SAIMAA UNIVERSITY OF APPLIED SCIENCES
Faculty of Technology, Imatra
Paper Technology

Zhang Huizhong

PROCESS MODELING IN PULPING PROCESS

Final Thesis 2010

ABSTRACT

Huizhong Zhang

Process Modeling in Pulping Process, 52 pages, 2 appendices
Saimaa University of Applied Sciences, Imatra
Unit of Technology, Degree Programme in Paper Technology
Bachelor's Thesis, 2010
Supervisor: Ms. Yang Guangyu, Lecturer, SUAS

The purpose of this bachelor's thesis is to know well the function and importance of process modeling in regards to an industry project, from the preliminary process design until shutting the plant down. A variety of software simulators in present are employed in process modeling, thus an additional purpose is get familiar with the application of one simulator. BALAS simulator is selected and offered by Saimaa University of Applied Sciences, Imatra. The results with the BALAS simulator are done on sources of variation in mechanical and chemimechanical pulping processes.

In the simulation part, PGW 70 and CTMP pulping process were employed. Various wood raw materials should effect the pulp production and consumptions of all kinds of raw material. The comparing analysis consists of the consumption of wood, chemicals, water, and energy by two processes, the proportions between the amount of water circulation and energy recovery and the amount of using water and energy. Though, the BALAS simulator is focuses on preliminary process design and operation. More accurate results cannot be obtained if process simulated with only one single simulator.

Keywords: Process Modeling, Process Design, Mass and Energy Balance, BALAS Simulator, Softwood and Hardwood, PGW 70, CTMP.

CONTENTS

1 INTRODUCTION

Process modeling is applied widely in various industries and it supports the different stages for a process life-cycle, e.g. plan, design and operation of a process. With the development of computer science, the various process simulators are developed and are used in chemical engineering, e.g. Aspen HYSYS, APROS and BALAS. In this work, BALAS simulator, especially developed for pulp and paper industry, was used to simulate the different mechanical pulping processes.

The thesis includes two main sections, i.e. literature review and simulation part. In the literature review, the function of process modeling in the process design and process operation is introduced. Also, the chemical products from woods and especially the different mechanical pulping processes are reviewed. In simulation part, the BALAS simulator, simulation parameters and simulation process are introduced. Then, the simulation results are discussed, such as raw materials consumption, water consumption, energy consumption and product yield etc.

BALAS simulator, developed for pulp and paper industry, can provide steady-state or dynamic simulation environment and it also includes the various unit operation models and different mathematical solvers. In this work, BALAS is used as the simulation tool for studying the steady-state mechanical pulping process, e.g. pressurized groundwood pulping process (PGW 70) and chemically pre-treated refining pulp process (CTMP). The raw materials investigated are softwood and hardwood species. Based on calculation of the mass balance and energy balance, the different performances of pulping processes are evaluated. By comparing the simulation results with the data or analysis from the real physical process, it is shown that process simulation can predict the behavior of the real mechanical pulping process. Therefore, process simulation can help us to design a process or to select the optimal operating condition in the efficient and cheap way.

2 PROCESS MODELING

Process modeling is one of the key activities in chemical process engineering. Its importance is reflected in various application areas that have been put together in below Figure 2.1. (Smith, W. & DuPont, E., 1999, pp. 62 – 73)

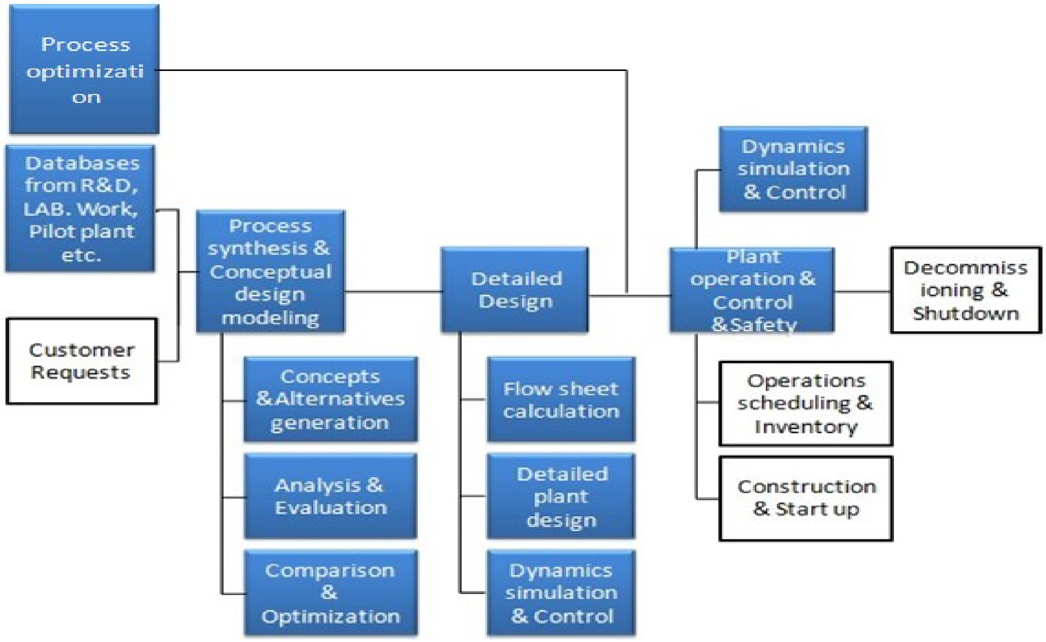


Figure 2.1, Life cycle of process. (Smith, W. & DuPont, E., 1999, pp. 65)

The block diagram presents the major steps in the process for designing such as a chemical plant, and blue blocks indicate places where process modelling is required and utilised in the process engineering. The plant could be led by three aspects of impetus: data from the experiments, customer request, or a needed capacity increase for an existing product. The first two factors are driven by a new product and its process.

An engineer is required to have a thorough knowledge of chemical and physical properties of pure components and mixtures, of reactions, and of mathematical models. At this stage it is important to generate, analyze and examine alternatives for working on process synthesis. A detailed process design requires more accurate calculation about such as kinetic and thermodynamic data. The process design also needs to develop more rigorous and detailed estimates of process performance and cost through dynamics simulation and control.

The dynamics simulation and control is also used for plant operation and optimization. The scheduling considerations are satisfied, the detailed equipment design and construction and plant optimization will be done. After the plant is built, engineers still have to run the plant and debottlenecking, the purpose of which is longer process running and safety operation until shutdown. (Jaako, J., 1998, pp. 5 - 13)

2.1 Process modeling in process design

The process design is the design of processes for desired physical and/or chemical transformation of materials. Process design can be the design of new processes (or facilities) or it can be the modification or expansion of existing processes (or facilities). The design starts at a conceptual level and ultimately ends in the form of manufacture and flow sheets. That is to say process design is comprised of the concept generation, alternative generation, analysis, evaluation, comparison and optimization.

About the concept generation, technical journals, encyclopedias, handbooks, textbooks, and patent literatures and so forth are obvious places to gathering information. Electronic searching and computer-based is provides information to aid process design. In addition, companies use consultants who know the real value of the literature. Gathering information allows us to begin a general search and to ask more specific questions.

Alternative generation implies that flow sheets were displayed. The goal is to provide a relevant but concise depiction of the alternatives that allows an easier recognition and evaluation of available alternatives. Representation of alternative decisions for the process is intimately tied to the way we intend to generate and search among these alternatives. (Biegler, L. & Grossmann, I. & Westerberg, A., 1997, pp. 25 -39)

Performance analysis and evaluation determine how economic, environmental friendly, safe, flexible, controllable, and so on a process is. Economic evaluation, establishes the cost of equipment and the costs associated with purchasing utilities. Environmental concerns involve satisfying the very large number of regulations the government imposes on the operation of a process. Safety analysis determines whether any reasonable combination of events leads to unsafe situations. Flexibility requires the manufacture of specified products in spite of variations in the feeds it handles. Controllability deals with the ability to operate the process satisfactorily while undergoing dynamic changes from one operating condition to another, or while recovering from disturbances.

Basically, for evaluating flow sheets, inputs of the process could include raw materials, water, steam, energy. Process steps should be sequentially drawn. Intermediates and any other by-product should also be represented. The process parameters of streams and units should be represented. Products, waste or by-products are indicted as their phase. For each process step as well as for an entire plant, energy and mass balance diagram should be observed.

Economic analysis of a candidate flow sheet requires knowledge of capital and operating costs. The knowledge is based on equipment sizes and capacities and their associated costs. Once we have obtained the process flows and heat duties through a mass and energy balance, we are ready to begin investment and operating costs.

Physical sizing of equipment units includes the calculation of all physical attribute that allow a unique costing of this unit. These sizing calculations will determine the capacities needed for the cost correlations developed in the future.

A common point says that process design needs more wide work than process modelling; simultaneously process modelling has wider application areas than process design. In process design, the behaviour of process modelling typically refers to representation of alternative generation by flow sheet and model; the steady-state or dynamic behaviour of the model can be predicted for solving the model; through verification and validation to inspect whether model has been correctly implemented and solutions are sufficiently accurate. (Biegler, L. & Grossmann, I. & Westerberg, A., 1997, pp. 25 -39)

2.2 Process modeling in plant operation

Once in operation, process modeling guide engineers to identify the root cause of inefficiencies and fine-tune the process. Even plants with the same process for producing the same product often have different capacities and layouts, and require separate optimizations to maximize production and minimize operational costs. When plant conditions change and no longer match those used in the original design simulations, the problems can become more complex, thus the process modeling is necessary. Modeling plant processes must be done before running control system simulations. Modeling approaches such as data-based and first-principles each have advantages and drawbacks, so engineers should understand model types and have insight into the level of model fidelity needed to solve their problem. However, it can be difficult to develop an accurate model that provides enough confidence to reconfigure a control system.

For greater process precision and speed, simulation is a cost-effective way to validate control systems, find and eliminate problems before implementation, and optimize plants already in operation. Desktop simulation software, already fully capable of performing such validation and optimization, continues to improve yearly as new features are added, helping engineers meet a rapidly expanding set of plant control challenges. (Lenon, T., 2010.)

2.3 Process simulation model

The simulative form of steady state is suited for process design and optimization. Through generation of mass and energy balances is achieved steady-state simulation, which is an idealization of the behaviour of most continuous processes. Relatively, dynamic simulation is practical for tuning process control, start-up and shut-down scenarios. (Kalliola, A. & Kangas, P., 2009.)

The identification and drawing up a process is a prerequisite for mass and energy balance, which assesses the input, conversion efficiency, output and losses. A mass and energy balance, used in conjunction with diagnosis, is a powerful tool for establishing the basis for improvements and potential savings. Mass balance is fundamental to the control of processing, particularly in the control of yields of the products. Energy balance is used in the examination of the various stages of a process, over the whole process and even extending over the total production system from the raw material to the finished product. Enthalpy balances is calculated only as energy balance are useful in many processing situations. It is the sum over all of these that are conserved. (Material and energy balance. 2005.)

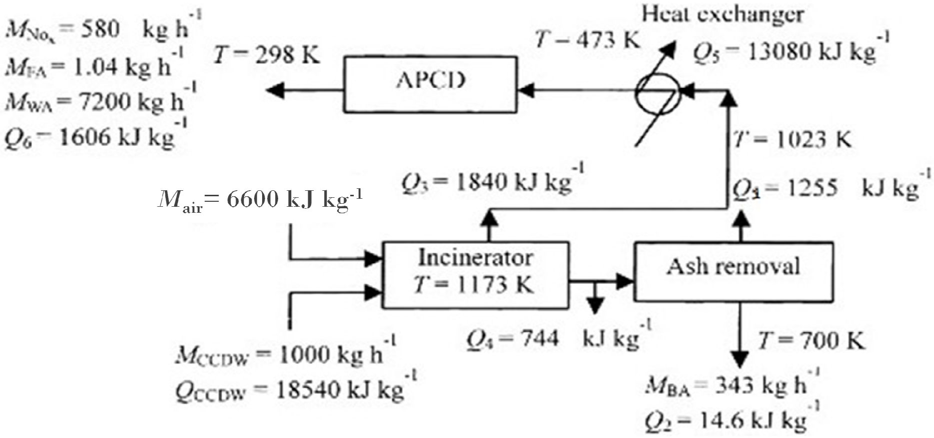


Figure 2.2, Mass and energy balance of the conceptual combustible fractions of construction and demolition waste (CCDW) incineration system (Chang, N. & Lin, K., 2000, pp. 1392 – 1401.)

The simplified combustible fractions of construction and demolition waste (CCDW) incineration system are introduced in Fig.2.2. There are four operating units: incinerator, ash removal, heat exchanger and APCD. The 1000 kg/h CCDW and 6000 kg/h air are fed into the incinerator, which is used to burn the CCDW to ash with high temperature 1173 K. After incinerator, part of ash (BA) is directly discharged from the ash removal. The rest of stream is accepted to the heat exchanger, where the temperature of stream decreases to 473 K. Finally, waste ash (WA) stream is output after APCD unit. The final output stream includes a certain amount of fly ash (FA) and vast amount of oxides of nitrogen (NO_X).

Normally, mass and energy balance of unit operations can be calculated following the basic form:

Content of inputs = content of products + waste/losses + changes in stored materials.

