermo groundwood*	*Grinding under atmospheric pressure, shower water temperature 80 °C or more*

Fig. 3.1 Principles of the griding procedures [5]

fractions. This heterogeneity confirms that physical disruption occurs through several structural layers of the cell wall [27, 35, 267]. In contrast, the high-temperature MDF process (165–180 °C) causes fiber separation within the middle lamella and therefore results in hydrophobic fibers with a lignin coating in a smooth film [27].

In general, fibers from mechanical pulps are more rigid and less collapsible than fibers from chemical pulps, as they retain substantially higher levels of lignin. However, they present large fine content which are important as they provide optical properties to the pulp, and, if they are present in large proportions, they can contribute to the mechanical strength as the hemicelluloses and the specific surface of the pulp will be high [36, 267].

For papermakers, the advantages of mechanical fibers include their high yield, retaining more than 90% of the solid wood material and producing pulps with high specific volume and rigidity, being widely used in the inner layers of paperboard.

Disadvantages include a high need for electrical energy and limited strength properties due to the reduction in the average length, in addition to the presence of hydrophobic materials on the fiber surfaces, that interfere with the development of hydrogen bonds between fibers when the paper is dried [34].

3.2 Chemical Pulping

Kraft pulping or sulfate pulping is the nowadays a most used process. Other chemical processes are sulfite and organosolv.

Kraft pulp is obtained by treating the chips with a mixture of sodium hydroxide and sodium sulfide. In the sulfite pulp, various sulfur acid salts are used, whereas in the organosolv process, alcohol is the main reagent.

In wood, the lignin present in the middle layer between the fibers has the function of uniting them, maintaining the structure of the plant's tissues. In chemical pulping, the objective is to remove lignin, in particular from the middle lamella between the fibers, to enable the fibers' individualization [34, 37, 267].

In kraft pulping, wood chips are exposed to an aqueous solution of sodium hydroxide and sodium sulfide at a temperature of about 170 °C. The process is a low selectivity one and carbohydrates are degraded by acetylation ("peeling") at the beginning of cooking, by alkaline hydrolysis at temperatures above 150 °C [34, 38, 265, 267].

About half of the wood's constituent material is removed during the process. Therefore, a certain residual amount of lignin, estimated by the kappa number of the pulp, will remain in the fibers [267]. Part of the dissolved material may be reabsorbed by the fiber surface at the end of cooking and during acid stages of bleaching.

The bleaching of kraft pulp, which is done by means of multi-stage sequences using reagents such as chlorine dioxide, sodium hydroxide, oxygen, ozone, and hydrogen peroxide, generally with at least one alkaline extraction step and several washing operations, results in a purification of the fibers [34, 351].

Compared with high-yield pulp fibers, those obtained by chemical pulping show a more hydrophilic surface, are more flexible, and have a greater tendency to flocculate conforming better to each other when forming the paper. In this way, the paper produced will have lower specific volume, small opacity, and porosity, but with higher levels of strength and better formation [26, 27, 34].

Chemical pulps are often mechanically refined to delaminate the cell wall layers releasing the cellulose microfibrils to the fiber surface [27].

3.3 The Main Uses of Each Type of Pulp

The following tables present the most common commercial pulps and their main contributions in the paper production or the quality of the finished product (Table 3.1) and the main contributions of each type of pulp on both papermaking process and paper quality (Table 3.2) [41, 42, 57, 343].

Table 3.1 Most common uses for chemical, semi-chemical, and mechanical pulps

Paper or paperboard	Pulp	Effect on production processes or product quality
Wood-free print and write papers	Long fiber kraft	Reinforcement for machine runnability
	Short fiber kraft	Opacity and formation – normally the mainly component
	Short fiber sulfite	Reinforcement for machine runnability
		Filler
Wood containing print and write papers	Long fiber kraft	Reinforcement for machine runnability
	Bleached mechanical pulp	Opacity and printability
Newsprint papers	Long fiber kraft	Reinforcement for machine runnability
	Mechanical pulp	Bleached in the case of dark woods or to improve the quality of the paper – it is the main component
Tissue paper	Chemical pulps	Softness and water absorption
	CTMP[a]	Water absorption and specific volume
Paper packing	Long fiber kraft	Physical strengths – tensile and delamination
Cardboard boxes	Chemical pulps in general	Appearance, printability, surface strength, and internal strength
	CTMP[a], TMP[b]	Specific volume and rigidity

[a]Chemical-thermo-mechanical pulps
[b]Thermo-mechanical pulps

Table 3.2 Contribution of each type of pulp to the process or product quality

Long-fiber pulps	Short-fiber pulps	Mechanical pulps	Fillers	Additives
Strength	Formation	Opacity	Opacity	Retention
	Opacity	Specific volume		Hydrophobicity
Machine runnability	Surface smoothness	Internal structure and porosity for printing		Strength
				Brightness

Chapter 4
The Modern Paper

Paper can present many different properties' combinations characterizing its quality for the final use. The wide range of paper types available on the market and the wide variation in their uses confirm this; each type of paper has its typical characteristics set in order to meet consumer demand [41].

To ensure the desired specifications, the type of pulp and the additives that will be used must first be selected, in addition to the method of pulp slurry preparing, which varies according to the type of fiber selected [411, 555].

For all types of papers, the quality must be uniform which means that the paper's structure and surface chemistry are homogeneous on both small and large scales. Such homogeneity, nowadays, is the result of the modern paper machine designs, the use of more adequate pulps, and the improvement in the operating control processes [41].

It is evident that the use of fibers having characteristics closer to the desired ones is an important factor for competitiveness. Thus, fibers that require lower complexity process and with lower levels of energy application should have priority when selecting the pulp to be used commercially.

4.1 Desired Paper Properties

4.1.1 Low Production Cost and Machine Runnability

Regardless of the type of paper being produced, the papermaker has basic needs to be met, such as maintaining high productivity, with high operational efficiency, low production cost, and uniform quality in the finished product.

As operating efficiency, it is possible to relate few breakdowns, few operating problems, little generation of scrap, few stops, that is, few problems… including in the conversion equipment [47, 49, 57, 67, 115].

V. Manfredi, *Eucalyptus Kraft Pulp Refining*,
https://doi.org/10.1007/978-3-031-47285-5_4

When the papermaker demands a uniform pulp, he is not asking for a specific property but for a series of directly related properties with a direct impact on the machine behavior and on the quality of the finished product. It also considers the suitability of the fibrous material to the constraints, or operating limits with which he has to work and, even so, allows it to produce the desired paper [41, 50–62, 665].

The quality criteria for fibrous material must include properties and criteria that are practically and economically measurable. The most parameters used in this evaluation have been:

- Strength properties of paper and individual fibers
- Ease of refining and drainage
- Whiteness and whiteness stability
- Environmental compatibility
- Process yield and paper production efficiency
- Recyclability, that is, fiber strength and optical properties with multiple cycles of use, which is the most difficult parameter to determine

The quality specifications for the pulp will be defined in order to ensure the best possible performance for the paper machine facilities. Among the most common restrictions in paper mills are the refining capacity, drainage and retention on the flat table, production speed, steam availability, wet or dry paper strength, and the finished product uniformity. The machine runnability is the main parameter to be considered because it is directly related to the operating production costs.

A good pulp, according to the papermaker's point of view, is one that allows adequate levels of drainage and retention in the forming section of the paper machine, attributing strength to the sheet along all the machine, mainly at the exit of the forming and pressing sections, and that meets to paper quality specifications as per customer demands [49, 57].

A good performance (runnability) is the result of a satisfactory performance in all production stages and not only of a particular subprocess. This behavior (machine performance) is conditioned by a series of factors combining structural aspects and mechanical properties of the paper, as well as the stress applied to the paper, as it runs through the paper machine [56, 60, 63–67, 69, 70, 406].

Most problems related to "machine running" (runnability) are caused by variations in tension in the pressing room, combined with wet paper moisture and basic. Along the paper machine, or in the paper converting machines, sheet tensions are created by speed variation in the sheet transfer from the pressing to the drying sections, or between rolls [70–74, 406]. Controlling the paper formation and fiber orientation contributes to optimizing both machine behavior and some paper properties [411, 60, 67, 76–79].

As fibers are the most abundant pulp component, their characteristics, especially their bonding and collapsing capacity, will be decisive factors, interfering with production costs and paper quality [8, 23, 32, 39, 41, 57, 80–108, 343, 798].

4.1.2 Printing and Writing Papers

In general, the paper must present a set of properties that guarantee its printability and machine performance during the printing and finishing processes.