For example, the mass balance of incineration unit can be described with equation 1(abbreviation as Eq. 1) and Eq.2

$$M_{air} + M_{CCDW} = M_{BA} + M_{WA} \quad (1)$$

$$6600 \text{ kg/h} + 1000 \text{ kg/h} \approx 343 \text{ kg/h} + 7200 \text{ kg/h} \quad (2)$$

The energy balance of whole flow sheet can be described with Eq.3 –Eq. 8,

$$Q_{CCDW} = Q_{LOSS} + Q_{WASTE} + Q_{RECOVERY} + Q_{OUT} \quad (3)$$

$$Q_{LOSS} = Q_1 + Q_3 + Q_4 = 1255 \text{ kJ/kg} + 1840 \text{ kJ/kg} + 744 \text{ kJ/kg} = 3839 \text{ kJ/kg} \quad (4)$$

$$Q_{WASTE} = Q_2 = 14.6 \text{ kJ/kg} \quad (5)$$

$$Q_{RECOVERY} = Q_5 = 13080 \text{ kJ/kg} \quad (6)$$

$$Q_{OUT} = Q_6 = 1606 \text{ kJ/kg} \quad (7)$$

$$18540 \text{ kJ/kg} = 3839 \text{ kJ/kg} + 14.6 \text{ kJ/kg} + 13080 \text{ kJ/kg} + 1606 \text{ kJ/kg} \quad (8)$$

The Fig. 2.2 is obtained based on the build-up mass balance and energy balance for unit operations as described in the above text.

2.4 Process simulators

Flow sheet is a descriptive representation of the designing process. Process simulator describes processes in flow sheet where unit operations are positioned and connected by streams. By setting the simulation target, mass balance and energy balance are solved by simulator and finally the simulator provides the suitable solution to reach the target. Process simulators cover the various scopes and modes of operation as shown in figure 2.3, where some examples of simulators are enumerated in plant life-cycle.

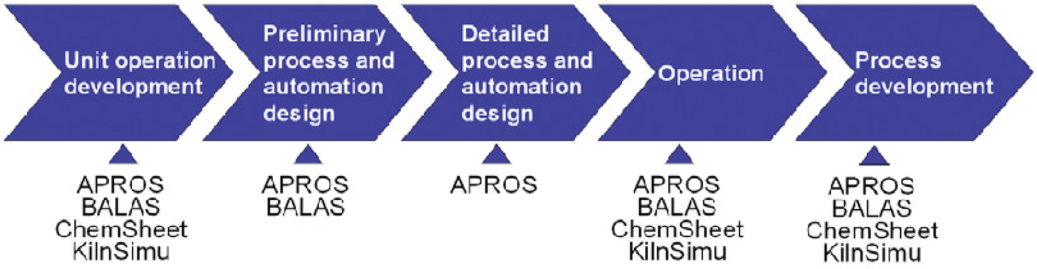


Figure 2.3, The use of simulators through the plant life-cycle (Kalliola, A. & Kangas, P., 2009.)

Steady-state simulation and dynamic simulation are two main simulation modes utilized in simulators. Steady-state simulation is good at finding the stable operating conditions in some processes which are not function of time, and it is suitable for process design and process optimization. Dynamic simulation is practical for tuning process control, start-up and shut-down scenarios. Furthermore, the different simulators have their specific applying fields, such as, for automation design, simulator APROS is a powerful tool, ChemSheet is a response for process chemistry and KilnSimu especially focuses on the rotary kiln simulation. The different simulators might have different physical models, mathematical solver and database of materials to support simulation.

The APROS simulator integrates process design and automation design by offering a common platform for engineers to demonstrate, discuss and further elaborate potential solutions. The real-time dynamic simulator is an ideal tool for examining and designing the cooperation of the process and its automation.

Aspen HYSYS is an efficient workflow for process design, equipment sizing, optimization, performance monitoring and preliminary cost estimation within one environment. Aspen HYSYS offers a comprehensive thermodynamics foundation for accurate calculation and also a comprehensive library of unit operation models. (Aspen HYSYS. Aspen Technology, Inc.)

ProSimPlus is used in the design and operation of the existing plants, for example for process optimization, unit troubleshooting or debottlenecking or performing front-end engineering analysis. It provides the thermodynamic module and the unit operations library, with which various processes can be modeled. (ProSim, Inc.)

SuperPro Designer facilitates modeling, evaluation and optimization of the integrated processes. The combination of manufacturing and environmental operation models enables the user to concurrently design and evaluate manufacturing processes and to practice waste minimization via pollution prevention as well as pollution control. (SuperPro Designer. Intelligen, Inc.)

For papermaking processes, APROS is an advanced tool for dynamic simulation. APROS is an efficient tool for the detailed simulation model configuration and high accuracy solution methods for pulp and paper quality modeling and for tracking the fiber processing history data. These features substantially increase the utilization potential of dynamic simulation in pulp and paper manufacturing processes. (Savolainen, J. 2008.)

BALAS simulator can treat the steady state simulation and also dynamic simulation for pulp and paper industry. The objective of BALAS is to create a comprehensive pulp and paper simulation environment. The typical applications for BALAS simulator are calculation of mass and energy balances, analysis of heat integration and heat recovery, “What if” analysis, process optimization and development of unit operation modules.

3 WOOD-BASED CHEMICAL PRODUCTS

3.1 Wood chemistry and chemical products from wood

Wood can be mainly divided into softwood and hardwood. The wood from conifers, such as pine and spruce, is called softwood; the wood from usually broad-leaved tree, such as birch and oak, is called hardwood. Cellulose is the main constituent of wood carbohydrates. This is leading to fiber structure, thus giving wood fibers mechanical support. Hemicelluloses comprise 20-30% of the dry mass of wood. Lignin is a natural multibranched polymer, whose purpose is to bind fibers tightly to one another inside the wood, thus providing strength. In wood, extractives are great variations between extractive composition and amount regarding the wood types, wood parts and growth place and wood age.

Table 3.1, chemical composition of wood as raw material (Knowpap 10.0. Raw Material.)

	Cellulose, %	Hemicelluloses, %	Lignin, %	Extractives,%
Spruce	42	28	28	2
Pine	42	26	27	5
Birch	40	37	20	3
Eucalyptus	50	20	27	3
Acacia	50	24	23	3

Table 3.1 shows some softwood, e.g. spruce and pine, and hardwood, e.g. birch and eucalyptus. The various softwood species do not greatly differ from one another in terms of chemical composition as shown in table 3.1. However, there are bigger differences in chemical composition between various hardwood species. The structure and composition of hemicelluloses in softwood and hardwood are different. In hardwood, eucalyptus has a very high cellulose content and low hemicellulose content, while in birch the exact opposite is true. The molecular mass of hardwood lignin is apparently lower than softwood lignin.

Wood as raw materials has very wide application area, such as building, paper and chemicals. Wood is still the most commonly used source of fuel to provide warmth, heat for cooking. The electricity is also generated by using steam drive generators based on the wood. Composite of cellulose fibers embedded in a matrix of lignin in wood is the mainly raw material in pulp and paper industry. Softwoods used for paper production are pine and spruce in Finland. One of the most important hardwoods used in paper production is the Nordic birch. It is one of the longest and densest fibered hardwoods, which makes it extremely well-suited to the production of paper pulp. Another important hardwood species is the eucalyptus.

Other wood-based chemicals derived from such as bark products, cellulose esters, cellulose ethers, charcoal, dimethyl sulfoxide, methanol, etanol, fatty acids, furfural, hemicelluloses extracts, kraft lignin, lignin sulfonates, pine oil, rayons, rosin, sugars, tall oil, turpentine, vanillin, flowers, pollen and numerous other products. Therefore, chemical derivatives of wood are used as the raw materials for a large number of other chemical and reprocessing industries. End use is as diverse as liquid fuels, explosives, pharmaceuticals, food products and paints.

Wood barks have high lignin content and when it is pyrolyzed, it yields a liquid bio-oil product rich in natural phenol derivatives. The phenol derivatives are isolated and recovered for applications such as in production of oriented strand board and plywood.

Dimethyl sulfoxide is a by-product of kraft pulping, which produces dimethyl sulfide as a side product. It is an important polar aprotic solvent for chemical reactions. It is also extensively used as an extractant in biochemistry and cell biology. Cellulose esters are made by reacting high purity cellulose with selected acid and anhydrides in a multistage process. In esterification and hydrolysis, the cellulose, acids and anhydrides are reacted under controlled catalyst concentrations and temperatures. In addition, cellulose ester, plasticizer and additives are compounded in the manufacturing step to produce the cellulose plastic.

Constituents of wood are broken down to simple gases by heating wood to high temperatures in the absence of oxygen. Methanol is recovered by the process known as gasification. The resulting carbon monoxide and hydrogen are treated under pressure in the presence of certain copper-based catalysts, producing significant volumes of methanol. Ethanol is recovered from the polysaccharides in wood by acid hydrolysis. Methanol and ethanol can be used as liquid fuels derived from wood. (Wood Chemicals, Forestry Insights.)

Many wood materials contain the polysaccharide hemicelluloses, which have undergone hydrolysis by heat and acid to become furfural. Furfural is used as solvent in petrochemical refining to extract dienes, and make solid resins. Tall oil, also called liquid resin, is obtained and circulated as a co-product of the Kraft pulp process. The black liquor produced during sulphite and kraft pulping contains significant quantities of resin acids, tall oil, complex sugars and other organic compounds. Some of their products are the by-products for nitration pulp and are used in explosives, lacquers, printing inks and rocket propellants. By-products from acetate pulp are used for textile fibres, cigarette filters, impact resistant plastics, photographic film and rigid packaging. By-products from viscose pulp can be used for production of high strength cord, textile fibres cellophane and sausage coatings. And for ether and microcrystalline pulps, a chemical intermediate for further processing into pharmaceuticals, food products, cosmetics, textile sizing, paints and cements. (Spaeth, J., 2004.)

3.2 Various pulping processes in paper industry

One of the most mainly consumers of wood is paper and pulp industry. Wood can be used to produce paper pulp in two different ways, i.e. chemical pulping and mechanical pulping. According to the different wood type, the different suitable methods can be used. For example, birch and pine are used primarily in chemical pulping, while spruce is normally used in the production of mechanical pulps. If the recycled paper is used, recycled pulp is also called deinked pulp

(DIP). Recycled paper is processed by chemicals, thus it is important to remove printing inks and other unwanted elements in order to free the paper fibers. Many newsprint and tissue grades commonly contain 100% deinked pulp and it can be found in many other office and home use grades. (Pulp and Paper. Forestry Insights.), (knowpap10.0 paper technology, general.)

Chemical pulping

Chemicals and heat are used to dissolve lignin, which results in the breaking of fiber bonds. In sulphate (Kraft) pulp, chips are processed into pulp and cooked in a mix of sodium hydroxide and sodium sulphide in recovery. Chemical losses in the process are made up by adding sodium sulphate which is reduced to sulphide in the recovery process. Kraft pulp is used where strength, wear and tear resistance and color are less important. Kraft pulp mills are totally self-sufficient in energy, with combustion of residues and waste products meeting all heat and electrical energy needs.

Sulphite pulp is often derived from less resinous softwood chips, cooked in magnesium, calcium or ammonium bisulphite with excess sulphur dioxide present. The process yields pulps with relatively high cellulose content and good bleaching properties. The pulp produced is made up of longer, stronger and more pliable fibers and is favored where strength properties are particularly important.

Soda pulp is produced by cooking chips of deciduous woods in a solution of sodium hydroxide under pressure. Soda pulp produces relatively soft, bulky papers. Caustic soda dissolves most of the lignin in wood while having little effect on the cellulose.

Mechanical pulping

Mechanical pulping, in which the lignin bonding the fibers together is softened with water, heat and repeated mechanical stress. Mechanical pulping methods are not used to dissolve anything from the wood, but a certain percentage of water soluble extractives and other components are dissolved during pulping. However, the yield is still very high. Mechanical pulps are used for products that require less strength, such as newsprint and paperboards.

Both of hardwoods and softwoods can be used in mechanical pulping. Figure 3.1 illustrates that the various grades of end products achieved from softwoods and hardwoods using the different pulping methods.

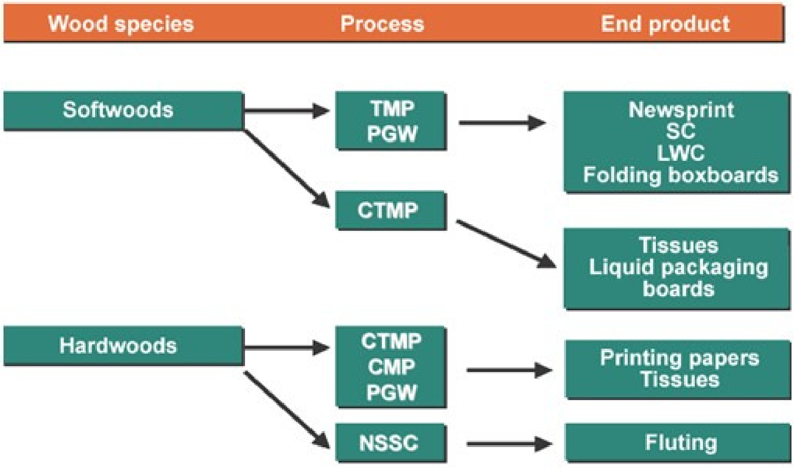


Figure 3.1, Wood species, mechanical pulp processes and end products (Knowpap10.0 paper technology, general.)

Groundwood process (GW) is produced by grinding cut-to-length and debarked softwood logs against a roughened stone. At grinding, the fibers are softened and broken by heat. The rotating stone transfers, through grit particles on the stone, energy to the wood, and the wood fibers are separated. If the wood is steamed prior to grinding it is known as pressurized groundwood, (PGW). Pressurized groundwood involves grinding at higher pressures, creating increased temperatures and improving pulp quality while reducing energy consumption.

Refiner is a form of mechanical pulping that involves the hot pressurized and high speed grinding and refining of chips, and further refining of the fiber bundles created during the first pass. If the chips are just ground up with the plates, the pulp is called refiner mechanical pulp (RMP) and if the chips are steamed while being refined the pulp is called thermomechanical pulp (TMP). Steam treatment significantly reduces the total energy needed to make the pulp and decreases the damage to fibers. Chemi-mechanical pulps (CMP) are essentially mechanical pulps that have been pre-treated with a sulphite liquor to improve breakdown and reduce energy requirements during processing. In the chemi-mechanical pulp process (CMP) chip pulping in the pulp refiner occurs under normal pressure, while, in the chemithermo-mechanical pulp process (CTMP), the pulp refiner is pressurized. (Pulp and Paper. Forestry Insights.), (knowpap10.0 paper technology, general.)

4 PULPING PROCESSES' SIMULATION WITH BALAS

4.1 Basics of BALAS simulator

BALAS is a process simulator with emphasis on pulp and paper developed in the VTT, Technical Research Centre of Finland, over the last 20 years. During the last three years BALAS has been extensively developed in close co-operation with Finnish forest industries and National Technology Agency of Finland. (Balas Manual. 2007. Version 3.2.)

The objective of BALAS is to create a comprehensive pulp and paper simulation environment. BALAS simulator's typical applications are calculation of mass and energy balances, analysis of heat integration and heat recovery, "What if" analysis, process optimization and development of unit operation modules.

BALAS simulator consists of two separate programs*:* program called FloSheet (see Figure 4.1) is used to design the process layout, while the user interface of BALAS is constituted between the user and the simulator. Moreover, BALAS 3.2 installation package contains beta version of BALAS add-in for Microsoft Visio that allows user to draw flowsheets using Visio.

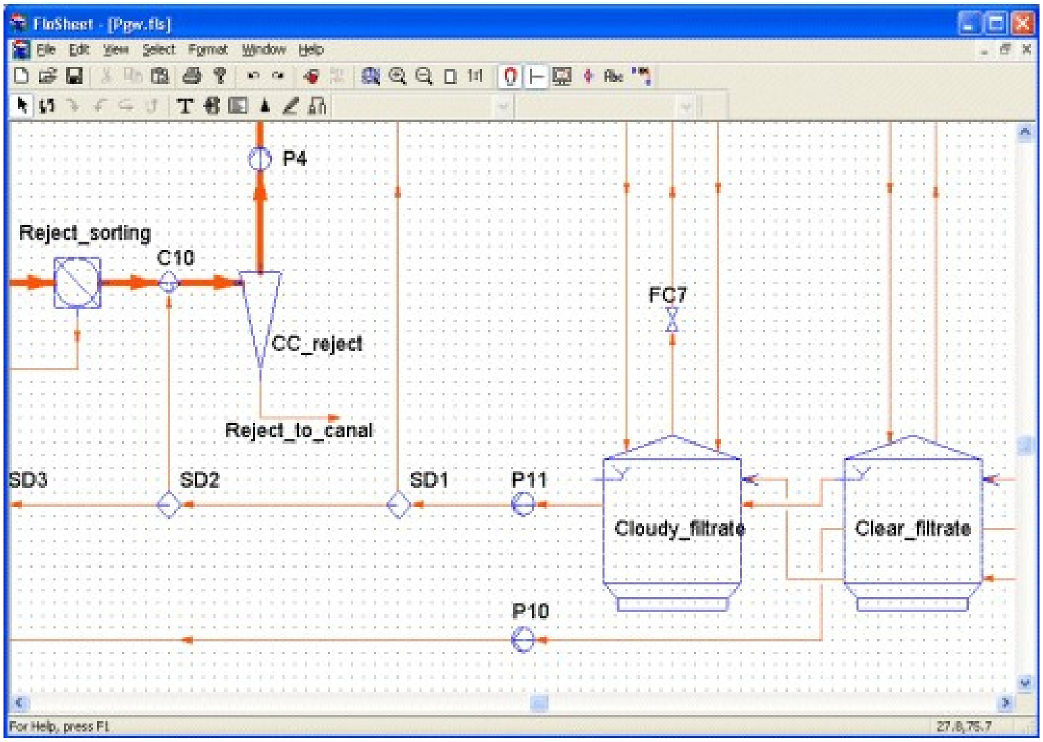


Figure 4.1, Illustration of simulation model drawn up by Flosheet (Balas Manual. 2007. Version 3.2.)

The user interface is the "control panel" of the simulator, which is means that simulation models are created and maintained through the user interface. It allows user to inspect and modify stream and unit data, define different simulator constructs such as simulation cases and output sets and to control simulation run parameters and progress.

The flowsheet is built up with program Flosheet by dragging and dropping unit processes from model library palettes, drawing streams connecting units, and entering input data using Initialization dialog windows. Process flow sheet is consists of streams carry matter, energy and information and units in the process.

BALAS Database of user interface contains all the data related to the simulation model: units and streams with their names and parameters, design functions, calculation cases, solver settings etc. BALAS allows user to inspect and modify stream and unit data, define different simulator constructs and output sets and to control simulation run parameters and progress. Each time the flowsheet must get "approval" from the user interface BALAS for the connections you have created to the flowsheet.

BALAS is connected to Microsoft Excel. The Excel enables the conversion of the simulation results into a more illustrative form. The simulator balance data can be sensitively analyzed using Microsoft Excel. The Excel-link also can be used for pre- and post-processing of results.

BALAS has an extensive selection of basic unit operations, and calculation modules. These unit operation modules enable the user to model the whole paper mill including mechanical pulping, heat recovery, utilities and wastewater treatment. Debarking plant, TMP, PGWS, PGW-70, DIP, uncoated paper machine, effluent treatment plant, water preparation plant, CHP power plant, and multi-effect evaporator are included and supplied with software as selections of ready-made model processes.

The simulator includes the process unit calculation modules, physical property estimation methods and various mathematical methods. Its task is to perform the actual calculation of the process.

BALAS has five different calculation modes (case type):

- Simulation steady-state mode calculates the behaviour of the process with fixed unit parameters.
- Design mode is used when one needs to define unit model parameters based on known output on measurement. A number of unit parameters corresponding to the number of the design constraints must be set free.
- The optimization mode has a solver for single objective nonlinear optimization problems with equality or inequality constraints and it can be used to minimize the objective function formulated by the user.
- When process model is fitted to measured process data, thus validation mode is applied for parameter estimation.
- The parameter estimation mode can be used to obtain the best fit between the measured data and the simulated values of the process streams from various parts of the process.

BALAS provides two solver routines, secant algorithm and Quasi-Newton. They are the calculation background corresponding to the above five case types. They can be selected as the user wants from the case definition dialogue box.

Furthermore, a hierarchical model refers to a model defined on various levels. Model hierarchy enables the user to build separate models at sub-process level and in the end link the sub-process models into a large process model. A hierarchical model consists of main level model and sub-process model. The main level incorporates the connections between the sub-process models, whilst their terminals in the input and output streams are connected to the main level.

Model hierarchy makes it easier to organize and maintain large process models. (Baasel, W., Preliminary Chemical Engineering Plant Design.) (Balas Manual. 2007. Version 3.2.)

4.2 Simulation of PGW 70 and CTMP process

In this simulation work, the mechanical pulping process, i.e. pressurized groundwood process at around 70°C (PGW 70) and chemical pre-treatment mechanical process (CTMP) are simulated based on the ready-made flowsheet outline in BALAS. The detailed simulation parameters and simulation process was done for the different raw wood materials and the different pulping processes, as shown in table 4.1.

Table 4.1 Simulation case studies for pulping process

Raw material	Pulping Process
Softwood	PGW70
Softwood	CTMP
Hardwood	PGW70
Hardwood	CTMP

Before starting the simulation, the feed streams were named, stream classes were created, and feed or iteration streams were initialised and the default values were checked for the input parameters of the process units. After that, running the simulation, the simulation messages appear in the message box in the BALAS main window. The number of the current iteration is shown followed by the residual value indicating converge of the process and in the successful simulation the residual value should steadily move towards zero. The detailed simulation process is described in the following section.

4.2.1 Simulation parameters for PGW 70 process

The PGW 70 pulping is described in Fig. 4.2. The black thick lines represent the pulp flow and the dotted lines refer to water circulation. Process PGW 70 includes grinding and hot circulation, screening, reject handling, centricleaning, thickening, bleaching, washing, storage towers and circulation water system. The typical pulp yield of the PGW 70 process is 92 -95% of wood used.

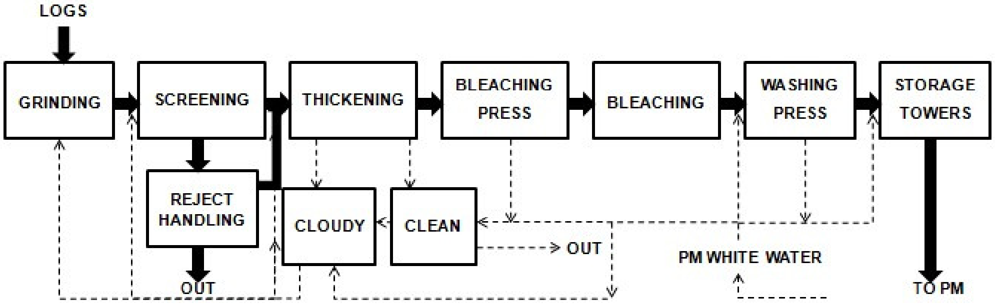


Figure 4.2, Block flow diagram of PGW 70 process including bleaching and water circulations from my own simulation.

Follow the above figure to learn PGW 70, the black thick lines represent the pulp flow, and the dotted lines refer to water circulation in PGW 70.

<u>Grinding</u>

At pressurized grinding, the wood is fed and the dissolved cellulose, lignin, metal irons and inorganic and organic components are disintegrated by grinder with pressure (max. 3 bars) to against a rotating pulpstone in presence of white water at 70 ℃ circulated from paper machine. The lignin may under favorable conditions come loose relatively intact. The energy is converted to heat up the cooling water from paper machine, and the internal temperature of the wood rises. Pressurized grinder produces pulp at around 2% consistency. The spray water temperature is implemented with what is called a hot loop or hot circulation. Since the process is closed, the temperature rising is undesired, therefore the spray water must be circulated and cooled in hot loop.

Screening

The function of screening and reject handling is to homogenize the groundwood and to reduce or remove contained impurities. Pulps contain undesired components, coarse rejects and the shives that consist of many fiber bundles. They have to be reworked. The shives content of unscreened pulp may be as high as 5% depending on the process. The screening process is carried out at high dilutions, below 1% dry content.

Reject handling

The rejects from screening are thickened and retreated with reject refiners and are then recycled to the main stream. Accepted pulp can be recirculated back to the main fiber line. Final rejects are discharged from the process as solid wastes. For the reject handling, the dry solids content of the wastes handled vary between 5 – 30% (CEPI 1997b). The rejected handling rate may be as high as 30% of the inflow.

Thickening

The screened and cleaned pulp is thickened by use of disc filter or thickening drums and then stored in tanks and storage towers. The purpose of thickening is to increase the storage capacity of pulp chests and tanks, to drain off water to recycle, and enhance the effect of chemicals on the fibers. A usual storage consistency is approximately 5 %.

Bleaching

Oxidative bleaching with peroxide (H_2O_2) is carried out in the pH range of 10-10.5. The pH has to be adjusted with sodium hydroxide (NaOH). The maximum economical amount of peroxide is 3 - 4% of the amount of pulp. When applying the maximum economical amount of peroxide an increase in brightness of up to 20 units can be achieved (Finnish BAT Report 1997). Sodium silicate (Na_2SiO_3) is added, 1.5-4 % of the amount of pulp, to buffer the pH and stabilize the peroxide. Chelating agents, DTPA is added before bleaching to form complexes with heavy metals (Fe, Mn, Cu, Cr), which prevents the pulp from discoloring and the peroxide from decomposing. The dosage of chelating agents is about 5 kg per ton of pulp. The bleached pulp is finally acidified with sulphuric acid or sulphur dioxide to a pH of 5-6. Peroxide bleaching is conducted at a consistency level of 25-35%. The yield drop in peroxide bleaching is approximately 2%, mainly due to the alkalinity during the bleaching that results in an increasing dissolving of organic substances out of the wood. Chemical consumption in PGW 70 process refers to bleaching chemicals.

Wood consumption: Logs are cut to 1 to 1.6 m and usually 10-20 cm in diameter, debarked in a debarking drum. The debarked logs are conveyed to the grinders. The use of wood is normally between 2.4m^3/Adt and 2.6m^3/Adt for PGW 70.

Water use: Fresh water is only be used for sealing and cooling of equipment. Surplus clarified waters from the paper machine are usually used to compensate for the water leaving the circuit with the pulp and the rejects and the amount of clarified water is around 5-10 m3/tonne of pulp. The largest portion of water used is white water recovery from paper machine. For PGW 70 process, the total water use is about 5 -15 m^3/Adt for per tonne of pulp.