For a graphic, the characteristics that a printing paper must have are: dimensional stability, absence of dust or imperfections, good contact with the printer's surface (smoothness), equal finish on both paper sides, compatible absorption for the type of ink to be used, color fidelity with high print gloss, high opacity, porous structure with good formation and high bulk (specific volume), neutral color, and, of course, adequate strength to ensure the printer runs without breakages [41, 51, 53, 56–58, 91, 109].

Although the properties required to guarantee a good printing surface may vary depending on the printing process, one of them is common to all: the paper must have good surface resistance, which allows for a uniform ink application and without the release of particles, which, when adhering to ink transfer surfaces, cause print failures or defects [50, 55, 56, 104, 665].

The printing and writing paper manufacturers prefer pulps that are easy to refine, that is, that have high strengths with low refining energy consumption because this reduces production costs [49, 57]. Theoretically, pulp fibers with a high specific surface, greater bonding capacities, and higher number of fibers per gram, such as eucalyptus ones, are the most suitable for use in these papers.

For printing and writing (P&W) papers production, higher hemicellulose contents in the fibers are desirable due to their positive effect on the refining and tensile strength of the pulp [115].

4.1.3 Tissue Papers

Absorbent papers correspond to one of the market segments with the highest growth rate and for which eucalyptus pulp has shown high acceptance.

There are four groups of papers classified as "tissue." They are toilet paper, napkins, paper towels, and tissues for various purposes. The properties required for tissue line papers in general are described below [52, 57, 58, 110–116, 621].

- Specific volume – The specific volume (bulk) is closely associated with the porosity of the paper. This is an important property of tissue paper as absorbency and structural softness correlate well with porosity and paper thickness.
- Poorly consolidated paper structure – Tissue papers require loose fibers in the paper structure and, to a certain extent, large number of bonds between the fibers is undesirable. The fibers cannot collapse because this would result in a flattening of the fibers and the surface of the paper, leading to increased tensile strength but reducing all tactile properties (feel of softness) due to the paper structure compaction.

- Liquid absorption (fast absorption and water holding capacity) – An important aspect related to absorption is the paper porosity. The microscopic spaces between the fibers form a capillary geometry, through which water passes, saturating the fiber surfaces. This property is more pronounced in papers produced with short fiber pulps, such as the eucalyptus one, due to its high specific surface,
- High surface and structural smoothness – Sensation when touching the surface of the paper in the act of smoothing or crumpling the paper, leading to the perception of a smooth, fluff, and soft paper. This property is more pronounced in papers produced with short fiber pulps due to its high fibrous population and formation of smaller flocs.
- Designs caused by dry creping and embossing (these designs improve the feeling of softness and provide better absorption and beauty to the sheet of paper).
- Paper's ability to retain anatomical pulp elements (fines and vessels) to avoid excessive dust generation during paper manufacturing or converting operations.
- Exact paper strength (wet and dry) to avoid machine breakages during paper production or conversion, and to ensure that the paper does not fall apart when the customer is using it. Wet resistance is an important property with different levels of requirement depending on the type of product. Paper towels are the ones that require greater resistance as they need to maintain their integrity when absorbing liquids. Toilet paper is generally the least resistant because it must disintegrate quickly in the flushing system. Napkins and handkerchiefs require intermediate strengths.
- Fast drainage in the paper machine.
- Low content of fines to avoid both the generation of dust, especially when drying the paper, and the accumulation of fines in the white water from the paper machine, which will be reflected as drainage losses and higher steam consumption in the drying process.

Absorbent papers require high specific volumes and porosity, with emphasis on uniform pore size and distribution, in addition to certain specific properties such as: rapid adsorption of liquids, high flexibility, structural softness (feeling of being soft or fluffy), and surface softness (soft to the touch). Higher water absorption rate and easy disintegration in water are also required [52, 57, 58, 110, 111, 114–117].

During production, tissue papers must not significantly lose strength when embossed, laminated, etc. The most modern papermaking technolgies involve structuring the paper looking for generate bulk softness and absorbency increases. This approach allows to obtain the highest quality products, combining a high specific volume and high softness [111].

Good quality papers are obtained by the appropriate combination between fiber characteristics, equipment and control systems of the paper production, and conversion processes [57, 113, 115, 118, 119].

If the fibers collapse, increasing their bonding capacity, there will be damage on papers' softness and porosity. Tissue paper manufacturers prefer pulps with high softness, high specific volume, and good absorption properties. The desired characteristics of the fibers include stiffness, predominance of short fibers, and a low content of hemicelluloses and extractives, to avoid dirt and incrustations in the drying