Energy use: The PGW process consumes electric power energy, ranges from about 1100–2200 kWh/t of pulp, one part of electric power energy is used for the mechanical work of the grinder and refiner. Meanwhile, some part of mechanical work is converted to thermal energy to heat up the water or steam by friction inside the grinder and refiner. In addition, a certain amount of the electric power energy is used for screening, thickening and refining the screen rejects (TEKES 1997). (Integrated Pollution Prevention and Control (IPPC))

4.2.2 Simulation parameters for CTMP process

Differences of PGW 70 and CTMP can mainly be found in the disintegrating fiber methods, by grinder or refiner, at the beginning of the process. The CTMP process consists of a fibre line and auxiliary systems. The latter include reject handling, storage of some chemicals and auxiliary power generation. Comparing with the PGW 70 process, the chips are given a mild chemical pre-treatment ahead of the refiners during the CTMP process. The main unit processes of manufacturing of CTMP can be seen in Figure 4.3. The typical bleached pulp yield of bleached CTMP is 80 -92%.

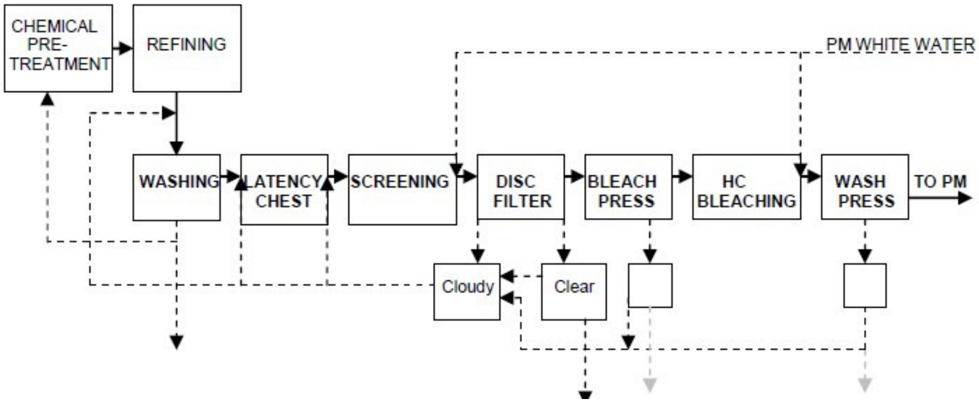


Figure 4.3, Block flow diagram of CTMP process including bleaching and water circulations from my own simulation.

The difference between PGW 70 and CTMP exists in some unit operations. For example, CTMP includes the chemical pre-treatment and refining and they have important role in this pulping process, however, for PGW 70 grinding is the key unit operation. In following text, chemical pre-treatment and refining are introduced in detailed.

Chemical pre-treatment

Chemical pre-treatment is carried out after debarking. During the chemical pre-treatment, which includes chipping, chip washing and screening, the wood chips are impregnated in an impregnation tower where the chips are immersed in an alkaline chemical solution. Pre-treating the chips with heat and sodium sulfite (Na_2SO_3) together with sodium hydroxide (NaOH) softens the wood matrix, where, during the mechanical stage, fibers are released in a more intact state than without pre-treating. Sodium sulphite (Na_2SO_3) is mostly used for softwoods, and lately alkaline peroxide has been predominantly used for hardwoods. The mild chemical pre-treatment of the chips enhances the softening of the wood by a sulfonation process and improves the properties of pulp produced by refining at pressurised refining. During the mechanical pulping process, fibers are released in a more intact state than that without chemical pre-treating.

Refining

After pre-treating, the chips are refined in the mechanical pulp refiner. The temperature of chips increases further in the two stages of refining machines (rotating refining plates), which results in much more softening of lignin bonds and fibres. A majority of the electricity supplied to the refiners is converted to steam by the shear forces the pulp is exposed to. This steam after treatment can be used, for example, in pulp drying or in a paper machine.

For CTMP process, an additional washing stage is included because of pre-treatment chemical circulation. This allows taking out waste water also at the beginning of the process.

Wood consumption: 2.8-3.0 m^3 wood for per ton of absolutely dry pulp in CTMP process (CEPI, 1997b). In Finland, CTMP pulp can be produced using both softwood and hardwood, the most common woods are spruce and aspen.

Water use: comparing with PGW 70, the resources of water are basically same but the quantity of water used for CTMP pulp is about 15 -50 m^3/Adt.

Consumption of chemicals: The main chemicals are used for pre-treatment of the wood chips and bleaching. For softwood, only Na_2SO_3 is used normally, 2-4% of the amount of pulp; NaOH with Na_2SO_3 are used for hardwood, the ratio is 2-4% of the amount of pulp for both chemicals. Oxidative bleaching consumption (kg/t): H_2O_2, 0 - 40; NaOH, 0 -25; Na_2SiO_3, 0 – 40; EDTA/DTPA, 0 – 5; H_2SO_4/SO_2, 0 - 5.

Energy use: The energy consumption range is from about 1,000 to about 4,300 kWh/t of pulp. About 60-65% of the total energy may be recovered as hot water and steam. For instant, a modern Finnish CTMP mill reported the following figures for electric power consumption: wood handling 20-30 kWh/Adt, refining (CSF450) 1,600-1,900 kWh/Adt, bleaching and screening about 500 kWh/Adt. In total about 2,100-2,400 kWh/Adt are required. (Integrated Pollution Prevention and Control (IPPC))

4.2.3 Simulative setup for streams and units modules

Setup streams

In simulator, from the Initialisation tab, stream classes are created and feed streams are initialised with BALAS. For example, see Figure 4.4.

	Name	Class
+	Logs	Wood
+	PM_wht_wtr_mkup	PM_water
+	Sealing_wtr_1	Water
+	Bleaching_chemicals	H2O2
+	DTPA	DTPA
+	Sealing_wtr_2	Water
+	Sealing_wtr_3	Water
+	PM_clear_mkup	PM_water

%CLASS41
DTPA
H2O2
PM_water
Water
Wood

Figure 4.4, The Initialisation window of BALAS simulator

Fig. 4.4 shows five stream classes: wood (logs), water (fresh water), PM water (white water recycled from paper machine), H_2O_2 (bleaching chemicals) and DTPA (chelating agents). For softwood, the chemical components of streams are indicated in table 4.2 for PGW 70. The same data can be used if the hardwood is selected to be raw material.

Table 4.2, Stream classes and their chemical components in simulation work (Appendix 1)

Stream classes	Chemical components
Logs	Softwood, water
Sealing water	Fresh water
PM water	Calcium carbonate, organic substances, inorganic substances, water, and softwood
H_2O_2	Sulfur dioxide, sodium hydroxide, sodium silicate, hydrogen peroxide, and water
DTPA	[DTPA](-5aq), water

While the stream classes and chemical components in feed streams of CTMP process are different from PGW 70 process. The setup for softwood is put together in table 4.3. The same data can be used if the hardwood is selected to be raw material.

Table 4.3, Stream classes and chemical components in simulation for CTMP process with softwood (Appendix 2)

Stream classes	Chemical components
Chips	Softwood, softwood bark, inorganic substances, organic substances, nitrogen, oxygen, water
Water	Fresh water

PM water	calcium carbonate, organic substances, inorganic substances, water, and softwood
Peroxides	inorganic substances, water
Sodium sulfite	inorganic substances, water
Air	Water(vapor), Nitrogen(vapor), Oxygen(vapor)

Setup unit modules

Using FlowSheet, the different unit modules can be selected and therefore the whole flow sheet can be made. In BALAS, the unit modules include auxiliary modules, chemical pulping modules, controller modules, drying modules, fibre processing modules, flow control modules, heat exchange modules, power production modules, pump modules, reactor modules, separation modules, solid-liquid separation modules, sorting modules, tank modules, vapour-liquid separation modules.

In simulation of PGW 70 process, a grinder machine is used. It is classified into fibre processing modules, its connection ports arrangement and input parameters are show in figure 4.5 and table 4.4.

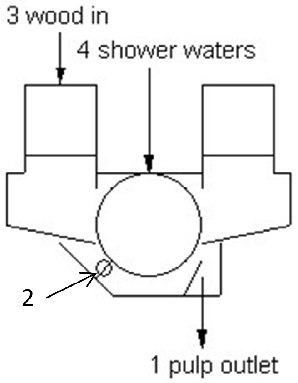


Figure 4.5, Module grinder mapped to symbol "Grinder" (Balas Manual. 2007. Version 3.2. VTT Technical Research Centre of Finland.)

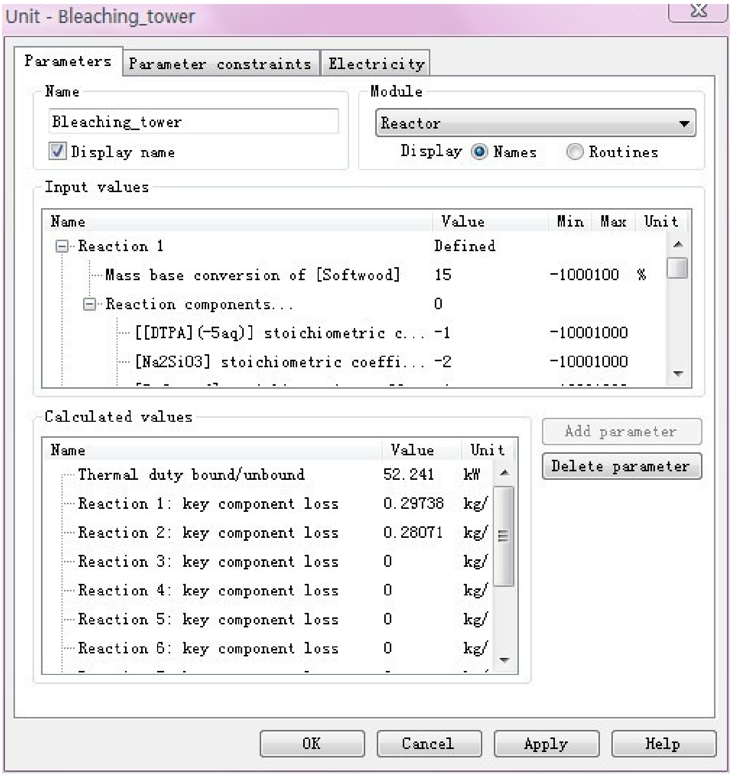
As a matter of fact, there are 4 ports in unit grinder, but the second (No.2) port usually is not in use. As illustrated in above figure, logs and shower water are put in the grinder respectively from port 3 and 4, and come out together from port 1.

Table 4.4, Input parameters for module grinder (Balas Manual. 2007. Version 3.2. VTT Technical Research Centre of Finland.)

Parameter	Unit	Default	Min	Max
Specific energy consumption	MWh/Adt	1.30	0.00	10.00
Coefficient of efficiency of motor	%	98.00	90.00	100.00
Grinder pressure	kPa	300.00	101.00	1000.00
Heat losses	%	5.00	0.00	20.00
Dissolving reaction		No	*No | Yes*	
Mass base conversion of [component]	%	0.00	0.00	100.00
Reaction components...				
[component] stoichiometric coefficient		0.00	-1000.00	1000.00

In above table, every input parameters could be modified with regard to specific process. The specific energy consumption represents the amount of motor load electricity consumption by units, and the value is related with the categories of wood. Normally, the higher specific energy consumption is used up if the softwood was used (SEC=1.2 - 1.5), and hardwood takes lower specific energy consumption (SEC=1.0-1.4). The coefficient of efficiency of motor refers to the efficiency for changing the electrical power into mechanical power, it influences the output cooling duty value. This coefficient and specific energy consumption and motor power of grinder are taken together to calculate the grinder productivity. The grinder is working in high temperature environment, therefore, the heat losses refers to the fraction of total electrical input power lost into the surrounding. Grinder pressure should be around 300 kPa.

One or more dissolving reactions might take place in some units. When the dissolving reaction is selected as “Yes” condition, it means that the grinder module also can be used to simulate a stoichiometric reactor with several separate consecutive reactions. Each separate reaction taking place in the unit is given a mass based conversion for reactant. The quantity of mass based conversion means that the efficiency of reaction. In other words, the higher quantity of mass based conversion gives the higher dissolved lignin in softwood and softwood. It is a generic model for simulating all kinds of chemical reactions and reactions are calculated in the specified order. The set-up of the unit module for bleaching tower is shown in figure 4.6. In addition to the mass-balance, the module calculates heat balance based on the formation enthalpies of the components taking part in the reaction.



Name: Bleaching_tower

☑ Display name

Module: Reactor

Display ● Names ○ Routines

Input values

Name	Value	Min	Max	Unit
Reaction 1	Defined			
Mass base conversion of [Softwood]	15	-1000100		%
Reaction components...	0			
[[DTPA](-5aq)] stoichiometric c...	-1	-10001000		
[Na2SiO3] stoichiometric coeffi...	-2	-10001000		

Calculated values

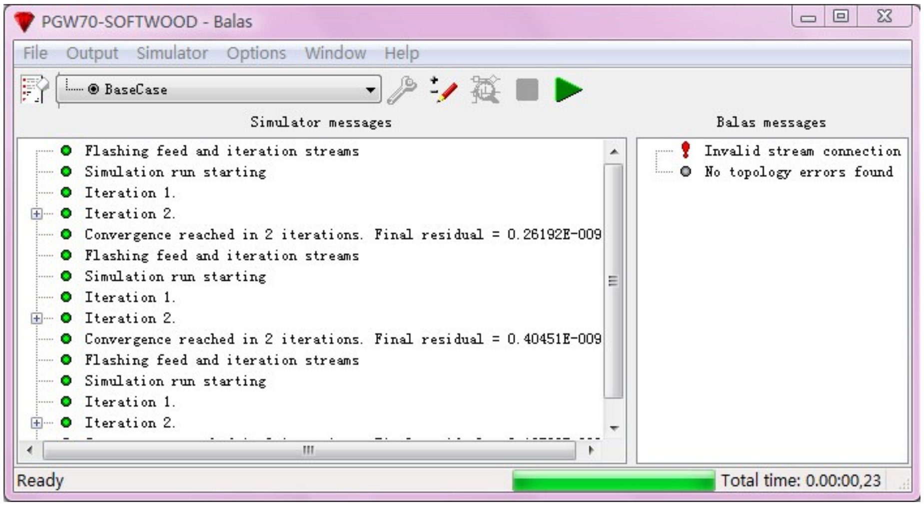
Name	Value	Unit
Thermal duty bound/unbound	52.241	kW
Reaction 1: key component loss	0.29738	kg/
Reaction 2: key component loss	0.28071	kg/
Reaction 3: key component loss	0	kg/
Reaction 4: key component loss	0	kg/
Reaction 5: key component loss	0	kg/
Reaction 6: key component loss	0	kg/

Figure 4.6 Setting up reactions in bleaching unit module

In order to set up the reaction, reactants must have negative value and reaction products have positive stoichiometric coefficients. According to the reaction equation, the value of stoichiometric coefficient can be set-up separately and the sum of stoichiometric coefficients should match to zero.

4.2.4 Iterative method and solver parameters

In this simulation work, Quasi-Newton solver is selected. The accuracy is set at 0.001%, and the maximum number of convergence is 50. BALAS simulator performs the simulation by repeatedly evaluating the flow sheet unit by unit. In this steady-state simulation work, recycle streams and equality constrains are contained. Therefore, by an iterative scheme, the simulation can reach convergence finally. The result of convergence during a simulation can be followed from iterations and residual values displayed in the simulator messages-window as shown in Fig. 4.7.



```
Flashing feed and iteration streams
Simulation run starting
Iteration 1.
Iteration 2.
Convergence reached in 2 iterations. Final residual = 0.26192E-009
Flashing feed and iteration streams
Simulation run starting
Iteration 1.
Iteration 2.
Convergence reached in 2 iterations. Final residual = 0.40451E-009
Flashing feed and iteration streams
Simulation run starting
Iteration 1.
Iteration 2.
```

```
Invalid stream connection
No topology errors found
```

Figure 4.7, the residual values displayed in simulator message-window

From the above figure, there are final residual values are calculated by following the convergence formula:

$$S = \left(\frac{100}{\varepsilon}\right)^2 \left(\frac{1}{n+m}\right) \left(\sum_{j=1}^{n} (\mathrm{v_j}/\mathrm{x_j})^2 + \sum_{j=1}^{m} \mathrm{g_j}^2\right), \qquad (1)$$

where ε is the specified error tolerance in %

n is the number of torn iteration variables

m is the number of design constraints

v_j is the error function value for torn iteration variable j

x_j is the value of torn iteration variable j

g_j is the error function value for design constraint j

The solution is regarded as converged when the iteration time in simulation message window has been less than unity on two subsequent iterations. (Balas Manual. 2007. Version 3.2. VTT Technical Research Centre of Finland.)

5 SIMULATION RESULTS

Based on the convergence of the simulation programme, the simulation results are discussed in the following text, as illustrated in charts and tables. Explanation below each chart and table interprets the distinction occurred when the different wood species used in PGW 70 and CTPM process. For a certain pulping process, the analysis of the various data, such as productivity, water and energy consumption, performance of the unit operation, are also shown. Whereas, only the primary units and streams' data are employed for calculation, a lot more detail data could be found in appendices.

5.1 Wood consumption and productivity

One of BALAS' typical applications is the steady-state simulation environment for chemical processes, which proved the mass and energy balance of input and output.

The target pulp production is 500 tonne of absolutely dry pulp per day from both wood species and two processes. However, in practical production could be a small deviation between the target productions. The efficiency of production is one of the most important factors to discuss concerning the process applicability. Therefore, we always need to calculate and control the process's productivity. In pulp and paper industry, we are using the pulp yield to express the process's productivity.

In general, the fiber morphology and ratio of chemical composition of softwood differs from hardwood; the most important is that softwood has higher lignin content, thus, the wood, and chemicals consumption of softwood is a little bit higher. The different wood species conduct to different total wood use. As same wood raw material is applied into different processes, their production yield should also differ. The amounts of wood used and pulp produced are compared in charts below.

In the below chart can be seen amounts of wood used versus simulation productions. From process PGW 70, 554.68 tonne per day of softwood logs are consumed, and 502.66 tonne are produced during daily production; a relatively lower logs consumption 538.27 tonne are used and 512.97 tonne hardwood mechanical pulp are produced.

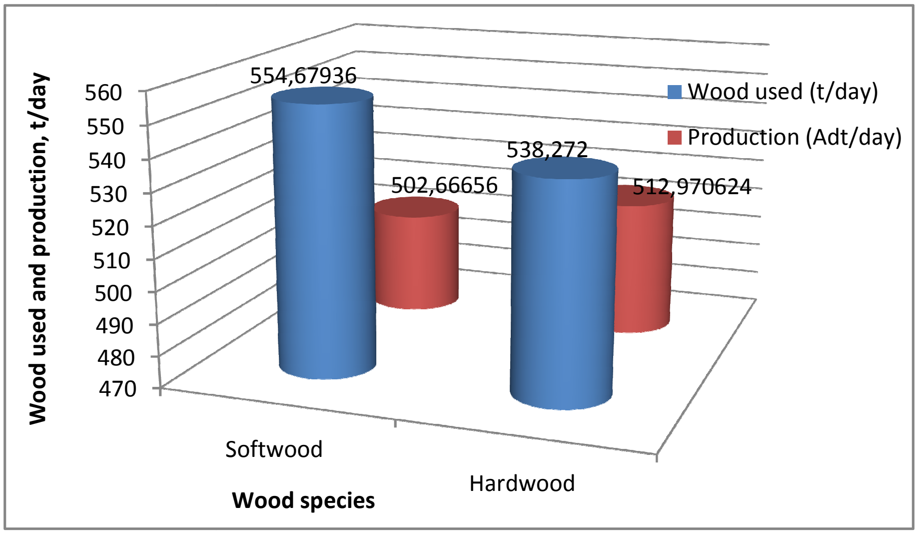


Chart 5.1 The consumption of amounts of wood used and pulp producted by PGW 70 process (Appendix 1)

From the process of CTMP, consuming 600.75 tonne of softwood logs per day while its pulp yield is 83%; the 91% yield is from the hardwood of 549.45 tonne per day.

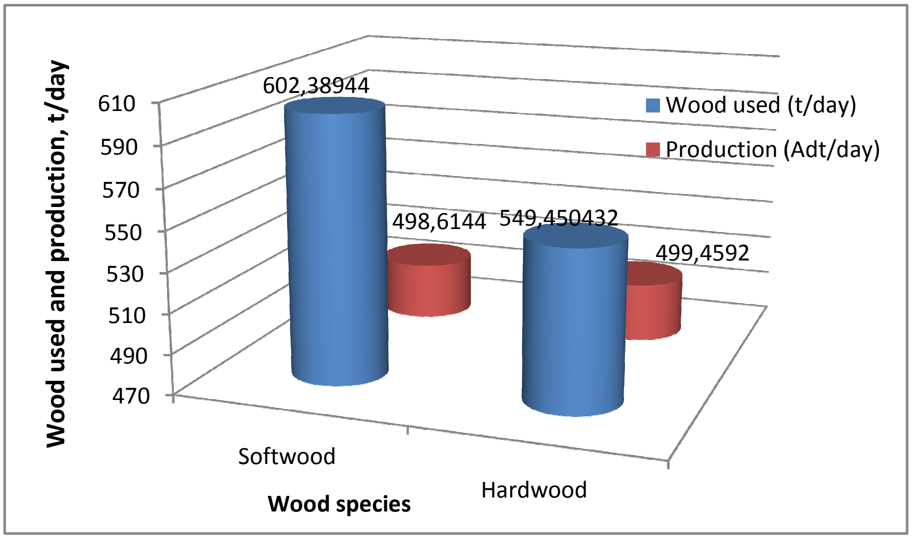


Chart 5.2 The consumption of amounts of wood used and pulp producted by CTMP process (Appendix 2)

As conclusion, the values of pulp yield from two processes have been put together in table 5.1.

Table 5.1 The comparison of pulp yield between different wood species and processes

	PGW-70 process		CTMP process	
	Softwood	Hardwood	Softwood	Hardwood
Pulp yield	90.623%	95.300%	83%	91%
Reference yield	92-96%		80-92%	

The typical pulp yield of PGW 70 process is 92 – 96%, and 80 – 92% for CTMP process. Through simulation, the pulp yield from softwood and hardwood in PGW 70 process respectively are 90.6% and 95.3%; and for CTMP process, softwood and hardwood are 83% and 91%.

Thereby, the pulp yield results are not only proving the processes were operated correctly and their pulp yield values were reasonable, but also verifying the mass conservation had been achieved.

5.2 Chemicals consumption in processes

The truly optical properties of pulp only could be practiced in mills or laboratories. Simultaneously, simulator is constrained by the purposed production, so that simulator has to neglect the final bleaching effects. In other words, the simulation results are obtained with the prerequisite condition of input and output balance, its emphasis on the better economical feed in.

Peroxide bleaching method was applied in process. Bleaching chemicals includes H_2O_2, NaOH, Na_2SiO_3, DTPA, and SO_2. For each compound, their consumed amounts by PGW 70 process have been put together in table below.

Table 5.2 Amount of chemicals usage by softwood in PGW 70 process compared with reference values (Appendix 1)

	Wood species	Na_2SiO_3	SO_2	NaOH	H_2O_2	DTPA	Logs
Simulation data (t/d)	Softwood	5.183827	2.592	26.78314	26.78314	2.592	554.6794
	Hardwood	5.826816	1.75392	23.56992	23.56992	2.913408	537.6672
Reference value (t/d)		0-20	0-5	0-22	0-22	0-2.5	-

Hardwood normally has higher metal charge content, and DTPA reacts with metal charges. That is the reason why more DTPA is consumed with hardwood, but the consumption is still following the required dosage, about 2.5 tonne per day. H_2O_2, NaOH are the chemicals which exactly go to disintegrate fibers' lignin component. Since there is higher lignin content in softwood than hardwood, then more H_2O_2, NaOH are used. The function of sulfur dioxide is to neutralize the alkaline in the pulp flow formed by H_2O_2, NaOH. More residual of H_2O_2, NaOH result in more SO_2 consumption.

The bleaching chemicals are consumed more in CTMP process because more wood is used and yield of process is relatively lower. As the simulation result, the total amount of bleaching chemicals used is 78, 06 tonne for per day.

According to the CTMP process, additional chemical components are applied in process. Chemical pre-treatment is carried out in CTMP process. Wood chips are impregnated in pre-treatment stage, where fibers are released in a more intact state than without pre-treating.

For softwood, only Na_2SO_3 is used normally, 2 - 4% of the amount of pulp; NaOH with Na_2SO_3 are used for hardwood, the ratio is 2 - 4% for both chemicals. That means, the hardwood usage should be about twice that of softwood.

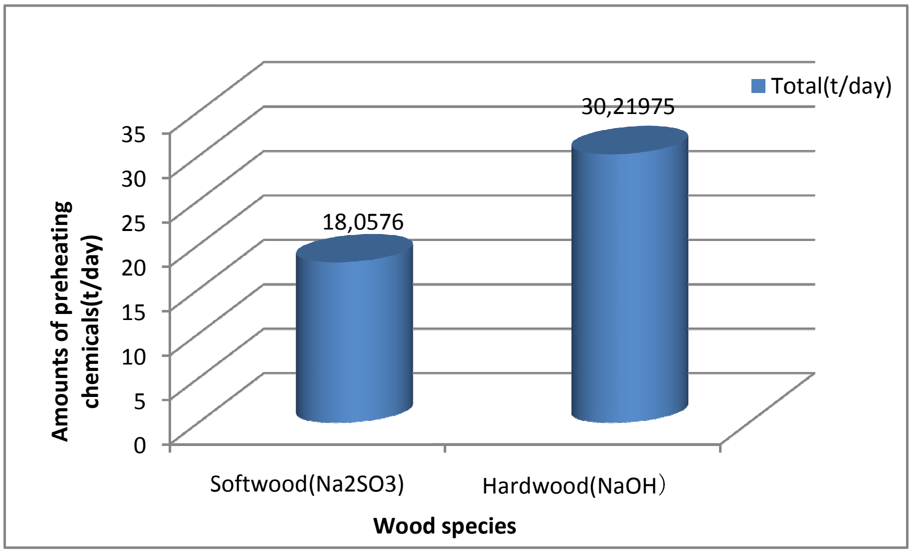


Chart 5.3 Comparison of the amount of wood pre-treatment chemicals in CTMP (Appendix 2)

As matter of fact, the used amount of hardwood is 30.22 tones in daily production, the value is only a little bit less than double of softwood usage. In addition, the transformed energy consumptions by chemicals are proportional to the chemical usage amount.

5.3 Water consumption and distribution in processes

Generally, in pulping production, the water consumption is always quite a large amount and almost all water comes from the recovery water resource in the pulp and paper production line. White water and clear water are recycled from paper machine with different purity. White water takes the biggest portion of total amount of water consumption, about ten times more than clear water is quantity.

There is a close relationship between fresh water and white water consumption in pulping process. The reuse of white water can reduce the amount of fresh water to be used in one of the great tasks, and hence it is an important factor and should be considered in the pulp process. The input water streams and their amounts are shown in table 5.3.

Table 5.3 The amount of water input to PGW 70 process (Appendix 1)

PROCESS PGW 70				
	SOFTWOOD		**HARDWOOD**	
Streams	**USED-IN**	SUM		SUM
PM-WHITE WATER (t/day)	16136.93	17406.58	17081.28	18307.73
PM-CLEAR WATER (t/day)	1016.496		973.296	
COME WITH BLEACHING (t/day)	31.536		31.53082	
COME WITH LOGS (t/day)	221.6246		221.6246	
	FRESH-IN			
SEALING WATER		276.48		133.92

The output water from pulping process has a different way to go. The largest amount of water goes away with pulp flow to paper machine, and then the water would be discharged and recirculated back. About one third of water is discharged directly to waste water treatment of pulping process. Centricleaners' reject part refers to the flow is let off with large amount of impurities, for instance, the rejected fiber, wood knots, sand. A little bit larger amount of water is used from hardwood due to higher efficiency of some units.

Table 5.4 The amount of water output from PGW 70 process (Appendix 1)

PROCESS PGW 70				
	SOFTWOOD		**HARDWOOD**	
Streams				
CERTRICLEANERS REJECT (t/day)	58.92307	17687.12	202.3661	18380.06
TO WASTE WATER TREATMENT (t/day)	5184		5184	
PULP TO PM (t/day)	12444.19		12993.7	

Combined table 5.3 and table 5.4, the simulation results show that the mass balance is calculated for water both for softwood and hardwood. It can also be seen that a lot less fresh water is used comparing with the white water, which means good design for water stream system in pulping process. Sealing water refers to fresh water.

In addition, the pulp process is required to ensure efficient operation and hence it is reasonable to distribute water for the different unit operations. The average consumption of water for softwood and hardwood for unit operations in PGW 70 process is explained in chart 5.4.

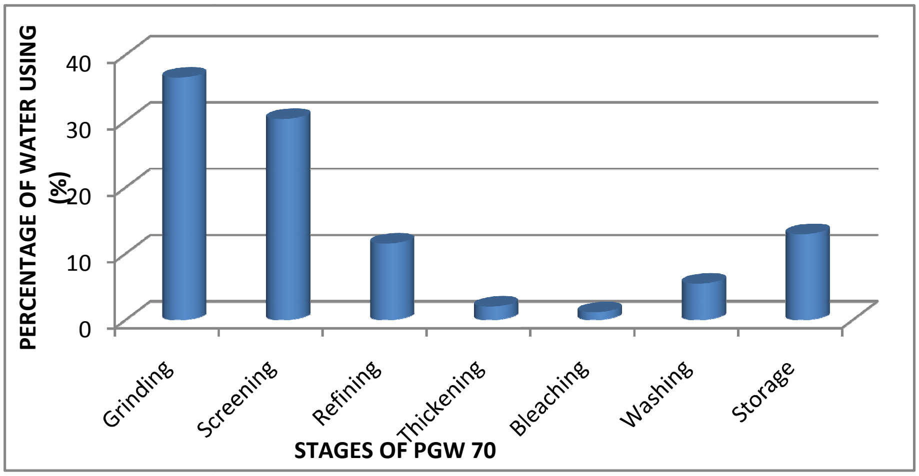


Chart 5.4 Distribution of water usage in PGW 70

The distribution of water consumption in PGW 70 process is explained in above column chart. Grinding and screening unit operations consume the largest amount of water. In the grinder, the major wood matrix is to disintegrate with the much large amount of shower water present. The rest part of wood matrix would be degraded in refining, where a certain amount of water is needed. Also some water is consumed to dilute the pulp flow to low consistency in screening stage, where the impurities are rejected. The main function of thickening is to make water drain off; therefore the water usage in thickening is quite small. The pulp flow must be stored at low consistency prior it goes to paper machine.

In CTMP process, both liquid and vapor phase of water are used. Comparing with the PGW 70 process, the total amount of water used in CTMP is more than twice the amount in PGW 70 process. The input water streams are listed in table 5.5.

Table 5.5 The liquid and vapor phases of water inputs (Appendix 2)

CTMP process			
Phase	Streams	Amount (t/day)	Total (t/day)
Liquid	COME WITH BLEACHING(SO2)	0.1728	38254.3776
	COME WITH BLEACHING(H2O2)	77.76	
	COME WITH PRE-TREATMENT	25.92	
	COME WITH CHIPS	545.95296	
	CLEAR_chemically purified water	95.04	
	CLEAR_fresh water	6099.4944	
	CLEAR_Makeup water from power plant	413.00064	
	ClEAR_from PM	1774.1376	
	WHITE WATER FROM PM	8460.9792	
	WIHTE WATER FROM PM	20761.92	
Vapor	AIR TO CHIP HANDLING	172.8	569.18592
	FROM POWER PLANT_MP	236.25216	
	FROM POWER PLANT_LP	43.2	
	TO PRE-TREATMENT	116.93376	

The above table indicates white water reuse, as over 75% of total amount of water comes from white water. The certain amount of steam is input with chips, chemicals input streams and also from power plant and process recovering.

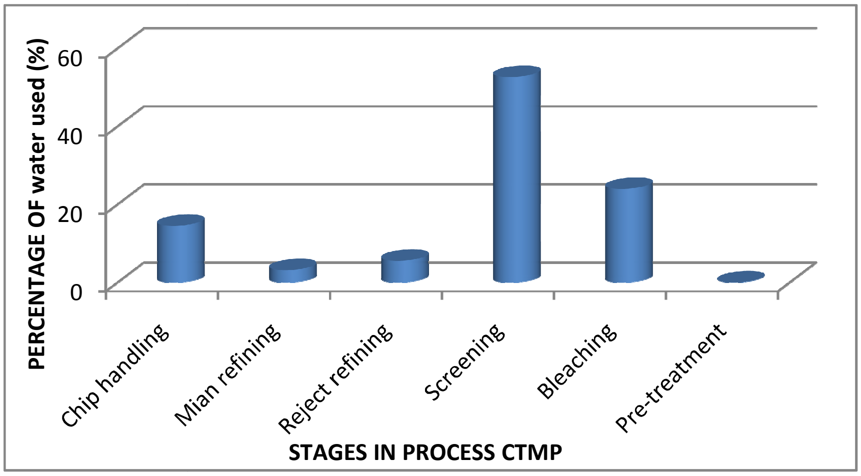


Chart 5.5 Distribution of water usage in CTMP

The consumption of the steam is primary to the units with less water used: chip handling, pre-treatment and main and reject refining stages as shown in chart 5.5.

A large amount of water is used in screening and bleaching operations because the pulp should be screened at low consistency and washed after bleaching.

5.4 Distribution of energy and energy conservation

Another typical application of BALAS simulator is used to calculate the heat integration and heat recovery. The pulping process plant is operated by electric power and heat (thermal) energy. Energy conservation is meant not to reduce the consumption of energy for operation, but to ensure waste-saving and effective use of energy. The way of reasonable distribution is contributed for energy effective use and conservation.

Firstly, the electric energy consumption for the different unit operations is shown in chart 5.6 and chart 5.7. The values of electric energy consumption are calculated by the average of the simulation results from softwood and hardwood.

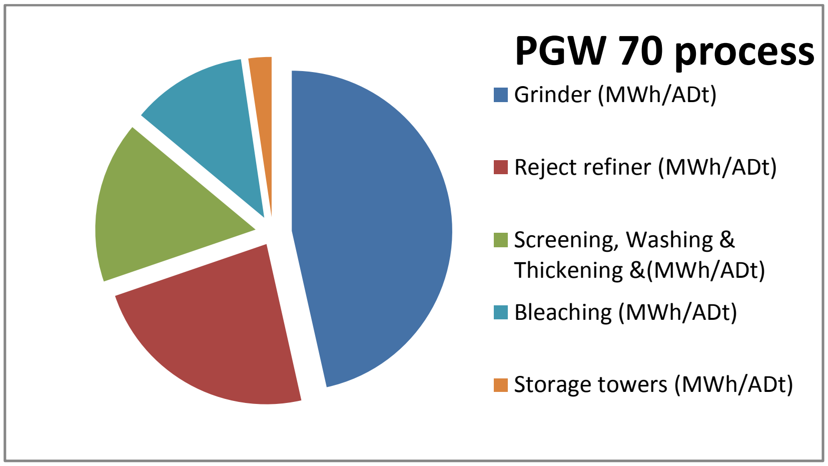


Chart 5.6 The consumption of electric energy distribution in PGW 70 process (Appendix 1)

In above chart, the electric energy consumption is classified by the process stages, and the values of electric energy consumption are calculated by the average from softwood and hardwood. In PGW 70 process, electric energy is mainly consumed by grinder, refiners, and bleaching tower; however, the energy requirement for screening, thickening and screening reject are also significant, their portion is about one fourth portion; the mechanism of selected unit modules for storage tower is centrifugal cleaning method, so that the water circulation stage consumes the least part of electric energy.

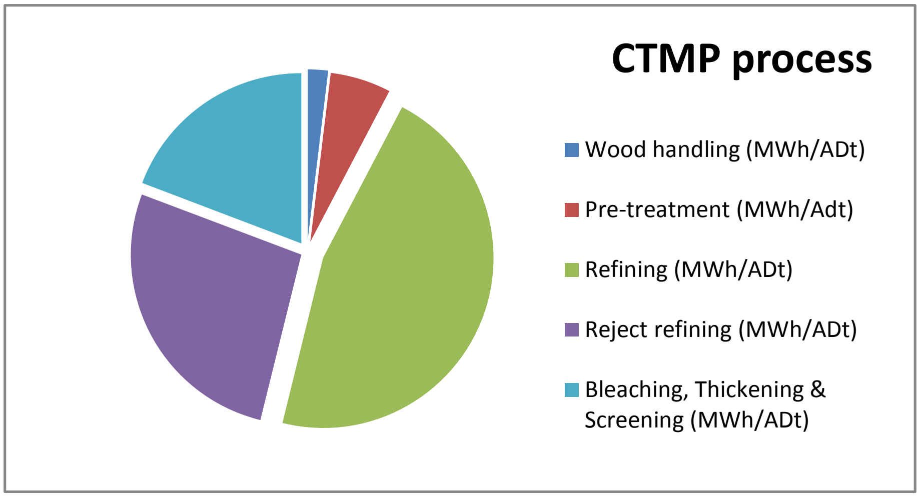


Chart 5.7 The consumption of electric energy distribution in CTMP process (Appendix 2)

A small portion of total electric energy is used to soften the wood matrix in wood handling and pre-treatment stages. Around quarter of the electric energy is used by the bleaching unit.

The wood matrix in chips disintegrated into fiber form during refining stage. The process CTMP has a two-stage refining, main refining and rejects refining. It is important for the effective use of refining energy to control the quality of pulp and the pressure at the inlet and the outlet of a refiner as specified. Three fourths of total electric energy is consumed by these two refining stages.

In addition, there is a more detailed case study about the electric energy consumption by unit operation for softwood and hardwood. The properties of wood species influence the consumption of energy in the pressurized grinding process, as shown in chart 5.8. The wood properties refer to wood composition, density, fiber cell wall thickness, and average fiber length.

Chart 5.8 Specific energy consumption (SEC) of grinder with various wood species for PGW70 (Appendix 1)

The above chart illustrates that the different wood species resulted in the different consumption of electric power for the grinder. Softwood performs very favorably in grinding and the specific energy consumption is 1 MWh/Adt. The reason is that softwood has high long fiber content, high tear and tensile strength.

Comparing with PGW 70 process, more than four times energy is consumed by CTMP process. The heat integrations by softwood from process CTMP and PGW 70 are introduced below in table 5.6.

Table 5.6 Comparison of heat integration and efficiency of heat recovery (Appendix 1 & 2)

INPUT/(MW)				
	TOTAL INPUT HEAT	CHIP&CHEMICAL HEAT	FEEDING RECOVERY HEAT	THERMAL DUTY FROM UNITS
CTMP	364.737529	0.824078959	285.27915	78.6343
PGW_70	83.28328044	0.512944795	41.12402821	41.639489
OUTPUT/(MW)				
	TOTAL OUTPUT HEAT	OUTPUT TO PM	OUTPUT TO HEAT RECOVERY	HEAT LOSSES FROM UNITS
CTMP	366.4422292	127.4448448	235.3059337	3.69145076
PGW_70	81.41683453	0.345890943	53.29962071	27.77132288

The total input thermal energy mainly come with wood, chemicals, recovery water streams and unit operations. The thermal energy is output to paper machine and heat recovery plant, and certain amount of heat is loss to surrounding. The recovered heat energy as input is applied to maintain or increase the temperature of white water in system. It can be seen that energy in the process is conserved. As conclusion, waste-saving from heat consumption and effective use are important methods to improve the continuous operation.

5.5 Waste production and pulping quality

The effluent amount of PGW 70 process is 5,184 tonnes per day, this number is calculated from average value of softwood and hardwood. The effluent consists of inorganic and organic components mainly from bleaching reactions, rejected fiber from such as screening stage, and certain amount of water. For CTMP process, the average value from softwood and hardwood is more than 6,000 tonnes per day. Comparing the composition of effluent from PGW 70 process, the bark exists in the effluent in CTMP process. In additional, gas emission in the CTMP process to atmosphere was about 155 tonnes per day, in contrast, the PGW 70 process only emits 10% of that from CTMP process.

BALAS simulator has certain limitations, for example, the practical pulp quality and properties cannot be shown from the simulation results, so that simulator neglects the final bleaching effects. In practical production line, the softwood pulp from PGW 70 process with bleaching could be used for producing the light weight coating papers, and the softwood bleached pulp from CTMP is suitable for tissues, liquid packaging papers. While the pulp comes from hardwood, printing papers and tissues can be produced by both PGW 70 and CTMP processes.

6 SUMMARY

Two different mechanical pulping processes, i.e. PGW 70 and CTMP, and two kinds of wood species, i.e. softwood and hardwood, are investigated using BALAS simulator. Mass conservation and energy conservation in the pulping process had been directly indicated during simulation.

Comparisons were made for the different pulping processes and the various raw materials from different aspects, e.g. the pulp yield, chemicals used, water integrations, electric power and thermal energy consumptions etc.

The softwood and hardwood have different chemical compositions and fiber morphology etc, which may result in the different process productivity for a fixed pulping process. Also wood species influence the performance of unit equipment, e.g. grinder, refiners, bleaching towers.

Comparing with the different pulping processes, the CTMP process consumed much more water and energy than the PGW 70 process, however, CTMP process still has good efficiency of water and energy recovery.

Simulation results show that a large amount of white water, recovered from the different unit operations in processes, obviously reduces the amount of fresh water input into the system. Therefore, it shows good design of the water recovery system in pulping process. Electrical energy transformed into heat energy has two efficient ways, which include thermal energy and hot steam, to decrease the quantities of total consumption.

Comparing with the analysis of real physical pulping process, it can be concluded that the BALAS simulator can correctly predict the performance of unit operations and the influence of the raw materials on the pulping process. Hence the simulator provides us an efficient tool to flexibly design and evaluate the pulping process.

REFERENCES

Aspen HYSYS. Aspen Technology, Inc.
http://www.aspentech.com/core/aspen-hysys.cfm (Accessed on 14 June 2010)

Baasel, W. Preliminary Chemical Engineering Plant Design. Second Edition. US: American Elsevier Publishing Company, Inc.

Balas Manual. 2007. Version 3.2. VTT Technical Research Centre of Finland.

Balas Support E-mail: balas@vtt.fi

Biegler, L. & Grossmann, I. & Westerberg, A. 1997. Systematic Methods of Chemical Process Design. US: Prentice Hall PTR. pp. 25 -39.

Chang, N. & Lin, K. 2000. Oxidation Kinetics of the Combustible Fraction of Construction and Demolition Wastes. Journal of Environmental Quality. Vol. 30 No. 4, pp. 1392 – 1401.

https://www.soils.org/publications/jeq/articles/30/4/1392#fig7 (Accessed on 11 August 2010)

Integrated Pollution Prevention and Control (IPPC) – Reference Document on Best Available Techniques in the Pulp and Paper Industry. 2001. European Commission.

Jaako, J. 1998. Aspects of Process Modeling. University of Oulu. Control Engineering Laboratory, Linnanmaa, FIN-90570, Oulu, Finland. pp. 5 – 13.

Kalliola, A. & Kangas, P. 2009. Modelling and simulation for process industry. VTT Technical Research Centre of Finland.

Knowpap10.0 paper technology, general. (Accessed on 08 June 2010)

Knowpap 10.0. Raw Material. (Accessed on 08 June 2010)

Lenon, T. 2010. Using Modeling Simulation to Optimize Plant Control Systems. InTech.

http://www.isa.org/InTechTemplate.cfm?Section=Control_Fundamentals1&template=/ContentManagement/ContentDisplay.cfm&ContentID=82972 (Accessed on 08 August 2010)

Material and energy balance. 2005. Bureau of Energy Efficiency.

http://www.emea.org/Guide%20Books/Book1/1.4%20MATERIAL%20%20AND %20ENERGY%20BALANCE.pdf (Accessed on 11 August 2010)

Pulp and Paper. Forestry Insights.

http://www.insights.co.nz/products_processes_wc.aspx#d (Accessed on 20 October 2010)

Savolainen, J. 2008. Apros for the Pulp and Paper Industry. VTT Technical Research Centre of Finland.

Smith, W. & DuPont, E. 1999. Impact of Advances in Computing and Communications Technologies on Chemical Science and Technology. US: National Academics Press.

Spaeth, J. 2004. Biomass Program. EERE Information Center.

http://www.insights.co.nz/products_processes_wc.aspx (Accessed on 20

Steady State Simulation Software Offers a Flexible Environment. ProSim, Inc.

http://www.chemicalprocessing.com/vendors/products/2009/181.html (Accessed on 14 June 2010)

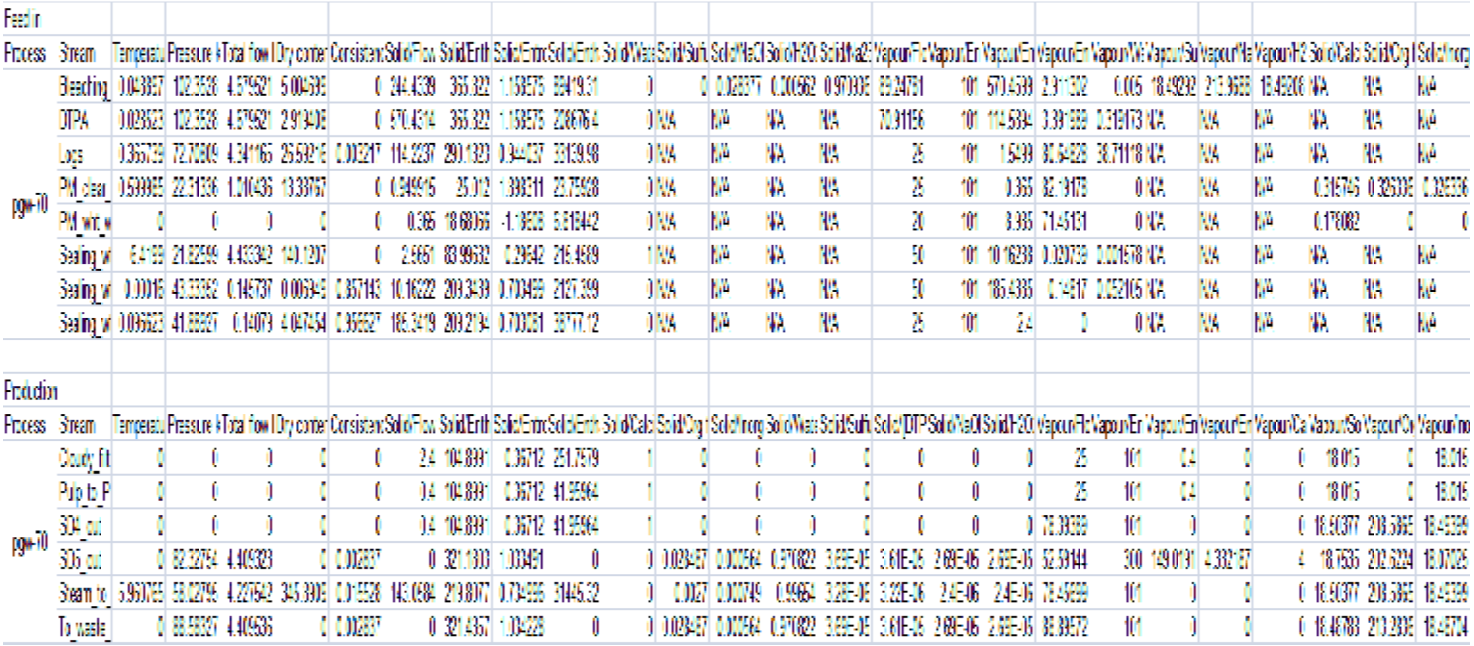
SuperPro Designer. Intelligen, Inc.

http://www.intelligen.com/superpro_overview.shtml(Accessed on 14 June 2010)

Wood Chemicals. Forestry Insights.

http://www.insights.co.nz/products_processes_wc.aspx#d (Accessed on 20 October 2010)

APPENDIX 1



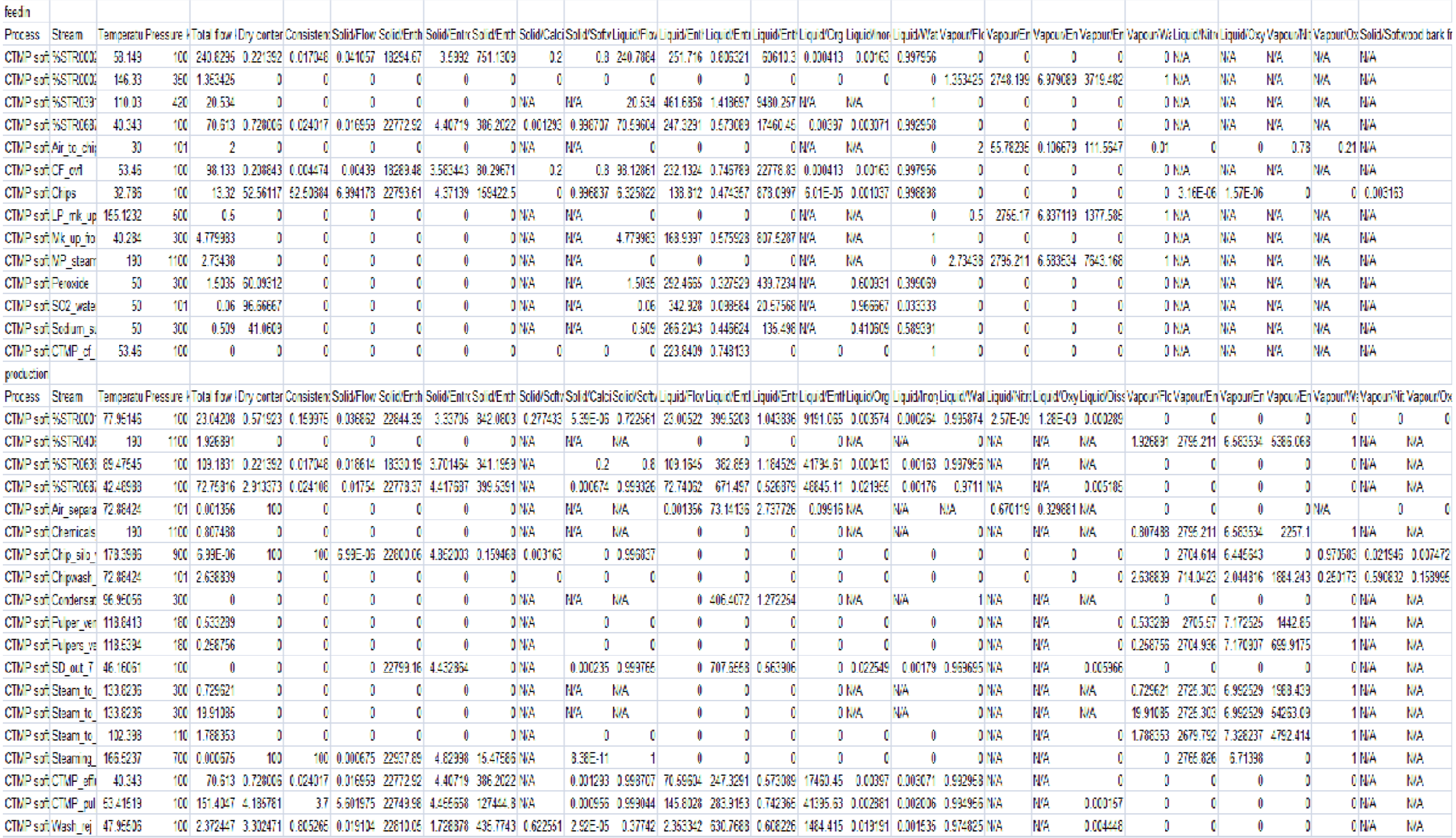
Feed in

Process	Stream	Temperatu	Pressure (	Total flow	Dry conte	Consisten	SolidFlow	SolidEnth	SolidEntro	SolidEnth	SolidWas	SolidSulfi	SolidNaCl	SolidH2O	SolidNa2S	VapourFlo	VapourEn	VapourEn	VapourEn	VapourWe	VapourSu	VapourNa	VapourH2	SolidCalc	SolidOrg	SolidInorg
pgw-70	Bleaching_	0.043857	102.3536	4.579521	5.004695	0	244.4539	365.322	1.158575	89419.31	0	0	0.028377	0.00562	0.970305	69.24781	101	570.4539	2.311302	0.005	18.49292	213.9685	18.45206	NA	NA	NA
	DTPA	0.023523	102.3536	4.579521	2.919406	0	570.4314	365.322	1.158575	208676.4	0	NA	NA	NA	NA	70.91156	101	114.5394	3.391589	0.319173	NA	NA	NA	NA	NA	NA
	Logs	0.365739	72.70809	4.341165	25.59216	0.003217	114.2237	290.1323	0.944037	3313.98	0	NA	NA	NA	NA	25	101	1.5499	80.64828	38.71118	NA	NA	NA	NA	NA	NA
	PM_clear_	0.539985	22.31336	1.010436	13.33767	0	0.949915	25.012	1.338311	23.75928	0	NA	NA	NA	NA	25	101	0.365	82.19173	0	NA	NA	NA	0.315745	0.325305	0.325336
	PM_wir_w	0	0	0	0	0	0.365	18.68066	-1.19508	5.815442	0	NA	NA	NA	NA	20	101	8.335	71.45131	0	NA	NA	NA	0.178082	0	0
	Sealing_w	6.4199	21.82599	4.433342	140.1207	0	2.5651	83.99532	0.29542	216.4589	1	NA	NA	NA	NA	50	101	10.16238	0.020739	0.001578	NA	NA	NA	NA	NA	NA
	Sealing_w	0.00016	43.33352	0.145737	0.006349	0.357143	10.16222	209.3439	0.700459	2127.399	0	NA	NA	NA	NA	50	101	185.4335	0.14917	0.052105	NA	NA	NA	NA	NA	NA
	Sealing_w	0.096623	41.88927	0.14073	4.047454	0.356527	185.3419	209.2134	0.700081	38777.12	0	NA	NA	NA	NA	25	101	2.4	0	0	NA	NA	NA	NA	NA	NA

Production

Process	Stream	Temperatu	Pressure (	Total flow	Dry conte	Consisten	SolidFlow	SolidEnth	SolidEntro	SolidEnth	SolidCalc	SolidOrg	SolidInorg	SolidWas	SolidSulfi	Solid(DTP	SolidNaOH	SolidH2O	VapourFlo	VapourEn	VapourEn	VapourEn	VapourCa	VapourSo	VapourOr	VapourIno
pgw-70	Cloudy_filt	0	0	0	0	0	2.4	104.8391	0.36712	251.7579	1	0	0	0	0	0	0	0	25	101	0.4	0	0	18.015	0	18.015
	Pulp_to_P	0	0	0	0	0	0.4	104.8391	0.36712	41.95964	1	0	0	0	0	0	0	0	25	101	0.4	0	0	18.015	0	18.015
	SO4_out	0	0	0	0	0	0.4	104.8391	0.36712	41.95964	1	0	0	0	0	0	0	0	78.38389	101	0	0	0	16.50377	208.5365	18.45399
	SO5_out	0	82.32754	4.409323	0	0.002837	0	321.1303	1.003451	0	0	0.003457	0.000564	0.970822	3.69E-05	3.61E-06	2.69E-06	2.69E-06	52.59144	300	149.0131	4.332167	4	18.7535	202.6224	18.07025
	Steam_to_	5.960765	58.02796	4.227542	345.3905	0.015528	143.0584	219.8077	0.734995	31445.32	0	0.0027	0.000749	0.99664	3.28E-06	3.22E-06	2.4E-06	2.4E-06	78.45699	101	0	0	0	16.50377	208.5365	18.45399
	To_waste_	0	88.56327	4.409536	0	0.002837	0	321.4357	1.04228	0	0	0.003457	0.000564	0.970822	3.69E-05	3.61E-06	2.69E-06	2.69E-05	88.89572	101	0	0	0	16.46783	213.2806	18.46704

APPENDIX 2



feedin

Process	Stream	Temperatu	Pressure k	Total flow k	Dry conter	Consisten	Solid/Flow	Solid/Enth	Solid/Entr	Solid/Enth	Solid/Calci	Solid/Softw	Liquid/Flow	Liquid/Enth	Liquid/Entr	Liquid/Enth	Liquid/Org	Liquid/Inor	Liquid/Wat	Vapour/Flo	Vapour/En	Vapour/En	Vapour/En	Vapour/Wa	Liquid/Nitr	Liquid/Oxy	Vapour/Nit	Vapour/Ox	Solid/Softwood bark fr
CTMP soft	%STR000	53.149	100	240.8295	0.221392	0.017046	0.041057	18294.67	3.5992	751.1309	0.2	0.8	240.7864	251.716	0.806321	60610.3	0.000413	0.00163	0.997956	0	0	0	0	0	N/A	N/A	N/A	N/A	N/A
CTMP soft	%STR000	146.33	350	1.353425	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.353425	2748.199	6.979089	3719.482	1	N/A	N/A	N/A	N/A	N/A
CTMP soft	%STR039	110.03	420	20.534	0	0	0	0	0	0	N/A	N/A	20.534	461.6858	1.418697	9480.257	N/A	N/A	1	0	0	0	0	0	N/A	N/A	N/A	N/A	N/A
CTMP soft	%STR068	40.343	100	70.613	0.728006	0.024017	0.016959	22772.92	4.40719	386.2022	0.001293	0.998707	70.59604	247.3291	0.573089	17460.45	0.00397	0.003071	0.992958	0	0	0	0	0	N/A	N/A	N/A	N/A	N/A
CTMP soft	Air_to_chi	30	101	2	0	0	0	0	0	0	N/A	N/A	0	0	0	0	N/A	N/A	0	2	55.78236	0.106679	111.5647	0.01	0	0	0.78	0.21	N/A
CTMP soft	CF_ovfl	53.46	100	98.133	0.208843	0.004474	0.00439	18289.48	3.583443	80.29671	0.2	0.8	98.12861	232.1324	0.746789	22778.83	0.000413	0.00163	0.997956	0	0	0	0	0	N/A	N/A	N/A	N/A	N/A
CTMP soft	Chips	32.786	100	13.32	52.56117	52.50884	6.994178	22793.61	4.37139	159422.5	0	0.996837	6.325822	138.812	0.474357	878.0997	6.01E-05	0.001037	0.998898	0	0	0	0	0	3.16E-06	1.57E-06	0	0	0.003163
CTMP soft	LP_mk_up	155.1232	600	0.5	0	0	0	0	0	0	N/A	N/A	0	0	0	0	N/A	N/A	0	0.5	2755.17	6.837119	1377.585	1	N/A	N/A	N/A	N/A	N/A
CTMP soft	Mk_up_fo	40.284	300	4.779983	0	0	0	0	0	0	N/A	N/A	4.779983	168.9397	0.575928	807.5287	N/A	N/A	1	0	0	0	0	0	N/A	N/A	N/A	N/A	N/A
CTMP soft	MP_steam	190	1100	2.73438	0	0	0	0	0	0	N/A	N/A	0	0	0	0	N/A	N/A	0	2.73438	2795.211	6.583534	7643.168	1	N/A	N/A	N/A	N/A	N/A
CTMP soft	Peroxide	50	300	1.5035	60.09312	0	0	0	0	0	N/A	N/A	1.5035	292.4665	0.327529	439.7234	N/A	0.600931	0.399069	0	0	0	0	0	N/A	N/A	N/A	N/A	N/A
CTMP soft	SO2_wate	50	101	0.06	96.66667	0	0	0	0	0	N/A	N/A	0.06	342.928	0.098584	20.57568	N/A	0.966667	0.033333	0	0	0	0	0	N/A	N/A	N/A	N/A	N/A
CTMP soft	Sodium_s	50	300	0.509	41.0609	0	0	0	0	0	N/A	N/A	0.509	266.2043	0.446624	135.498	N/A	0.410609	0.589391	0	0	0	0	0	N/A	N/A	N/A	N/A	N/A
CTMP soft	CTMP_cf_	53.46	100	0	0	0	0	0	0	0	0	0	0	223.8409	0.748133	0	0	0	1	0	0	0	0	0	N/A	N/A	N/A	N/A	N/A

production

Process	Stream	Temperatu	Pressure k	Total flow k	Dry conter	Consisten	Solid/Flow	Solid/Enth	Solid/Entr	Solid/Enth	Solid/Softw	Solid/Calci	Solid/Softw	Liquid/Flow	Liquid/Enth	Liquid/Entr	Liquid/Enth	Liquid/Org	Liquid/Inor	Liquid/Wat	Liquid/Nitr	Liquid/Oxy	Liquid/Diss	Vapour/Flo	Vapour/En	Vapour/En	Vapour/En	Vapour/Wa	Vapour/Nit	Vapour/Ox
CTMP soft	%STR000	77.95146	100	23.04208	0.571923	0.159975	0.036862	22844.39	3.33706	842.0803	0.277433	5.39E-06	0.722561	23.00522	399.5208	1.043836	9191.065	0.003574	0.000264	0.995874	2.57E-09	1.28E-09	0.000289	0	0	0	0	0	0	0
CTMP soft	%STR040	190	1100	1.926891	0	0	0	0	0	0	N/A	N/A	N/A	0	0	0	0	N/A	N/A	0	N/A	N/A	N/A	1.926891	2795.211	6.583534	5386.068	1	N/A	N/A
CTMP soft	%STR063	89.47545	100	109.1831	0.221392	0.017046	0.018614	18330.19	3.701464	341.1959	N/A	0.2	0.8	109.1645	382.859	1.184529	41794.61	0.000413	0.00163	0.997956	N/A	N/A	N/A	0	0	0	0	0	N/A	N/A
CTMP soft	%STR068	42.46988	100	72.75816	2.913373	0.024106	0.01754	22778.37	4.417687	399.5391	N/A	0.000674	0.999326	72.74062	671.497	0.526879	46845.11	0.021955	0.00176	0.9711	N/A	N/A	0.005185	0	0	0	0	0	N/A	N/A
CTMP soft	Air_separa	72.88424	101	0.001356	100	0	0	0	0	0	N/A	N/A	N/A	0.001356	73.14136	2.737726	0.09916	N/A	N/A	N/A	0.670119	0.329881	N/A	0	0	0	0	N/A	0	0
CTMP soft	Chemicals	190	1100	0.807488	0	0	0	0	0	0	N/A	N/A	N/A	0	0	0	0	N/A	N/A	0	N/A	N/A	N/A	0.807488	2795.211	6.583534	2257.1	1	N/A	N/A
CTMP soft	Chip_silo_	178.3986	900	6.99E-06	100	100	6.99E-06	22800.06	4.852003	0.159468	0.003163	0	0.996837	0	0	0	0	0	0	0	0	0	0	0	2704.614	6.445643	0	0.970583	0.021946	0.007472
CTMP soft	Chipwash_	72.88424	101	2.638839	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.638839	714.0423	2.044816	1884.243	0.250173	0.590832	0.158995
CTMP soft	Condensat	96.95056	300	0	0	0	0	0	0	0	N/A	N/A	N/A	0	406.4072	1.272254	0	N/A	N/A	1	N/A	N/A	N/A	0	0	0	0	0	N/A	N/A
CTMP soft	Pulper_ver	118.8413	180	0.533289	0	0	0	0	0	0	N/A	0	0	0	0	0	0	0	0	0	N/A	N/A	0	0.533289	2705.57	7.172525	1442.85	1	N/A	N/A
CTMP soft	Pulpers_ve	118.5394	180	0.268756	0	0	0	0	0	0	N/A	0	0	0	0	0	0	0	0	0	N/A	N/A	0	0.268756	2704.936	7.170907	699.9175	1	N/A	N/A
CTMP soft	SD_out_T	46.16061	100	0	0	0	0	22799.16	4.432864	0	N/A	0.000235	0.999765	0	707.6558	0.563906	0	0.022549	0.00179	0.969695	N/A	N/A	0.005966	0	0	0	0	0	N/A	N/A
CTMP soft	Steam_to_	133.8236	300	0.729621	0	0	0	0	0	0	N/A	N/A	N/A	0	0	0	0	N/A	N/A	0	N/A	N/A	N/A	0.729621	2725.303	6.992529	1988.439	1	N/A	N/A
CTMP soft	Steam_to_	133.8236	300	19.91085	0	0	0	0	0	0	N/A	N/A	N/A	0	0	0	0	N/A	N/A	0	N/A	N/A	N/A	19.91085	2725.303	6.992529	54263.09	1	N/A	N/A
CTMP soft	Steam_to_	102.398	110	1.788353	0	0	0	0	0	0	N/A	0	0	0	0	0	0	0	0	0	N/A	N/A	0	1.788353	2679.792	7.328237	4792.414	1	N/A	N/A
CTMP soft	Steaming_	166.5237	700	0.000675	100	100	0.000675	22937.89	4.82998	15.47586	N/A	8.38E-11	1	0	0	0	0	0	0	0	N/A	N/A	0	0	2765.826	6.71398	0	1	N/A	N/A
CTMP soft	CTMP_efl	40.343	100	70.613	0.728006	0.024017	0.016959	22772.92	4.40719	386.2022	N/A	0.001293	0.998707	70.59604	247.3291	0.573089	17460.45	0.00397	0.003071	0.992958	N/A	N/A	0	0	0	0	0	0	N/A	N/A
CTMP soft	CTMP_pul	53.41519	100	151.4047	4.186781	3.7	5.601975	22749.98	4.455658	127444.8	N/A	0.000956	0.999044	145.8028	283.9153	0.742365	41395.63	0.002881	0.002006	0.994956	N/A	N/A	0.000157	0	0	0	0	0	N/A	N/A
CTMP soft	Wash_rej	47.95506	100	2.372447	3.302471	0.805266	0.019104	22810.05	1.728878	436.7743	0.622561	2.92E-05	0.37742	2.363342	630.7688	0.608226	1484.415	0.019191	0.001536	0.974825	N/A	N/A	0.004448	0	0	0	0	0	N/A	N/A

FIGURES

CHARTS

TABLES